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Rapid synthesis and fluorous-phase purification of α-perfluorohexyloligothiophenes

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Abstract—A high-throughput methodology that facilitates the synthesis, purification and characterisation of π-conjugated oligothiophenes has been developed. α-Perfluorohexyltetrathiophene was synthesised by sequential α-bromination and microwave promoted Stille cross-coupling reactions. Each synthetic transformation was followed by a fluorous solid-phase extraction (F-SPE) procedure to isolate the desired α-perfluorohexyloligothiophene. After a single F-SPE, each oligomer gave essentially one peak by GC–MS, which enabled stepwise growth of a tetrathiophene with no additional purification of the intermediate building blocks required. We anticipate that microwave accelerated synthesis in conjunction with fluorous-phase purification of π-conjugated systems will find generic application in the high-throughput parallel-synthesis of novel organic materials for semiconductor applications.

High-throughput synthesis, purification and characterisation of π-conjugated systems would facilitate the discovery of novel organic materials for semiconductor and optoelectronic applications.[1] Oligothiophenes have attracted great interest as organic semi-conducting components in thin film transistor devices due to their chemical/environmental stability, high carrier mobilities and excellent on/off ratios.[2]

Generally, oligothiophenes are synthesised by palladium-catalysed cross-coupling reactions.[3] These reactions have the inherent limitation of a slow conversion to product and can generate significant levels of impurity. Reaction times for palladium-catalysed cross-coupling reactions can be reduced considerably by microwave dielectric heating of the reaction mixture, which heats the reaction mixture homogeneously by coupling between the electromagnetic radiation and the molecular dipoles of the solvent(s)/reagent(s).[4]

Purification of oligothiophenes for use in organic electronic devices generally requires extensive chromatographic separation. This time-consuming process may be circumvented by employing a solid-phase synthetic strategy in which a thiophene residue is attached covalently to an insoluble support via a linker group. This thiophene can then be coupled sequentially with additional thiophene monomers to generate an oligothiophene of desired length.[5] Following each synthetic transformation the oligothiophene, tethered to the solid-support, is separated and purified simultaneously from by-product(s) and excess reagent(s) by simple washing and filtration procedures. However, there are several disadvantages associated with solid-phase synthesis. The unfavourable heterogeneous reaction kinetics necessitates the use of a large excess of reagent(s) to ensure a complete reaction. This can be problematic as selective α-bromination of thiophene immobilised on a polystyrene based resin may only be achieved with *N*-bromosuccinimide (NBS) in a stoichiometric amount, excess reagent leading to multiple bromination.[6] In addition, reaction conditions must be optimised from the solution-phase to the solid-phase and intermediate compounds must be cleaved from the insoluble-support to be analysed using conventional techniques.[7]

There is an imperative need for a generic high-throughput methodology that facilitates the synthesis, purification and characterisation of π-conjugated systems, which circumvents the limitations that are associated with both solution-phase and solid-phase techniques. Fluorous-phase techniques integrate the advantages of both solid-phase purification and solution-phase synthe-

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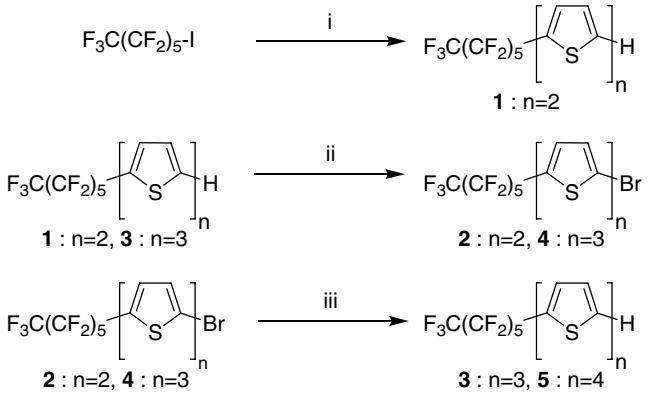
sis and characterisation.[8] In this approach, a fluorinated tagged compound is reacted with a stoichiometric amount of reagent(s) using solution-phase reaction conditions. Following each synthetic transformation the fluorinated compound is separated selectively from non-fluorinated molecules by employing a fluorous separation media.[9] For instance, fluorinated-compounds (>60% fluorine by molecular weight) can be efficiently partitioned into fluorous solvent from either organic or aqueous solvent in a liquid–liquid extraction procedure and fluorous-silica gel retains fluorinated-compounds (>40% fluorine by molecular weight) by selective adsorption. In a typical fluorous-solid phase extraction (F-SPE) procedure, the crude reaction mixture (5–15% weight of fluorous-silica gel) is loaded onto fluorous-silica gel and washed with a fluorophobic solvent to elute non-fluorinated compound(s) and then washed with a fluorophilic solvent to elute the fluorinated compound(s), which may be analysed using conventional solution-phase techniques without prior cleavage of the fluorous tag.[9]

A high-throughput approach for the preparation of oligothiophenes using fluorous-phase chemistry is reported for the first time. This approach is demonstrated by the preparation of α-perfluorohexyltetrathiophene **5** (Scheme 1). Related α,ω,-perfluorohexyl substituted oligothiophenes have been shown to be excellent n-type organic semiconductors ($\mu > 0.2\ cm^2\ V^{-1}\ s^{-1}$).[10]

Initially, Ullman type reaction conditions were employed to couple bromobithiophene with 1-iodoperfluorohexane to provide α-perfluorohexylbithiophene **1** (78%).[11] Bithiophene **1** was then reacted with a solution of NBS in *N*,*N*-dimethylformamide (DMF) to afford the corresponding bromide **2** (78%).[10a] A microwave promoted Stille cross-coupling reaction between bromide **2** and 2-(tributylstannyl)thiophene proceeded smoothly and rapidly (1 min) to give trithiophene **3** (90%). α-Bromination and Stille cross-coupling reactions were repeated sequentially to furnish the corresponding bromide **4** (88%) and finally the desired tetrathiophene **5** (54%).



Scheme 1. Synthesis of α-perfluorohexyloligothiophenes **1**–**5**. Reagents and conditions: (i) 5-bromo-2,2′-bithiophene, Cu, DMSO, 125 °C; (ii) NBS, DMF and (iii) 2-(tributylstannyl)thiophene, $Pd(PPh_3)_4$, ClC_6H_5, μW, 190 °C, 150 PSI, 1 min.

α-Perfluorohexyloligothiophenes **1**–**5** were isolated following each synthetic transformation by employing a F-SPE procedure. The crude product mixture of each reaction was loaded onto a F-SPE cartridge and washed with methanol/water (4:1) to elute non-fluorinated material. The F-SPE cartridge was then washed with methanol and tetrahydrofuran to elute the desired α-perfluorohexyloligothiophene **1**–**5**, which was confirmed rapidly by gas chromatography–mass spectrometry (GC–MS) (Fig. 1).

The α-perfluorohexyloligothiophenes **1**–**5** were isolated by a single SPE with sufficient purity to give essentially one peak in the chromatograph and a concomitant increase in retention time with increase in molecular mass. This highly efficient methodology enables the stepwise growth of tetrathiophenes with no additional purification of the intermediate oligomers required.

The optical absorption and emission spectra of **5** were determined both in solution ($\lambda_{max}^{ABS} = 396$ nm, $\lambda_{max}^{PL} = 488$ nm) and the solid state ($\lambda_{max}^{ABS} = 346$ nm and $\lambda^{ABS} = 450$ nm, $\lambda_{max}^{PL} = 559$ nm) (Fig. 2). Broad, unstructured signals are observed, consistent with the high degree of rotational freedom between individual thiophene residues both in the ground and excited states. A large molar extinction coefficient ($\varepsilon = 42{,}996\ mol^{-1}\ dm^3\ cm^{-1}$) indicates that these signals originate from the allowed π–π^* transition associated with the tetrathiophene core. The blue shift (50 nm) of the maximum absorption in the solid-state relative to the solution state is a consequence of H aggregation.[10a,12] The interaction between molecules of **5** with their long axis parallel results in coupling of the transition dipoles, which leads to Davydov splitting of the excited level into two excitation bands. The major absorption signal (346 nm) corresponds to the allowed high energy transitions and the small signal (450 nm) corresponds to low-energy transitions that are forbidden. The optical band gap (E_g^{op}) was estimated from the intercept of the normalised absorption and emission spectra both in solution ($E_g^{op} = 2.79$ eV) and the solid-state ($E_g^{op} = 2.49$ eV). In addition, the electrochemical behaviour of **5** was investigated by cyclic voltammetry to determine the energy level of the highest occupied molecular orbital (HOMO).[13] The voltammo-

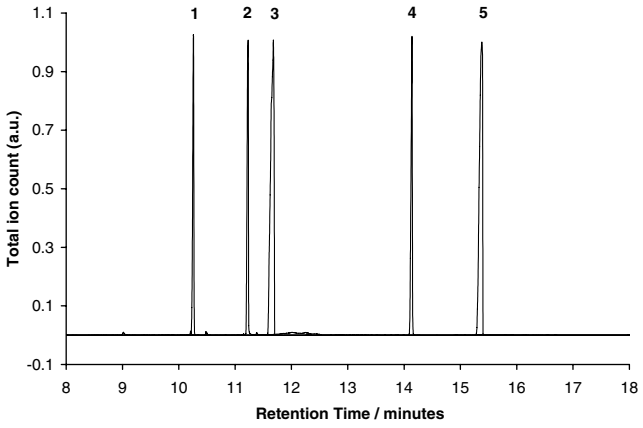


Figure 1. Gas-chromatogram of α-perfluorohexyloligothiophenes **1**–**5**.

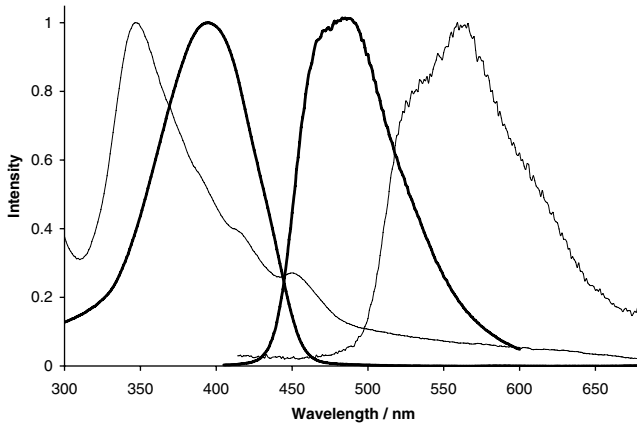


Figure 2. Optical absorption and emission spectra of **5** in CH_2Cl_2 (bold line) and as a thin-film (thin line). Emission spectra were obtained by exciting the solution and thin-film at 396 nm and 346 nm, respectively. Intensities are in arbitrary units.

gram showed a one-electron oxidation at 1.02 V (vs Fc/Fc^+), consistent with a value for the HOMO of 6.02 eV. The energy of the lowest unoccupied molecular orbital (3.23 eV) was calculated by subtraction of the optical band gap from the HOMO.

In conclusion, α-perfluorohexyltetrathiophene **5** was synthesised efficiently from α-perfluorohexylbithiophene **1** by sequential α-bromination and microwave promoted Stille cross-coupling reactions. Following each synthetic transformation a F-SPE procedure was employed to isolate the desired α-perfluorohexyloligothiophene compound in a high purity, which was confirmed by GC–MS. The optical absorption and emission spectra of **5** identified a high degree of rotational freedom between individual thiophene residues in both the ground and excited states and also H-aggregation in the solid-state. We anticipate that microwave accelerated synthesis in conjunction with fluorous-phase purification of π-conjugated systems will find generic application in the high-throughput parallel-synthesis of novel organic materials for semiconductor and optoelectronic applications. Further work is currently in progress to develop related systems in which the fluorous tag can be cleaved from the final product.

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Supplementary data

Experimental procedures and spectroscopic data. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2006.11.165.

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