Ladder-type conjugated oligomers prepared by the Scholl oxidative cyclodehydrogenation reaction: synthesis, characterization and application in field effect transistors†

Wei Huang, Hejian Zhang, Ji Ma, Moyun Chen, Haoyun Zhu and Weizhi Wang*

Two novel well defined ladder-type conjugated oligomers have been successfully designed and synthesized through a solution processing method in an excellent yield. The field effect transistors (FETs) fabricated by these ladder-type oligomers with a nice planar structure exhibit excellent charge carrier mobilities, up to 0.10 cm² V⁻¹ s⁻¹ and 0.33 cm² V⁻¹ s⁻¹; furthermore, the devices can work well with a low gate voltage. The ladder-type oligomers are both converted from two precursor co-oligomers, poly(2,7-(1,2-diphenylethene)-9,9-diocetylfluorene) (PDPF), via an anhydrous FeCl₃ oxidative cyclodehydrogenation. The pronounced red shift shown in the preliminary photoluminescence spectra and the changes of band gaps measured by electrochemical analysis both testify that the better electronic transmission capacity in the FET performance is due to the expanded molecular chain planarization after the chemical cyclodehydrogenation. Interestingly, the precursor oligomers having a linear-type chain and a zigzag-type chain (L-PDPF and Z-PDPF, respectively) show many characteristic differences in their thermal, optical and electrochemical properties. The differences caused by the different types of main chains demonstrate that the macromolecular configurations have a tremendous impact on the functioning of the oligomers.

Introduction

Graphene as a promising two dimensional material has attracted great interest for a wide range of electronic applications, and the related research has developed rapidly in recent years. It can be obtained by a great number of physical methods, such as the mechanical exfoliation of graphite, the unzipping of carbon nanotubes, lithography and the reduction of graphite oxide. Inspired by these developments, many research groups have devoted plenty of effort to the design and synthesis of diverse graphene-like materials in the fields of oligomers and macro-molecules. Within this research, the conjugated oligomer is a category of significant materials. The applications of conjugated oligomers in photovoltaic cells, electroluminescent diodes, thin film transistors and chemical sensors have been paid more and more attention. Compared to small molecules, the conjugated oligomers, especially those with ribbon- or ladder-type frameworks, not only form graphene-like structures, but also possess some unique characteristics such as largely defect-free accurate structures and excellent film forming properties. In addition, unlike the zero-band gap graphene, ladder-type conjugated oligomers (LCOs) with different band gaps show an outstanding semiconducting nature and are fit to be applied in manifold electronic devices as the active materials.

Up to now there exist two principal chemical methods to synthesize ladder-type materials: one is the polymerization of some multifunctional monomers, generating a ladder type material in just a single reaction; the other is the cyclization of suitably functionalized open-chain precursors in a polymer-homologous process. Compared with physical methods, chemical synthesis could precisely control the structure to give the desired shape and dimension of the achieved products. Because it is more atom-economical and straightforward, late-stage cyclization by the direct transformation of C–H bonds has been studied by many chemists and W. R. Dichtel’s group have both employed an efficient way to prepare well defined polycyclic aromatic hydrocarbons by the Scholl oxidative cyclodehydrogenation reaction, in which a precursor for a potential graphene-like molecule is oxidized by an iron(III) chloride (FeCl₃)–nitromethane system. Inspired by the above examples and the properties of LCOs, we propose to develop a method for synthesizing a novel type of LCO to

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† Electronic supplementary information (ESI) available: Experimental section including materials, measurements and characterizations; mass spectra, NMR data for new compounds and oligomers, cyclic voltammetry figures and GPC data for the oligomers. CCDC 1043775 and 1043776. For ESI and crystallographic data in CIF or other electronic formats see DOI: 10.1039/c5tc00354g
overcome the drawbacks of small molecules. Moreover, the LCOs will be applied to manufacture high-performance semiconductor devices like FETs.\textsuperscript{39,40}

In this work, 9,9-dioctylfluorene and two isomers of 1,2-diphenylethene were chosen as the monomeric units. The reason for choosing fluorene is that the fluorene-based polymers have exhibited favourable chemical and thermal stability and exceptionally high photoluminescence, electroluminescence and fluorescence quantum efficiency in thin solid films.\textsuperscript{41–45} Moreover, the long alkyls in the 9-position of the fluorene unit can make the target oligomers exhibit good solubility in common organic solvents. Prior to the polymerization, the cis and trans isomers of the 1,2-diphenylethene monomers were successfully synthesized, and the isomers were used to obtain two alternating co-oligomers only differing in their configurations: one is (\(Z\))-poly(2,7-(1,2-diphenylethene)-9,9-dioctylfluorene) (\(L\)-\(\text{PDPF}\)) which possesses a linear-type chain, and the other, (\(E\))-poly(2,7-(1,2-diphenylethene)-9,9-dioctylfluorene) (\(Z\)-\(\text{PDPF}\)), has a zigzag-type chain. Interestingly, the disparate fluorescence emission colours of these two oligomers under the same UV irradiation inspired us to consider the influence of the different configurations on their performance as well. Therefore, we further investigated how the different configurations affect the properties of these oligomers. Most importantly, \(L\)-\(\text{PDPF}\) and \(Z\)-\(\text{PDPF}\) can be converted into oligomers of a ladder type (\(L\)-\(\text{PDPF-O}\) and \(Z\)-\(\text{PDPF-O}\)) after the FeCl\(_3\) oxidation. Accordingly, the corresponding model molecules of the precursor oligomers, (\(E\))-1,2-diphenylethene-1,2-bis(9,9-dioctyl-9H-fluoren-2-yl) (\(L\)-\(\text{DPBF}\)) and (\(Z\))-1,2-diphenylethene-1,2-bis(9,9-dioctyl-9H-fluoren-2-yl) (\(Z\)-\(\text{DPBF}\)) and their oxidation products \(L\)-\(\text{DPBF-O}\) and \(Z\)-\(\text{DPBF-O}\) were synthesized to elucidate the cyclodehydrogenation. The efficient planarization of the precursor oligomers into the LCOs was corroborated by \(^1\)H NMR and FT-IR spectra. Subsequently, these LCOs were fabricated into FETs as the semiconductor layer to measure their performance. Additionally, the relevant properties to prove whether the intramolecular cyclization enhances the electronic transmission capacity by extending the molecular plane are all discussed as well in this work.

### Results and discussion

The overall synthetic procedures for the model molecules, monomers and oligomers are clearly outlined in Scheme 1. It is easy to see that the linkages of 1,2-diphenylethene in the obtained \(L\)-\(\text{PDPF}\) and \(Z\)-\(\text{PDPF}\) actually exhibit cis-trans isomerism, so these two precursor oligomers possess different main chain configurations. To acquire these two configurations, the monomers 1 and 2 were directly synthesized according to the methods described in the literature.\textsuperscript{46,47} What is more, the pure single crystals of these monomers were both fortunately recrystallized from their CH\(_2\)Cl\(_2\)-n-hexane solution. The accurate structures of 1 and 2 were identified by the X-ray crystallographic analysis in Fig. 1 plus the data in the ESI (Table S1). Another fluorene derivative monomer,
2,7-dibromo-9,9-dioctylfluorene, was prepared in advance as reported.\textsuperscript{48} Normally, the long alkyl chains in the 9-position can enhance the solubility of the oligomer in organic solvents like THF and toluene, which allows solution-processing and thus is beneficial to the degree of polymerization.

The elemental approach employed for the synthesis of the precursor is a Suzuki cross-coupling reaction,\textsuperscript{49} as described in Scheme 1. Obviously, the difference between these two oligomers is that \textit{L-PDPF} presents a linear-type main chain and \textit{Z-PDPF} has a zigzag-type chain, as pictured in the schematic. The much more flexible zigzag-type chain enables the building blocks in its twisted chain to rotate more easily. As displayed in Table 1, the $M_w$ values of \textit{L-PDPF} and \textit{Z-PDPF} were determined, using gel permeation chromatography (GPC, Fig. S1 and S2, ESI\textsuperscript{†}) with THF as the eluent and polystyrene as the standard, to be 9900 and 6800. Their polydispersity indices (PDIs) calculated by means of $M_w/M_n$ are 1.32 and 1.36, respectively. THF and toluene were both tested as the solvent in the polymerization. The reaction temperature was 60 °C when the solvent is THF, which led to products with a lower degree of polymerization. The molecular mass increased obviously when toluene was selected to replace THF and the reaction temperature was brought up to 95 °C. This is likely due to the low temperature negatively influencing the activities of the monomers, which results in a deviation of their actual concentration ratio in solution; thereby the monomers could not react in the envisioned proportion in this alternating copolymerization.

After that, we expected to obtain the LCOs with greater conjugated planarization via one-step chemical cyclization. An efficient reaction route, called the Scholl reaction on the basis of ref. 50, was adopted. Herein, anhydrous FeCl$_3$, which has been used for the synthesis of polycyclic aromatic hydrocarbons because of its avoidance of severe disadvantages such as dealkylation, chlorination or migration of the alkyl substituents, is utilized as an oxidant for these transformations.\textsuperscript{51} At the end, methanol is poured into the mixture to consume the extra anhydrous FeCl$_3$, and the oxidized products are purified through column chromatography.

All the prepared monomers and final products were carefully purified and further characterized by nuclear magnetic resonance (NMR) spectra, and the successful intramolecular cyclization can demonstrated by these $^1$H NMR spectra. For instance, the $^1$H NMR spectra of \textit{Z-PDPF} and \textit{Z-PDPF-O} are shown in Fig. 2a. It is pronounced that the peaks within the 7–8 range representing the hydrogens on the phenyl rings were weakened drastically after the oxidative cyclodehydrogenation, which might

<table>
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<th>Table 1</th>
<th>Molecular weights of \textit{L-PDPF} and \textit{Z-PDPF}</th>
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<td>Oligomer</td>
<td>Yield (%)</td>
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<tr>
<td>\textit{L-PDPF}</td>
<td>44.7</td>
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<tr>
<td>\textit{Z-PDPF}</td>
<td>52</td>
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Fig. 1 The ORTEP drawings of \textit{1} and \textit{2}.

Fig. 2 (a) $^1$H NMR spectra of \textit{Z-PDPF} and \textit{Z-PDPF-O}; (b) $^1$H NMR spectra of \textit{Z-DPBF} and \textit{Z-DPBF-O}: $R$: C$_8$H$_{17}$. 

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indicate the formation of C–C bonds between the phenyl rings to produce more six-membered rings in the backbones to take on a ladder-type structure. The detailed $^1$H NMR spectra of the model compounds (Z-DPBF and Z-DPBF-O) in the ESI† (Fig. S19 and S21) demonstrate clearly the cyclization between the substituted phenyl rings. Simultaneously, the corresponding $^3$H NMR spectra of the products in the L-PDPF system exhibit the same trend. The complete $^1$H NMR and $^13$C NMR spectra of all the synthesized products, which are included in the ESI† (Fig. S3–S22), could also be further evidence to illustrate the success of these syntheses. Moreover, the decline of the aromatic proton signals after cyclization has been reported in ref. 15, 16 and 37. However, the reason for the decline has lacked a reliable and reasonable explanation until now. A variable-temperature experiment (25 °C to 50 °C) of Z-PDPF-O in 1,1,2,2-tetrachloroethane-$d_2$ solution was carried out (Fig. S23, ESI†). The unchanged spectra at different temperatures indicate that the chemical shifts of the aromatic resonances are independent of temperature, and it is not attributed to aggregation.

Moreover, the mass spectrometric data of the small molecules 1 and 2 and the model molecules are used to demonstrate the successful synthesis in the ESI† (Fig. S24–S29). The divergences between the mass spectral data of the model molecules before and after chemical oxidation also testify to the successful synthesis of the expected oxidized products. Exactly four hydrogens are removed after the oxidation. The cyclization process could be further confirmed by the measurement of Fourier transform infrared (FT-IR) spectra, as shown in Fig. 3. From Fig. 3a and b, the band at about 4050 cm$^{-1}$ can be taken as a palpable marker of the existence of the free rotating phenyl rings in the molecules, therefore, it is distinctly observed in the spectra of L-PDPF and Z-PDPF. The disappearance of this peak in the spectra of the obtained LCOs indicates the absence of the hydrogens on the substituted phenyl rings. Altogether, the changes after the cyclodehydrogenation demonstrate the restrictions to the movement of the substituted phenyl rings. Additionally, in Fig. 3c and d, the pronounced disappearance of the characteristic peaks of these oligomers can be observed by comparing the spectra from before and after the oxidation. These reveal the disappearance of the out of plane C–H deformation bands at 698, 728 and 775 cm$^{-1}$, which are typical for mono- and disubstituted phenyl rings, and the noticeable triad of peaks of the aromatic C–H stretching vibrations at 3023, 3056 and 3079 cm$^{-1}$ are attenuated, which verifies the efficient conversion from PDPF into PDPF-O.

The UV-vis absorption and photoluminescence (PL) data of the oligomers in THF are listed in Table 2. L-PDPF-O displays an absorption wavelength ($\lambda_{abs}$) at 405 nm, resulting in a 3 nm red shift compared with that of L-PDPF. The related absorption spectra of the obtained oligomers are displayed in the ESI† (Fig. S30), and their PL spectra have a similar red-shifted behaviour with the emission peak moving from 418 nm to 447 nm. For Z-PDPF and its oxidized product Z-PDPF-O, the corresponding spectral shift shows a similar trend: the absorption maximum of Z-PDPF is at 420 nm, compared with 451 nm for Z-PDPF-O. Furthermore, their emission wavelengths exhibit a similar red shift from 498 nm to 551 nm. All of these bathochromic-shifted tendencies indicate that the broader planarization of the molecular chain and the degree of conjugation after the oxidation are increased because of the cyclization between the substituted phenyl rings. The PL efficiencies ($\Phi_e$) of the oligomers were measured in dilute THF solution using quinine sulfate ($\Phi_e = 54\%$ in 0.1 M H$_2$SO$_4$) or fluorescein ($\Phi_e = 92\%$ in 0.1 M NaOH) as standards.

It could be observed intuitively by our naked eyes from Fig. 4a that L-PDPF emits luminous blue light, while Z-PDPF emits faint yellow light under the same 365 nm UV irradiation. We consider the tremendous intensity difference to be induced by the molecular configurations. The zigzag chains of Z-PDPF...
are more flexible than the linear chains of L-PDPF, so the zigzag chains can deactivate excited species through nonradiative rotations to consume the excited energy. After the cyclization, L-PDPF-O emits purple fluorescent light and Z-PDPF-O emits redder light with stronger intensity as demonstrated in Fig. 4b, which is consistent with the red-shifted behaviour as noted earlier. The stronger intensity of Z-PDPF-O is owing to the broader planarization, which promotes the rigidity of the zigzag chains to hinder the rotations of the building units so that more excited energy is consumed by emitting light. The lifetime (τ) of L-PDPF-O is 0.507 ns, as long as the 0.501 ns of L-PDPF. However, the τ of Z-PDPF-O is 1.988 ns, compared to 1.114 ns for Z-PDPF, showing a greater change after the oxidation. This is likewise due to the stronger rigidity of the chains after the intramolecular cyclization. In addition, the insert photograph of Fig. 4c shows the emitted light of all the four oligomers in the solid state. L-PDPF emits a green light and Z-PDPF emits a strong yellow light. Through comparison between Fig. 4a and the insert photograph in Fig. 4c, it is seen that Z-PDPF has a remarkable aggregation-induced emission (AIE) phenomenon; some non-luminescent dyes can be induced to emit light effectively by aggregate formation.52,53 The changed fluorescence lifetime and the AIE phenomena are both caused by steric interactions in the materials. Parts of the chains of Z-PDPF are able to pack closer through a π-π stacking process owing to their twisted zigzag shape, which weakens the transfer of electronic quenching.

At the same time, the rotations of segments in their chains are mainly restricted due to the physical constraint. This restriction of intramolecular rotations blocks the nonradiative pathways and opens up a radiative channel. As a result, Z-PDPF becomes emissive in the solid state. From this photograph, L-PDPF-O and Z-PDPF-O in the solid state both show a red-shift to emit redder light, as we anticipated in advance.

Likewise in the insert photograph, we can observe directly that Z-PDPF-O on the right possesses redder light with stronger intensity. The further proof to illustrate this phenomenon is the PL emission spectra of the oligomers in the solid state in Fig. 4c. L-PDPF-O shows a red shift from 438 nm to 480 nm while Z-PDPF-O has a longer wavelength emission light at 595 nm compared to 510 nm. The emission wavelength of Z-PDPF-O is indeed closer to the visible red light range. It’s supposed that the intramolecular cyclization broadens the conjugated plane in the backbones of the LCOs to boost electron transmission in the delocalization. Although there are still some rotations between different segments, the chemical oxidation expands the cofacial surface at different rotation degrees on the main chain to result in a greater conjugated planarity in the whole molecule. According to the studies carried out by F. Cacialli54 and A. C. Grimsdale,55 the ratio of cis-linkage in the main chains can influence the emission wavelength, and the oligomer consisting of more cis-1,2-diphenylethene was found to exhibit a more pronounced red-shift of the emission wavelength. The PL measurements in our work are consistent with this phenomenon as well, showing that Z-PDPF and Z-PDPF-O with cis-1,2-diphenylethene in the repeat units both emit longer wavelength light in the solid state than L-PDPF and L-PDPF-O.

The thermal properties of the synthesized oligomers L-PDPF and Z-PDPF measured using thermal gravimetric analysis (TGA) in N2 both show marvellous thermal stability. The onset decomposition temperature of L-PDPF is 415 °C and the other one is 419 °C as illustrated in Fig. 5a. Nevertheless, the differential scanning calorimetry (DSC) measurements (Fig. 5b) exhibit clear divergence in that Z-PDPF has a glass transformation at around 130 °C and 240 °C; however, L-PDPF does not have a glass transformation within the measured temperature range. This difference in the glass transformation indicates that the main chain of Z-PDPF in the solid state is more flexible than L-PDPF, which leads to significant relationships with the linear and nonlinear configurations because of the trans- and cis-linkages of 1,2-diphenylethene. The more twisted zigzag shape configuration of the Z-PDPF chain increases the intermolecular interactions like π-π packing to make up more crystalline regions, which makes it manifest some glass transformations. However, the rigid linear chains of L-PDPF are less flexible, causing the formation of amorphous regions instead of ordered crystallization, so there is no glass-transition temperature.

To explore the electrochemical redox behaviour of the oligomers, it’s well known that the lowest unoccupied molecular orbital (LUMO), the highest occupied molecular orbital (HOMO) and the energy band gaps (ΔEg) are three crucial parameters for electro-luminescent materials. In order to better understand the relationship between the electronic structure and the optical properties,
and also to explain the pronounced fluorescence red-shift, cyclic voltammetry analyses of the synthesized compounds coated on a glassy carbon electrode were carried out in an electrolyte of 0.1 M tetrabutylammonium hexafluorophosphate (TBAPF₆) in acetonitrile using ferrocene as the internal standard at a scan rate of 100 mV s⁻¹ at room temperature under the protection of argon. An Ag/AgNO₃ electrode was used as the reference electrode and a Pt wire was applied as the counter electrode. According to the empirical relationships, the HOMO value can be derived from the equation: 

$$\text{HOMO} = -\left( \frac{E_{\text{onset-ox}} - 0.0468 \text{ V}}{4.8 \text{ eV}} \right),$$

where $E_{\text{onset-ox}}$ is the onset oxidation potential determined from cyclic voltammetry in acetonitrile for oxidation potentials and the value 0.0468 V is for FOC vs. Ag/Ag⁺. LUMO = Δ$E_g$ + HOMO. The corresponding data of the oligomers are summarized in Table 3, and the cyclic voltammograms can be found in the ESI† (Fig. S31).

The oxidation onset values of L-PDPF, L-PDPF-O, Z-PDPF and Z-PDPF-O versus an Ag electrode appear at 0.98, 0.80, 0.82 and 1.00 V, respectively. The band gaps of L-PDPF, L-PDPF-O, Z-PDPF and Z-PDPF-O are 3.00, 2.74, 2.81 and 2.68 eV, respectively, based on their onset oxidation potentials and the onset wavelengths of their UV absorptions. The narrower band gaps after the oxidation clearly show that cyclization can decrease the energy levels of electronic migration in the conjugated backbone. Differences in the band gaps and HOMOs between the oligomers may originate from their different extents of conjugation; additionally the band gaps show the same trend compared with the PL spectra red shift from L-PDPF and Z-PDPF to their oxides. The measured values match well with the shifts in optical measurements and are in agreement with the increased degree of molecular conjugation.

Afterwards the LCOs were applied as the semiconductor in FETs to measure their performance. The fascinating part is that ion gel is used as the gate dielectric instead of some typical inorganic oxides like SiO₂, ZrO₂ and Al₂O₃.⁵⁶–⁵⁹ The gate dielectric is another significant factor that influences the FET performance. Although some research groups have made several high-performance FETs with an inorganic dielectric,⁶⁰–⁶² organic dielectrics like ion gel possess distinctive advantages. Besides the promising mechanical flexibility, ion gel, with extraordinarily high capacitance, allows low voltage operation which effectively diminishes the heat generated by the devices.⁶³,⁶⁴ Therefore, ion gel was chosen to combine with the synthesized LCOs to fabricate the FETs in this work.

Fig. 6a is a photograph of the FET devices prepared by us, and the inserted 3D model simply displays the device structure...
of the thin film top-gate FET with ionic gel as the dielectric and aluminium as the gate layer. The obtained LCOs were spin-coated on the Si/SiO2 substrates as the solution processing thin-film semiconductor. The gold drain and source electrodes (typical channel length is 1000 μm with a width/length ratio of about 1) were vapor-deposited between the dielectric and the oligomer semiconductor layers. Fig. 6b and c show the typical output and transfer characteristic curves of the FET devices with L-PDPF-O as the semiconductor layer after thermal annealing at 150 °C in a vacuum environment. Meanwhile, Fig. 6d and e show the same characteristic curves of the FET devices containing Z-PDPF-O.

The output curves in Fig. 6b and d both confirm clear p-channel FET characteristics with the oligomer layer in devices. The key device parameters for these two devices, such as the charge carrier mobility (μ) and on-to-off current ratio (Ion/Ioff), are estimated from the drain-source current (ID) versus gate voltage (VG) characteristics at VDS = 1 V, employing the metal-oxide semiconductor FET formula for the saturation regime:

\[ I_D = \frac{\mu W C_i (V_G - V_{TH})^2}{2L} \]

where W is the channel width, L is the channel length, C_i is the gate oxide capacitance per unit area, and V_{TH} is the threshold voltage. From a linear relationship between the [ID]1/2 versus [VG] curve obtained at VDS = 1 V (Fig. S32, ESIF), the V_{TH} values of the devices with L-PDPF-O and Z-PDPF-O were evaluated to be −1.0 V and −2.7 V, respectively. The C_i of the prepared ion gel was measured to be 20 μF cm⁻². The transfer characteristics have a low conductivity at the low VG of around 0 V, which shows a promising air stability due to the low HOMO energy levels (−5.35 eV and −5.75 eV) of the obtained LCOs. According to the V_{TH} and the transfer characteristics, the balanced value of μ for L-PDPF-O is 0.10 cm² V⁻¹ s⁻¹ with an Ion/Ioff of 2.1 × 10³, and μ for Z-PDPF-O is 0.33 cm² V⁻¹ s⁻¹ with an Ion/Ioff of 8.2 × 10³. The excellent μ and Ion/Ioff of the devices involving the obtained LCOs at a low operating voltage is a great advantage in the practical application of the organic FETs.

Conclusions

In summary, two well defined alternating co-oligomers, L-PDPF and Z-PDPF, consisting of 9,9-dioctylfluorene and 1,2-diphenylethene have been successfully designed and synthesized via a palladium-catalyzed Suzuki cross-coupling reaction in good yields. These two oligomers were exceptionally converted into the ladder-type conjugated oligomers L-PDPF-O and Z-PDPF-O by the anhydrous FeCl₃ oxidative cyclodehydrogenation, which presents a relatively straightforward solution processing method. This intramolecular cyclization was clearly corroborated by the ¹H NMR and FTIR spectra of the oligomers and their model molecules. In addition, the preliminary photoluminescence spectra showing pronounced red shifts and changes of the band gaps measured by electrochemical analysis both testified that the expanded planarization of L-PDPF-O and Z-PDPF-O increased their electronic transmission capacity. Subsequently, the FET devices fabricated with the ladder-type conjugated oligomers as the semiconductor layer not only exhibited excellent air stability, but also possessed good performance. Their mobilities were up to 0.10 cm² V⁻¹ s⁻¹ and 0.33 cm² V⁻¹ s⁻¹ respectively, showing their potential to conform to the actual requirements in practical FET applications.

Additionally, we presented the similarities and differences between the two precursor oligomers caused by the cis–trans isomerism in the linkage of 1,2-diphenylethene, which resulted in a linear and a zigzag shaped chain: L-PDPF emitted green light while Z-PDPF emits yellow light in the solid state; both of them possessed excellent thermal properties and high fluorescence efficiency in solid films; Z-PDPF underwent a glass transition at around 130 °C and 240 °C, however L-PDPF didn’t show a clear glass transition, which may be owing to the easier rotation of the building blocks because of the more flexible zigzag chains; moreover, Z-PDPF displayed an obvious AIE phenomenon because the excited energy is mainly consumed by a nonradiative route, like the rotation of chains in solution, while this non-radiative way is restrained in the solid state. The next studies in the future will take full advantage of the solution processing of the conjugated oligomer films to make high performance electrical devices with some other fabricating techniques, such as ink-jet printing.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (21274027 and 20974022) and the Innovation Program of Shanghai Municipal Education Commission (15ZZ002). H. J. Zhang thanks the FDUROP (Fudan’s Undergraduate Research Opportunities Program) for support.

Notes and references

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