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Devices performance tuned by molecular film-forming properties and electron trap for WORM memory application

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1. Introduction

With information technology progressing, research for appropriate materials and technologies to achieve high-density data storage devices has intrigued many scientists' interests. Organic materials are promising candidates for molecular-scale device applications in the future due to their good processability, excellent scalability, low-cost potential, 3D stacking capability and large capacity for data storage [1–6]. At present, material research is mainly concentrated on polymers or organic/inorganic doped materials [7–9]. Small molecules are rarely reported in this field [10,11] but are frequently employed in Organic Field Effect Transistors (OFET) and Organic Light-Emitting Diodes (OLED) [12-15]. Therefore, it is necessary to research into the memory materials. The azo double bonds showed excellent storage performance in the related literature in which some have even exceeded the "binary" to "ternary" [16-18,10]. In addition, the materials including 8hydroxyquinoline showed excellent performance in OFET and OLED [19-22].

In recent years, Naphthalene amine compounds with larger conjugated plane and good electronic liquidity have attracted many

ABSTRACT

Small molecules with different film-forming properties and electron traps were synthesized and characterized in the meantime. An electrical memory device with the indium-tin-oxide (ITO)/Small-Molecule/Al sandwich structure was fabricated and its electrical performance was investigated. WORM storage devices with different threshold voltages were obtained, some of which present "ternary" property. The relationship between turn-on voltage and the energy barrier between active materials and electrodes was revealed by the cyclic voltammetry measurement. The molecular film-forming properties and electron traps are responsible for device performances collectively, which could be elucidated unambiguously from UV–vis absorption spectra and X-ray diffraction patterns.

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scientists' attention. Therefore, it is necessary to research into memory materials consisted of the 8-hydroxyquinoline and azo double bonds. In this paper, a series of small molecules containing azonaphthalene and 8-hydroxyquinoline chromophore was synthesized and characterized. Meanwhile, flexible chains different in length were adopted to modulate molecular film-forming properties so as to adjust the performance of the memory devices. We obtained the WORM storage devices with different threshold voltages, and some of them exhibited promising ternary behavior. UV–vis absorption spectra and X-ray diffraction patterns were introduced to explain the conductance switching mechanism attributed to the molecular film-forming properties and electron traps collectively.

2. Experimental

2.1. Materials

 α -Aminonaphthalene, naphthol, 8-Hydroxyquinoline, p-Toluenesulfonic Acid Methyl Ester, Sodium nitrite, concentrated hydrochloric acid, 1-Bromobutane, 1-Bromooctane, Sodium Hydroxide, Tetrahydrofuran, and N, N-dimethylformamide were purified by vacuum distillation. Other solvents were obtained from commercial source and used as received.





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2.2. Route

The synthesis routes are shown in Fig. 1.

2.2.1. Preparation of azo intermediate

1-Aminonaphthalene (2.86 g, 0.02 mol), water (8 mL) and concentrated hydrochloric acid (8 g. 0.08 mol) were mixed in 100 mL flask with stirring, and heated to 80 °C for 30 min. Then the mixture was put into an ice-salt bath and stirred rapidly to precipitate the hydrochloride salt as fine crystals. Keeping the temperature at 0-5 °C and the solution of sodium nitrite (0.024 mol) in 10 mL water was added dropwise into the mixture with stirring. After 30 min, urea (5 mg) was added to consume the residual sodium nitrite and confirmed by the starch-iodide paper. Then filtered and the diazonium salt solution was obtained. 8-Hydroxyguinoline (2.90 g, 0.02 mol) and NaOH (2 g, 0.05 mol) were dissolved in 200 mL water and the solution was kept at 0-5 °C. The solution of the diazonium salt was slowly added and reacted for 30 min, after adjusting pH to 7–8 and continue reaction for 4 h, then the solution was filtered, and dried at 80 °C under vacuum at 10^{-3} Torr overnight. The obtained mixture was recrystallized from ethanol to give yellow powder (yield 74.5%). ¹H NMR (400 MHz, DMSO) δ 9.28 (d, J = 8.3 Hz, 1H), 8.93 (d, J = 8.1 Hz, 1H), 8.68 (s, 1H), 8.26 (d, J = 9.1 Hz, 1H), 7.96 (d, J = 8.0 Hz, 1H), 7.91–7.80 (m, 2H), 7.60 (dt, J = 14.8, 7.4 Hz, 4H), 6.68 (d, J = 9.0 Hz, 1H).

2.2.2. Preparation of compound 1

Azo intermediate (0.60 g, 0.002 mol) and potassium carbonate anhydrous (0.414 g, 0.003 mol) were dissolved in 50 mL DMF, and stirred for 2 h at 80 °C. Then the solution of p-Toluenesulfonic Acid Methyl Ester (0.56 g, 0.003 mol) in 10 mL DMF was added dropwise with stirring. The mixture was heated to 125 °C and reacted for 4 h. The solvent was removed through vacuum evaporation and the obtained mixture was purified by chromatography on a silica gel column to give yellow powder (yield 78%). ¹H NMR (400 MHz, DMSO) δ 9.38 (d, *J* = 8.6 Hz, 1H), 9.06–8.93 (m, 2H), 8.18 (dd, *J* = 20.3, 8.3 Hz, 2H), 8.09 (d, *J* = 7.9 Hz, 1H), 8.01 (d, *J* = 7.3 Hz, 1H), 7.73 (ddd, *J* = 25.6, 14.0, 5.6 Hz, 4H), 7.43 (d, *J* = 8.6 Hz, 1H), 4.12 (s, 3H).

2.2.3. Preparation of compounds 2 and 3

Azo intermediate (0.60 g, 0.002 mol) and potassium carbonate anhydrous (0.414 g, 0.003 mol) were dissolved in 50 mL DMF, and

stirred for 2 h at 80 °C. Then the solution of 1-Bromobutane or 1-Bromooctane (0.003 mol) in 10 mL DMF was added dropwise with stirring. The mixture was heated to 125 °C and reacted for 4 h. The solvent was removed through vacuum evaporation and the obtained mixture was purified by chromatographed on a silica gel column to give yellow powder.

(Compound 2 yield 90%). ¹H NMR (300 MHz, CDCl₃) δ 9.43 (dd, J = 8.5, 1.5 Hz, 1H), 9.16–8.92 (m, 2H), 8.15 (d, J = 8.6 Hz, 1H), 8.05–7.88 (m, 3H), 7.73–7.55 (m, 4H), 7.21 (d, J = 8.7 Hz, 1H), 4.33 (t, J = 7.0 Hz, 2H), 2.20–2.04 (m, 2H), 1.16 (t, J = 7.4 Hz, 3H).

(Compound 3 yield 84%). ¹H NMR (400 MHz, CDCl₃) δ 9.47 (d, J = 8.6 Hz, 1H), 9.11 (d, J = 4.0 Hz, 1H), 9.00 (d, J = 8.4 Hz, 1H), 8.16 (d, J = 8.6 Hz, 1H), 8.00 (d, J = 8.1 Hz, 1H), 7.94 (t, J = 7.6 Hz, 2H), 7.64 (ddd, J = 22.8, 13.4, 7.3 Hz, 5H), 7.22 (d, J = 8.7 Hz, 1H), 4.36 (t, J = 7.1 Hz, 2H), 2.17–2.04 (m, 2H), 1.63–1.52 (m, 2H), 1.39 (ddd, J = 32.6, 19.7, 10.5 Hz, 8H), 0.89 (t, J = 6.6 Hz, 3H).

2.2.4. Preparation of compound 4

The synthesis of compound 4 is similar to compound 2 to give compound 4 (orange powder, yield 79%). ¹H NMR (400 MHz, CDCl₃) δ 9.06 (dd, *J* = 13.6, 8.5 Hz, 2H), 8.38 (d, *J* = 8.4 Hz, 1H), 8.14 (dd, *J* = 8.3, 3.9 Hz, 1H), 8.03–7.92 (m, 3H), 7.74–7.56 (m, 5H), 6.96 (d, *J* = 8.5 Hz, 1H), 4.27 (t, *J* = 6.4 Hz, 2H), 2.02–1.93 (m, 2H), 1.71–1.59 (m, 2H), 1.06 (t, *J* = 7.4 Hz, 3H).

2.3. Instruments

¹H NMR spectrum was obtained on an Inova 400 MHz (or 300 MHz) FT-NMR spectrometer. UV–vis absorption spectra were recorded by a Perkin–Elmer Lambda-17 spectrophotometer at room temperature. SEM images were taken on a Hitachi S-4700 scanning electron microscope. X-ray diffraction (XRD) analysis was performed on film using a Shimadzu XRD-6000 spectrometer with a Cu KR monochromatic radiation source at 40 kV and 30 mA. The 2θ angle was scanned from 5° to 30°.

2.4. Fabrication and measurement of the memory devices

The indium-tin-oxide (ITO) glass was pre-cleaned with water, acetone, and alcohol, in that order, in an ultrasonic bath for 30 min. The active organic film was deposited under high vacuum about 10^{-6} Torr. The film thickness was about 80 nm. A layer of Al, about 80 nm in thickness was thermally evaporated and deposited



Fig. 1. The synthetic route of the Azo.

onto the organic surface at about 5×10^{-6} Torr through a shadow mask to form the top electrode. The active device area about 0.0314 mm² was obtained (as shown in Fig. 2). All electrical measurements of the device were characterized under ambient conditions, without any encapsulation, using an HP 4145B semiconductor parameter analyzer equipped with HP 8110A pulse generator.

3. Result and discussion

3.1. Characterization of compounds 1-4

The ¹H NMR spectra of compounds 1–4 are shown in Figure S1 in the supporting information.

3.2. Memory effect of the compound

The memory effect of compound 1 is demonstrated by the typical *I*–*V* curves of this sandwich device, as shown in Fig. 3(a). In the first voltage scan from 0 to -4.0 V (sweep 1), a sharp current increase occurred from 10^{-6} A to 10^{-3} A at a threshold voltage around -2.05 V, indicating the transition from a low-conductivity state (OFF state, "0") to an intermediate-conductivity state (ON1 state, "1"). This electrical transition serves as the "writing" process for the memory device. And the current could further increase to the high-conductivity state (10^{-2} A, ON2 state, "2") at a threshold voltage around -2.77 V. The cell remained in this high-conductivity state during the subsequent scan from 0 to -4.0 V (sweep 2). Sweep 3 was operated on another cell of the device over a voltage range from 0 to -2.5 V and showed one switching threshold voltages at -2.07 V. The intermediate-conductivity state was maintained during the subsequent scan from 0 to -2.5 V (sweep 4). ON2/OFF

Al

а

current ratio is up to 10^4 , and ON1/OFF current ratio is about 10^3 , allowing a voltage (e.g., -1.0 V) to read the "0" or "OFF" signal (before writing), "1" or "ON1", and "2" or "ON2" signal (after writing) of the memory device (as shown in Fig. 3(b)). The storage cells in the device show highly repeatable *I*–*V* characteristics. As long as the devices were activated to ON state, it would not return to the original OFF state. Therefore the memory device fabricated with compound 1 exhibits ternary WORM (write once read many times) memory behavior.

The conductance switching effect of Compound 2 is similar to that of compound 1 (as shown in Fig. 3(c)). In the first sweep from 0 to -4.0 V, two abrupt increases in current were observed at a switching threshold voltage of -1.72 V and -2.35 V, respectively, indicating the transition from a low-conductivity ("0") state to an intermediate-conductivity ("1") state and then to a high-conductivity state ("2"). And a constant voltage of -1 V can be used to read all the different states. Compared with compound 1, the device of compound 2 would lower the switching threshold voltages measurably. In addition, the ON2/ON1 current ratio is about 10^2 , which means that the device has a lower misreading rate. The differences in performance may be associated with the flexible chain in molecules.

In order to understand the effect of flexible chain on the device, compound 3 was synthesized and characterized. Fig. 3(e) is the I-V curves of this sandwich device. As can be seen, the threshold voltage is at -2.2 V; ON/OFF current ratio is up to 10^4 . And only one switching threshold voltage could be observed. Once the device was switched to the ON state, neither the subsequent repeated voltage sweep (sweep 2 on cell "1") or the reverse voltage sweep (sweep 3 on cell "1") could switch the device to the original OFF state. The storage cells in the device show highly repeatable I-V characteristics (cell 2 sweep 1-3). This device

Fig. 2. Illustration of the sandwich device. (a) Schematic diagram of memory device based on compound; (b) Optical image of the prototype device. (c) SEM image of the cross section of a storage cell.



Fig. 3. (a) Current–voltage (I-V) characteristics of the memory device based on compound 1; (b) Effect of retention time on the ON2, ON1 and OFF states of the memory device under a constant stress of -1.0 V; (c) Current–voltage (I-V) characteristics of the memory device based on compound 2; (d) Effect of retention time on the ON2, ON1 and OFF states of the memory device under a constant stress of -1.0 V; (e) Current–voltage (I-V) characteristics of the memory device based on compound 2; (d) Effect of retention time on the ON2, ON1 and OFF states of the memory device under a constant stress of -1.0 V; (e) Current–voltage (I-V) characteristics of the memory device based on compound 3; (f) Effect of retention time on the ON2, ON1 and OFF states of the memory device under a constant stress of -1.0 V.

exhibits typical binary WORM behavior. This "binary" storage performance can be explained by the long flexible chain which exerts amorphous properties onto the film, and the evidence is presented as follows.

3.3. Memory mechanism discussion

Fig. 4 shows the electrostatic potential (ESP) of the compounds. The surface of these molecules has a continuous positive ESP (in red) along the conjugated backbone, which indicates that charge carriers can migrate through this open channel. However, there are negative ESP regions (blue) caused by electron—acceptor groups. These negative regions can serve as "traps" that impede the mobility of the charge carriers. In the first stage, electrons fill the first trap (the trap of Azo), making the molecule partially

conductive. As the applied voltage is increased to the other switching threshold voltage, electrons fill the second trap and the whole molecule becomes conductive.

X-ray diffraction (XRD) analysis was carried out to clarify the film properties at the device level. The XRD results (as shown in Fig. 5) show that the film of compounds 1 and 2 has some sharp diffraction peaks at $6.4^{\circ}-17.3^{\circ}$. These peaks indicate that the films of compound 1 and 2 are crystalline, and the film of compound 2 has a better crystallinity. But the film of compound 3 shows amorphous morphology. These results are in correspondence with performance of the devices, and indicate that the flexible chain will affect the morphology of molecular films as well as the electrical memory performances.

In addition, the UV–vis absorption spectra of the compounds can also be supported by the results of X-ray diffraction patterns.



Fig. 4. Molecular simulation results for ESP surfaces of compounds 1–4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



Fig. 5. X-ray diffraction (XRD) scans of thin films of compounds 1-3.

Fig. 6(a) is UV-vis spectra of compounds 1–3. The maximum absorption peaks of the compound at 410 nm are due to the π - π ^{*} electronic transition of the aromatic ring. Each compound exists as a free state in solution, so their spectra are similar. But obvious change took place during the film-forming process (Fig. 6(b)) that all of the absorption bands were broadened. And the film of compound 2 has the best crystallinity because it has the largest redshift. The result is consistent with XRD analysis. This demonstrates that the properties of the film are very important to the performance of the memory device. In addition, from Fig. 6(a) the band gap between the HOMO and LUMO level of compounds 1–3 can be estimated to be about 3.20 eV.

In order to verify the effect of the "electron traps" on the device performance, compound 4 was synthesized and characterized. Fig. 7 is the *I*–*V* curves, UV–vis absorption spectrum and X-ray diffraction (XRD) analysis of compound 4. It shows an excellent crystalline film. And the band gap between the HOMO and LUMO level of compound can be estimated to be about 3.36 eV from the UV–vis absorption spectrum. Since compound 4 only has one "trap" (the trap of Azo), it exhibits typical "binary" WORM behavior, and the turn-on voltage is -2.08 V with ON/OFF current ratio up to 10^4 . These indicate that molecular film-forming properties and electron traps are collectively responsible for device performances. The charge transport mechanism can be obtained from the *I*–*V* curves in OFF and ON states according to theoretical models shown in Figure S2. The OFF state follows the Poole-Frenkel model



Fig. 6. UV-vis spectrum of compound in DMF solution (a) and films (b).

and the ON state conforms to the ohmic current model for all of the devices. And the detailed explanation is shown in the supporting information.

The HOMO and LUMO energy level of compounds 1–4 and the work function of Al top and ITO bottom electrodes were considered here to understand the turn-on voltage of the devices. Fig. 8 is the cyclic voltammetry (CV) curves of the films on ITO substrate in acetonitrile with 0.1 M n-Bu4NPF6 as the supporting electrolyte. The HOMO energy levels can be calculated from the onset oxidation potential based on the reference energy level of ferrocene (Fig. 6(a)).

HOMO (eV) = $-(E_{OX} + 4.8 - E_{FOC})$

LUMO (eV) = HOMO - $E_{UV edge}(bandgap)$

wherein E_{OX} is the onset oxidation potential and E_{FOC} is the external standard potential of the ferrocene/ferricinium ion couple. And the results are listed in Table 1. The energy barrier between ITO (-4.8 eV) and HOMO energy level of the molecule is much lower than that between Al (-4.28 eV) and the LUMO energy level, which indicates that hole injection from ITO into the



Fig. 7. (a) *I–V* characteristics of the memory device fabricated with compound 4; (b) Stability of the device in three states under a constant "read" voltage of –1 V; (c) UV–vis spectrum of compound in DMF solution and film; (d) X-ray diffraction (XRD) scans of thin films of compound 4.



Fig. 8. Cyclic voltammetry (CV) curves of compounds 1-4 film on ITO substrate in acetonitrile with 0.1 M n-Bu4NPF6 as the supporting electrolyte.

HOMO of compound (corresponding to ITO as the anode) is easier than electron injection from Al into LUMO of the compound. Thus, the compound is a p-type material and holes predominate the conduction process, and the turn-on voltage increases with the energy barrier [23].

To further confirm that the performance of the devices is arising from the intrinsic properties of the organic films and not from metallic filaments, a liquid-Hg droplet was used as the top electrode in place of the Al contacts. Compound 2 was selected as a representative. Together with the good reproducibility and stability of the memory phenomena observed in the devices, as well as the structure dependent electrical switching behavior (as shown in Fig. 9). The possibility of electrical transition due to filament conduction and Azo molecules degradation effects can be ruled out. In addition, the work function of liquid-Hg metal is about 4.5 eV, resulting in a higher energy barrier for electron injection into the LUMO. Because hole injection occurs from the ITO electrode, with hole transport as the main conduction mechanism, the change in the top electrode probably does not have a great effect on the electrical behavior of the devices. Thus,

 Table 1

 The energy barrier between the HOMO and LUMO of compounds 1–4.

	Compound 1	Compound 2	Compound 3	Compound 4	Al	ITO
HOMO (eV)	-5.38	-5.23	-5.63	-5.49	-4.28	-4.8
LUMO (eV)	-2.18	-2.03	-2.43	-2.13		
Energy gap	0.58 eV 2.10 eV	0.43 eV 2.25 eV	0.83 eV 1.85 eV	0.69 eV 2.15 eV	Homo Al – Ll	— ITO JMO

similar conductance switching and the associated memory property were observed in the devices using Hg as the top electrode. The observed memory effect with a different metal electrode provides additional evidence that the memory effect observed is intrinsic to the Azo molecules and not due to external effects associated with the use of an Al electrode [24]. The high surface tension of the cold deposited Hg electrode also reduces the



Fig. 9. Current density–voltage (J-V) characteristics of the ITO/compound 2/Hg memory device.

possibility of short circuits if any pinholes were present, as well as damage to the polymer film.

4. Conclusions

In this study, devices with a simple sandwich structure based on compounds 1–4 with film thickness of 80 nm were fabricated and their electrical characteristics were investigated. All the devices show WORM memory behavior, with ON2/OFF current ratio of approximately 10^4 and its ON1/OFF counterpart about 10^3 . The ON2, ON1 and OFF states are all stable under a constant read voltage stress of -1.0 V and can even endure 10^8 read cycles under a pulse read voltage. We obtained the WORM storage devices with different threshold voltages, and some of them exhibit promising ternary behavior. UV–vis absorption spectra and X-ray diffraction patterns were measured to understand the effect of the molecular film-forming properties and electron traps on the device's performances. Filament conduction and Azo molecules degradation effect can be ruled out by the similar memory behavior of the device utilizing liquid-Hg instead of the Al as top electrode.

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Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.dyepig.2012.04.021.

References

- Scott JC, Bozano LD. Nonvolatile memory elements based on organic materials. Adv Mater 2007;19:1452–63.
- [2] Ling QD, Liaw DJ, Zhu CX, Chan DSH, Kang ET, Neoh KG. Prog Polym Sci 2008; 33:917-78.
- [3] Ouyang JY, Chu CW, Szmanda CR, Ma LP, Yang Y. Programmable polymer thin film and non-volatile memory device. Nat Mater 2004;3:918–22.
- [4] Liu CL, Hsu JC, Chen WC, Kenji SY, Hirao A. Non-volatile memory devices based on polystyrene derivatives with electron-donating oligofluorene pendent moieties. ACS Appl Mater Interf 2009;1:1974–9.

- [5] Lee TJ, Park S, Hahm SG, Kim DM, Kim K, Kim J, et al. Programmable digital memory characteristics of nanoscale thin films of a fully conjugated polymer. J Phys Chem C 2009;113:3855–61.
- [6] Yang Y, Ouyang JY, Ma LP, Tseng RJH, Chu CW. Electrical switching and bistability in organic/polymeric thin films and memory devices. Adv Funct Mater 2006;16:1001–14.
- [7] Ling QD, Chang FCY, Song Y, Zhu CX, Liaw DJ, Chan DSH, et al. Synthesis and dynamic random access memory behavior of a functional polyimide. J Am Chem Soc 2006;128:8732–3.
- [8] Chu CW, Ouyang JY, Tseng JH, Yang Y. Organic donor-acceptor system exhibiting electrical bistability for use in memory devices. Adv Mater 2005; 17:1440-3.
- [9] Kondo TS, Lee SM, Malicki M, Domercq B, Marder SR, Kippelen B. A nonvolatile organic memory device using ITO surfaces modified by Ag-nanodots. Adv Funct Mater 2008;18:1112–8.
- [10] Li H, Xu QF, Li NJ, Sun R, Ge JF, Lu JM, et al. A small-molecule-based ternary data-storage device. J Am Chem Soc 2010;132:5542–3.
- [11] Lee WY, Kurosawa T, Lin ST, Ueda THM, Chen WC. New donor-acceptor oligoimides for high-performance nonvolatile memory devices. Chem Mater 2011;23:4487–97.
- [12] Tsuji H, Mitsui C, Sato Y, Nakamura E. Bis(carbazolyl)benzodifuran: a highmobility ambipolar material for homojunction organic light-emitting diode devices. Adv Mater 2009;21:3776–9.
- [13] Dong YM, Bolduc AD, McGregor N, Skene WG. Push-pull aminobithiophenes – highly fluorescent stable fluorophores. Org Lett 2011;13:1844–7.
- [14] Li RJ, Hu WP, Liu YQ, Zhu DB. Micro- and nanocrystals of organic semiconductors. Acc Chem Res 2010;43:529–40.
- [15] He YD, Dong HL, Meng Q, Jiang L, Shao W, He LF, et al. Mica, a potential twodimensional-crystal gate insulator for organic field-effect transistors. Adv Mater 2011;23:5502–7.
- [16] Li NJ, Lu JM, Li H, Kang ET. Nonlinear optical properties and memory effects of the azo polymers carrying different substituents. Dyes Pigm 2011;88: 18–24.
- [17] Lim SL, Li NJ, Lu JM, Ling QD, Zhu CX, Kang ET, et al. Conductivity switching and electronic memory effect in polymers with pendant azobenzene chromophores. ACS Appl Mater Interf 2009;1:60–71.
- [18] Li H, Li NJ, Gu HW, Xu QF, Yan F, Lu JM, et al. Two different memory characteristics controlled by the film thickness of polymethacrylate containing pendant azobenzothiazole. J Phys Chem C 2010;114:6117–22.
- [19] Kumar PK, Misra A, Bhardwaj R, Kamalasanan MN, Jain SC, Chand S, et al. Synthesis and characterization of some 5-coordinated aluminum-8hydroxyquinoline derivatives for OLED applications. Displays 2008;29: 351–7.
- [20] Wang FX, Xiong T, Qiao XF, Ma DG. Origin of improvement in device performance via the modification role of cesium hydroxide doped tris(8hydroxyquinoline) aluminum interfacial layer on ITO cathode in inverted bottom-emission organic light-emitting diodes. Org Electron 2009;10: 266–74.
- [21] Tang AW, Teng F, Qian L, Hou YB. Electrical bistability of CdS nanoparticles sandwiched between aluminum tris (8-hydroxyquinoline) layers. Solid State Commun 2009;149:107–10.
- [22] Onlaor K, Tunhoo B, Thiwawong T, Nukeaw J. Electrical bistability of tris-(8hydroxyquinoline) aluminum (Alq3)/ZnSe organic–inorganic bistable device. Curr Appl Phys 2012;12:331–6.
- [23] Chi CY, Wegner G. Chain-length dependence of the electrochemical properties of conjugated oligofluorenes. Macromol Rapid Commun 2005;26: 1532-7.
- [24] Colle M, Buchel M, de Leeuw DM. Switching and filamentary conduction in non-volatile organic memories. Org Electron 2006;7:305–12.