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276 Graphical Abstract

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**Controlled emission enhancement and quenching by self-assembly of low-molecular-weight thiophene derivatives**
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Controlled emission enhancement and quenching by self-assembly of low-molecular-weight thiophene derivatives

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Abstract—Three thiophene-containing compounds were newly synthesized as low-molecular-weight blocks to construct non-covalent and highly ordered π-conjugation systems. Typical emission enhancement and quenching based on the J- and H-type orientations, respectively, of the thiophene moiety were realized and controlled by lipid membrane-like phase transition and separation behaviours. © 2010 Elsevier Science. All rights reserved

π-Conjugated molecules such as polythiophene have attracted considerable attention for their potential as alternatives to inorganic semiconductors with many advantages over existing materials, including mechanical flexibility, processability and lightweight solutions. However, it is common knowledge that the low solubility and miscibility of unmodified polythiophenes is a major limitation in precisely controlled fabrication, especially at the nano level. To overcome this, many chemical modifications have been developed, e.g., polyalkylthiophene, poly(3,4-alkylene dioxythiophene), conjugated oligomer-pendant polymer and so on. Another solution is to adopt self-assembling low-molecular-weight derivatives containing a thiophene moiety. In this approach, a long-range π-conjugation would be realized by molecular ordering of the thiophene moieties; good examples are thiophene derivatives modified by alkoxys, alkylureido and cholesteryl groups. Furthermore, Park et al. modified this system by developing new kinds of the thiophene-containing self-assembling compounds such as 2,3-bis[5-(trifluoro-methylphenyl)]thiophen-2-yl]acrylonitrile, which have neither steroidal nor long alkyl chain groups as an electro-inactive moiety and can exhibit J-type aggregation leading to strong fluorescence emission on nano-crystallization.

Here we introduce a new class of low-molecular-weight thiophene derivatives (gT and gBT) and one terthiophene-containing compound (gT3) that exhibit emission enhancement and control through lipid membrane-like functions such as phase transition and separation behaviours. © 2010 Elsevier Science. All rights reserved

Two kinds of the monothiophene-containing compounds (gT and gBT) and one terthiophene-containing compound (gT3) were newly synthesized (Scheme 1). All compounds were functionalized by the didodecyl L-glutamide (g) unit which is known as a versatile self-assembling tool for the creation of nano-sized fibrillar aggregates both in aqueous and non-aqueous systems. Table S1 summarizes the dispersity (solubility) of these compounds in various organic media from methanol to n-hexane. Clearly, gT and gBT show good dispersity in all of the solvents used in this work whereas gT3 shows relatively poor dispersity especially in polar alcohols and non-polar n-hexane. This is further proof that monothiophene derivatives have better processability (directly related to dispersity) than polythiophene derivatives.

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Scheme 1
Table 1. Minimum gelation concentrations of thiophene derivatives at 10°C

<table>
<thead>
<tr>
<th>Solvent</th>
<th>gT</th>
<th>gBT</th>
<th>gT3</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-hexane</td>
<td>1 mM</td>
<td>1 mM</td>
<td>I</td>
</tr>
<tr>
<td>methylcyclohexane</td>
<td>1 mM</td>
<td>1 mM</td>
<td>1 mM</td>
</tr>
<tr>
<td>cyclohexane</td>
<td>1 mM</td>
<td>1 mM</td>
<td>1 mM</td>
</tr>
<tr>
<td>toluene</td>
<td>30 mM</td>
<td>3 mM</td>
<td>1 mM</td>
</tr>
<tr>
<td>benzene</td>
<td>30 mM</td>
<td>1 mM</td>
<td>3 mM</td>
</tr>
<tr>
<td>chloroform</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>ethyl acetate</td>
<td>30 mM</td>
<td>3 mM</td>
<td>1 mM</td>
</tr>
<tr>
<td>tetrahydrofuran</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>dichloromethane</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>acetone</td>
<td>S</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>ethanol</td>
<td>S</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>methanol</td>
<td>S</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>acetonitrile</td>
<td>S</td>
<td>1</td>
<td>I</td>
</tr>
</tbody>
</table>

S: soluble, I: insoluble in 1.0 mM.

On the other hand, mass gelation behaviours were observed by adjusting temperature and concentration in certain solvents. Table 1 summarizes apparent minimum gelation concentrations (mgc) in various solvents at 10°C. For example, the mgc is ~1 mM in methylcyclohexane (MCH), cyclohexane and n-hexane at 10°C. Mass gelation was also observed in other solvents such as benzene, toluene and ethyl acetate at higher concentration: the mgc in benzene is 3 mM in gBT at 10°C. Such thermotropically and lyotropically induced gelation resemble the low-molecular mass gelation through nano-fibrillar aggregation from cholesteryl, sugar-containing and peptide derivatives. In fact, TEM indicated that fibrillar aggregates were produced in our thiophene derivatives; the gBT MCH solution (0.25 mM) shows well-developed fibrils with 20–30 nm diameters, showing that gelation was brought about by the formation of a three-dimensional network from the one-dimensional fibrils. Similar fibril formations were observed with gT and gT3 as well.

The special properties of gBT and gT3 were furthermore emphasized in the fluorescence study. As shown in Fig. 1 and 2 remarkable enhancement of the fluorescence intensity was observed with a slight red shift in the absorption spectrum in a gBT MCH solution on changing the temperature from 90 to 25°C, while gT3 showed remarkable fluorescence quenching. Similar fluorescence enhancement phenomenon has been called aggregation-induced emission enhancement (AIEE), and the typical examples are seen in solvent-dependent crystallization of non-planar and long range π-conjugated molecules such as hexaphenylsiloles, poly (phenylene-ethynylene) and bis(3,5-ditrifluoromethyl-phenyl)cyanostilbene. The fluorescence quenching is called aggregation-caused quenching (ACQ), and it is rather common in planar π-conjugated molecules such as pyrene. However, it should be noted that there are some distinct differences between our fluorescence enhancement system and the previous AIEEs. Firstly, the chromophoric moiety of gBT is benzothiophene which is much smaller than the previous AIEE π-conjugated molecules. Secondly, our chromophore is planar and promotes plane-to-plane stacking, whereas AIEE is achieved by moderation of intramolecular torsional structure and suppression of intramolecular vibration/torsional motions by aggregation. Thirdly, gBT exhibits emission enhancement even at higher concentration than 0.025 mM, which is minimum assembly concentration (mac) at gBT in MCH. Finally, this emission enhancement is induced thermotropically in gBT. The origin of these differences can be probably explained by the molecular ordering assisted with the g moiety, whereas the previous AIEE was related to the specific structure of the chromophoric groups.

We obtained several results that elucidate the mechanism of the emission enhancement in gBT: a gBT solution showed a temperature-dependent red-shift on absorption of a benzothiophene moiety in UV spectroscopy. This spectral change was accompanied by specific chirality induction. As shown in Fig. 2, there is almost no CD signal at 90°C although one exception is seen at around 250 nm. New
Cotton effects appear with decreasing temperature at around 230, 285 and 320 nm which correspond to those observed in UV spectroscopy. The [α] values reach -9.6, -5.2 and 1.0 × 10^4 deg cm^2 dmol^-1 at 230, 285 and 320 nm, respectively. Since the benzothiophene moiety has no chiral structure and almost no CD signals was detected in a good solvent such as chloroform promoting disaggregation, the specific chiroptical behaviours are assigned to induction of secondary chirality such as chiral π - π stacking with a J-type (head-to-tail) orientation^10,11 among the thiophene moieties (Fig. 3). In addition, neither a red shift nor induction of CD were observed in benzothiophene without the g moiety, and thus these specific chiral arrangements must be promoted by chirally self-assembling property of the g moiety.

By contrast, gTg showed a blue shift with induced CD (Fig. 2) indicating a H-type (head-to-head) orientation^11-13 and gTg showed no significant spectral changes under the same condition. Interestingly, all of the thiophene derivatives (gTgBT and gTg) can form nano-sized fibrillar aggregates at 0.10 ~ 0.25 mM in MCH. These results suggest that their critical aggregation concentrations are much lower than their mgc and their stacking structures are remarkably tuned by the chemical structures around the thiophene moieties. Furthermore, it is presumed that an asymmetric structural thiophene such as BT tends to exhibit J-type stacking^15, whereas a symmetric structural thiophene such as Tg tends to exhibit H-type stacking (Fig. 3). On the basis of these assumptions, gTg must be similar to gTg but the thiophene-thiophene interaction may be too weak to allow detection of the stacked structure by UV and CD spectroscopy.

On the basis of these results, we conclude that the emission enhancement and quenching with the g derivatives are closely related to J- and H-type orientations among the thiophene moieties, respectively. In addition to the above, we found that emission control could be achieved by phase separation phenomenon^12,20 in a binary component system. The successful example was obtained as follows: a β-aminoopropanoyl l-glutamide derivative (gAP)10 was selected as the matrix component because of its good solubility in a wide range of solvents (from water to n-hexane) as well as its high self-assembling ability in these media. A mixed system composed of gBT and gAP (1 : 5) was prepared by dissolution in hot MCH. At 90 °C, the fluorescence intensity was very similar to that observed in a system with gBT alone. There was no significant CD induction in the absorption band around the thiophene moiety. Therefore, it is estimated that gBT is in monomeric or disordered states at 90 °C regardless of gAP. On the other hand, the fluorescence intensity increased when temperature was reduced (Fig. 4a): e.g. 1.3 and 1.7 folds at 25 and -5 °C, respectively. Further increase (3.8 fold) was observed by addition of a small amount (1.0 eq.) of sulphuric acid. According to the concentration dependency of sulphuric acid on the fluorescence intensity (Fig. 4b), the critical enhancement occurs in the range of 0.75-1.0 eq. of sulphuric acid against gAP. Additionally it was confirmed that the UV and CD spectra approached those in a system with gBT alone. These results indicate that the binary component system provides a phase separation-induced emission enhancement. Such similarity to lipid membrane functions clearly is based on the characteristics of the lipid-like g moiety.

In conclusion, we have established controlled aggregation-induced emission enhancement and quenching in a new class of low-molecular-weight thiophene derivatives. The solubility was considerably improved by derivatization of monothiophene, and intramolecular π-conjugation was realized through controlling the molecular ordering states, viz., the J- and H-type orientations of the thiophene moiety. In addition, we realized emission control by using the phase separation behaviour in a binary component system. This success is due to use a lipid-like self-assembling unit, and therefore, may have possible applications in molecular switching devices.
Experimental

Synthesis of N,N'-Didodecyl-N'-(2-thienocarboxy)-L-glutamide (gT)

2-Thiopheneacetic acids (0.217 g, 1.69 mmol) and triethylamine (0.187 mL, 1.69 mmol) and N,N'-didodecyl-l-glutamide (gT) were dissolved in THF (100 mL) at 0 °C. Diethyl cyanoformate (DEPC, 1.25 mL, 1.69 mmol) was added to the mixture at RT. After being stirred for 1 day at room temperature, the solution was concentrated in vacuo. The residue was redissolved in chloroform (50 mL), and the organic layer was washed with water (50 mL) and 0.5 N HCl (30 mL), then washed with water (30 mL), and dried with sodium sulfate. The solution was concentrated in vacuo, and the residue was purified by recrystallization from acetonitrile to give gT as white powders (60%): mp 120-121 °C; Found: C, 68.8; H, 10.3; N, 7.10. C34H61O3N3S requires C, 65.87; H, 8.95; N, 5.59; C; Found: C, 70.87; H, 10.29; N, 6.58; C38H63O3N3S + H2O requires C, 66.19; H, 8.63; N, 5.99; C42H65O3N3S + H2O requires C, 71.09; H, 9.89; N, 6.55%; FT-IR (KBr) 3305, 3099, 2955, 2920, 2850, 1656, 1631, 1543, 1468, 1443, 1317, and 799 cm⁻¹; δ H (400 MHz; CDCl₃; MeSi) 0.87 (6H, t, J = 7 Hz, -CH₃), 1.24 (36H, brs, -(CH₂)₈-CH₃), 1.47-1.52 (4H, m, -NHCH₂CH₂-), 2.14-2.20 (4H, m, -CHCH₂CH₃-), 2.31-2.62 (2H, m, -(C=O)CH₂CH₃-), 3.25 (4H, m, -(C=O)CH₂CH₃-), 4.47 (1H, q, J = 6 Hz, -CH₂-), 5.81 (1H, t, J = 6 Hz, -NHC=), 6.87 (1H, t, J = 6 Hz, -NH₂), 7.04 (1H, dd, J = 4, 3 Hz, -C=CHCH=CHS-), 7.10 (1H, d, J = 3 Hz, -CH=S), 7.13 (1H, d, J = 4 Hz, -C=CHCH=CHS-), 7.16 (1H, d, J = 4 Hz, -C=CHCH=CHS-), 7.20 (1H, d, J = 4 Hz, -C=CHCH=CHS-), 7.24 (1H, d, J = 4 Hz, -(C=O)CH₂CH₃-), 7.54 (1H, d, J = 3 Hz, -(C=O)CH₂CH₃-), and 8.10 (1H, d, J = 7 Hz, -NH₂).

Acknowledgments

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Supplementary data†

Synthesis and characterization of tiophene-derivatives. Experimental details: solubility, gelation properties, UV-vis spectra and TEM measurements.

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