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Reverse Selectivity in *m*-CPBA Oxidation of Oligothiophenes to Sulfones

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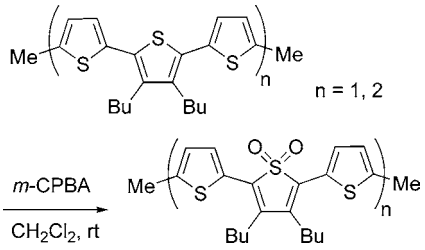
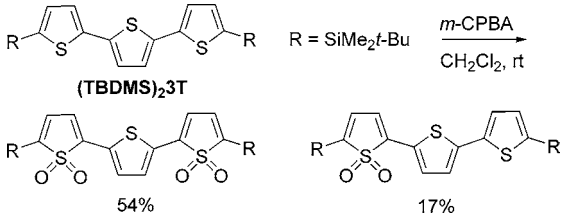
ABSTRACT



Oligothiophene sulfones of up to six rings can be conveniently prepared by the direct oxidation of butyl-substituted thiophene oligomers with *m*-CPBA in dichloromethane. Reverse selectivity of oxidized rings is observed relative to previously reported systems without *β*-substitution. The selectivity in the trimer and hexamer is confirmed with single-crystal X-ray structure data. The sulfones possess red-shifted absorptions and increased electron affinities relative to the parent oligomers.

Dominated by the work of Barbarella et al., oligothiophene sulfones (or *S*,*S*-dioxides) are an important class of organic materials for applications including opto-electronic devices and biodiagnostics.[1] Oligothiophene sulfones are attractive materials with highly modified redox and luminescent behavior in comparison to their parent oligomers.[2] The most common method for the synthesis of these materials utilizes Stille coupling of brominated thiophene *S*,*S*-dioxides with thienyl stannanes.[3] A convenient alternative first constructs the parent oligomer then oxidizes one or more rings with a suitable oxidant. For example, fully *S*,*S*-dioxygenated oligothiophenes can be obtained using the powerful oxygen-transfer agent HOF·CH_3CN, as reported by Amir and Rozen.[4] Barbarella et al. report that *m*-CPBA oxidation of a bis-silylated terthiophene **(TBDMS)$_2$3T** occurs predominantly at the terminal rings (Scheme 1).[2a] A substitution effect seems

Scheme 1. Oxidation of a Bis-silylated Terthiophene



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(1) For examples, see the following and references therein: Barbarella, G.; Melucci, M.; Sotgiu, G. *Adv. Mater.* **2005**, *17*, 1581−1593.

(2) (a) Barbarella, G.; Pudova, O.; Arbizzani, C.; Mastragostino, M.; Bongini, A. *J. Org. Chem.* **1998**, *63*, 1742−1745. (b) Barbarella, G.; Favaretto, L.; Zambianchi, M.; Pudova, O.; Arbizzani, C.; Bongini, A.; Mastragostino, M. *Adv. Mater.* **1998**, *10*, 551−554.

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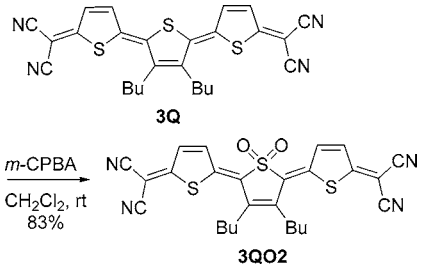
responsible as oxidation of both rings is the major product for 5,5′-diTBDMS-bithiophene but is not observed for 5,5′-dihexylbithiophene unless a more powerful reagent is used.[4] Barbarella also reports *m*-CPBA oxidation of longer oligomers was problematic, however, giving mixtures of partially oxygenated oligomers that were difficult to separate by chromatography or crystallization.[2a,3b]

Recently, we reported on the synthesis and physical properties of the quinoid-type oligothiophene sulfone **3QO2**.[5] This material was prepared in 83% yield by direct oxidation of the parent oligomer **3Q** with *m*-CPBA (Scheme 2).

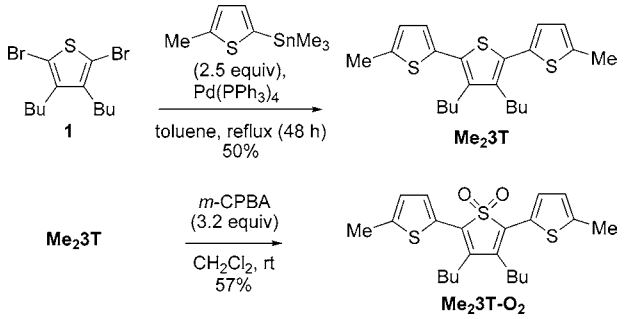
Scheme 2. Oxidation of a Quinoid-Type Terthiophene



Selectivity for the center ring is the reverse of that observed in the aromatic systems reported by Barbarella (vide supra). Reversed selectivity can be rationalized on an electronic basis from alkyl substitution of the center ring and/or the electron-withdrawing nature of the $=C(CN)_2$ groups of the outer rings. Application to aromatic systems should shed additional light on this selectivity. In this communication, we apply this method (i.e., direct oxidation) to β-alkyl-substituted oligothiophenes.

We chose aromatic oligothiophenes with the identical β-alkyl substitution pattern as **3Q** in our investigation. Methyl caps were chosen for the α positions due to their relative ease of synthesis and their ability to stabilize oxidized forms of oligothiophenes.[6] The preparation of a trimer is outlined in Scheme 3. Stille coupling[7] of 2,5-dibromo-3,4-dibutylthiophene **1**[8] with 2.5 equiv of trimethyl(5-methyl-2-thienyl)-stannane[9] afforded the trimer **Me$_2$3T** in 50% yield. Addition

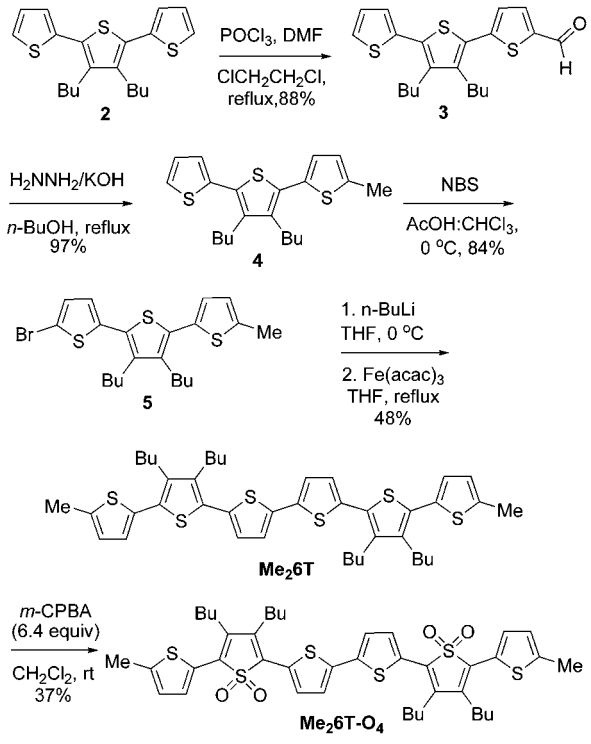
Scheme 3. Synthesis of **Me$_2$3T** and **Me$_2$3T-O$_2$**



of *m*-CPBA to **Me$_2$3T** resulted in the formation of a symmetric product by NMR analysis. Mass spectrometry, combustion analysis, and X-ray crystallography confirmed the structure to be the monosulfone **Me$_2$3T-O$_2$** with oxidation occurring on the sulfur of the middle thiophene ring. This selectivity, similar to that observed for the oxidation of **3Q**, is again the reverse of that for unsubstituted β-alkyl oligomers (vide supra).

To test the application of this method to longer systems, we prepared the analogous hexamer. The synthetic strategy was to first prepare the asymmetric methyl-capped trimer and dimerize via homocoupling.[6b] Scheme 4 outlines the

Scheme 4. Synthesis of **Me$_2$6T** and **Me$_2$6T-O$_4$**



synthesis of the hexamer **Me$_2$6T**. Direct routes to **4** from dibutylterthiophene[10] **2** using *n*-butyllithium/dimethyl sulfate[6b] were only mildly successful. The reaction afforded a mixture

(3) (a) Ridolfi, G.; Camaioni, N.; Samori, P.; Gazzano, M.; Accorsi, G.; Armaroli, N.; Favaretto, L.; Barbarella, G. *J. Mater. Chem.* **2005**, *15*, 895−901. (b) Barbarella, G.; Favaretto, L.; Sotgiu, G.; Zambianchi, M.; Antolini, L.; Pudova, O.; Bongini, A. *J. Org. Chem.* **1998**, *63*, 5497−5506.

(4) Amir, E.; Rozen, S. *Angew. Chem., Int. Ed.* **2005**, *44*, 7374−7378.

(5) Casado, J.; Zgierski, M. Z.; Ewbank, P. C.; Burand, M. W.; Janzen, D. E.; Mann, K. R.; Pappenfus, T. M.; Berlin, A.; Perez-Inestrosa, E.; Ortiz, R. P.; Lopez Navarrete, J. T. *J. Am. Chem. Soc.* **2006**, *128*, 10134−10144.

(6) (a) Yu, Y.; Gunic, E.; Zinger, B.; Miller, L. L. *J. Am. Chem. Soc.* **1996**, *118*, 1013−1018. (b) Miller, L. L.; Yu, Y. *J. Org. Chem.* **1995**, *60*, 6813−6819. (c) Zinger, B.; Mann, K. R.; Hill, M. G.; Miller, L. L. *Chem. Mater.* **1992**, *4*, 1113−1118. (d) Hill, M. G.; Penneau, J.-F.; Zinger, B.; Mann, K. R.; Miller, L. L. *Chem. Mater.* **1992**, *4*, 1106−1113. (e) Hill, M. G.; Mann, K. R.; Miller, L. L.; Penneau, J.-F. *J. Am. Chem. Soc.* **1992**, *114*, 2728−2730.

(7) (a) Stille, J. K. *Pure Appl. Chem.* **1985**, *57*, 1771−1780. (b) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508−523. (c) Stille, J. K.; Groh, B. L. *J. Am. Chem. Soc.* **1987**, *109*, 813−817.

(8) Araki, K.; Hiroaki, E.; Masuda, G.; Ogawa, T. *Chem.−Eur. J.* **2004**, *10*, 3331−3340.

(9) Seitz, D. E.; Lee, S.-H.; Hanson, R. N.; Bottaro, J. C. *Synth. Commun.* **1983**, *13*, 121−128.

of mono-, di-, and unmethylated oligomers which were difficult to separate on a column due to their similar retention times. Therefore, a polar intermediate strategy[11] was employed to obtain the desired monomethylated terthiophene arm **4**. Formylation of **2** using a Vilsmeier reagent (DMF/$POCl_3$)[12] afforded oligomer **3** in good yields. The polar end group provided easy separation on a column, and the reaction provided only traces of disubstituted oligomers. Subsequent Wolf−Kishner reduction[13] of **3** afforded the desired arm **4** in excellent yield. Bromination with NBS afforded oligomer **5** in 84% yield.

The hexamer **$Me_2$6T** was prepared in moderate yield by homocoupling of the organolithium species from oligomer **5** with $Fe(acac)_3$ in THF. Oxidation of the hexamer with *m*-CPBA was done analogously to that of the trimer. Once again, the reaction resulted in the formation of a symmetric product by NMR analysis. Given the fact that no starting material is recovered in this reaction, the low yield is attributed to oxidation beyond the bis-sulfone as evidenced by more polar compounds remaining on the column (but not isolated). Mass spectrometry, combustion analysis, and X-ray crystallography confirmed the structure is the bis-sulfone **$Me_2$6T-O_4** with oxidation occurring at the butyl-substituted rings. To our knowledge, such selectivity in long oligomers is unprecedented and formation of oligothiophene sulfones via direct oxidation beyond the tetramer has not yet been reported.[14]

The oxidized trimer and hexamer were characterized by X-ray crystallography. Single crystals were grown from CH_2Cl_2:2-propanol and CH_2Cl_2 solutions, respectively, for the trimer and hexamer. The asymmetric unit of **$Me_2$3T-O_2** consists of two crystallographically independent molecules, each with some positional disorder of the outer thiophene rings or butyl groups. The asymmetric unit of **$Me_2$6T-O_4** consists of exactly half the substituted sexithiophene molecule with an inversion center at the middle of the molecule. A methylene chloride solvent molecule is also present in the structure. Disorder is present in the *S*-oxidized thiophene rings and butyl groups in the structure of the hexamer. Transoid orientations of sulfur atoms in adjacent thiophene rings are present in the structures of both the trimer and hexamer (Figure 1).

The crystal packing of each oligomer, however, is unique. The structure of **$Me_2$3T-O_2** consists of adjacent stacks of molecules but not π-stacks typically seen with thiophene oligomers with electron-withdrawing substituents.[15] Molecules of **$Me_2$3T-O_2** pack in an antiparallel fashion orienting sulfone moieties in opposite directions. There is no π-stacking: molecules pack with butyl groups of adjacent molecules above and below the ring system. One molecule of the asymmetric unit pair is tilted with respect to the other; therefore, every other molecule in a stack is tilted. As a result of these packing effects, short contacts from the atoms of the thiophene rings to other thiophene rings are minimal (Supporting Information Figures S12−S13). Rather, almost all of the short contacts within the structure involve butyl groups, including contacts to the sulfone oxygen atoms. One more interesting close intermolecular contact (2.437 Å) occurs from a sulfone oxygen to an adjacent exterior thiophene hydrogen atom.

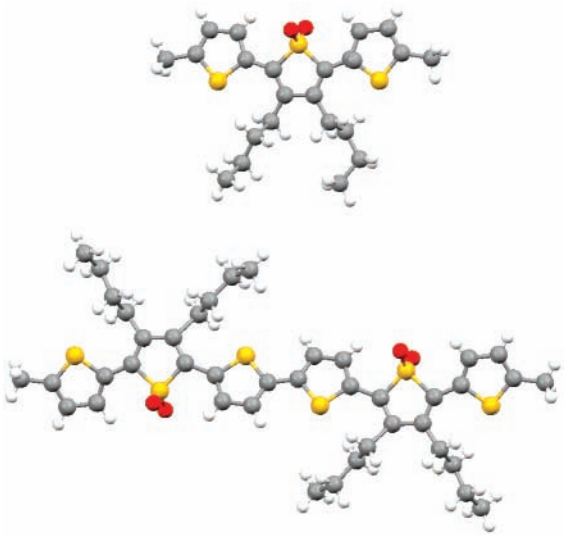


Figure 1. Molecular structures of **$Me_2$3T-O_2** (top) and **$Me_2$6T-O_4** (bottom) from X-ray crystallographic analyses. Solvent and/or disorder have been omitted for clarity.

The packing of **$Me_2$6T-O_4** molecules (Supporting Information Figures S14−S15) shows significant intermolecular interactions best described as π-stacks with the axis perpindicular to the π-stacking axis shifted 50% out of registry. The distance between the least-squares planes formed by the third and fourth ring bithiophene units of adjacent **$Me_2$6T-O_4** molecules is 3.511 Å. The overlap of one sexithiophene molecule with adjacent molecules (both above and below) is about 4 thiophene rings of one molecule and about 1 ring of overlap with another molecule. Two interesting close intermolecular contacts found in the structure are a sulfone oxygen atom close to the methyl group hydrogen atom of an adjacent sexithiophene (2.488 Å) and a sulfone oxygen atom close to a thiophene sulfur atom of an interior thiophene (3.664 Å). Structural variations in oligothiophene sulfones upon increasing the oligomer size have been reported previously and can have a significant effect on the solid-state properties (e.g., photoluminescence efficiencies).[16]

(10) Pappenfus, T. M.; Burand, M. W.; Janzen, D. E.; Mann, K. R. *Org. Lett.* **2003**, *5*, 1535−1538.
(11) Katz, H. E.; Laquindanum, J. G.; Lovinger, A. J. *Chem. Mater.* **1998**, *10*, 633−638.
(12) Wei, Y.; Wang, B.; Wang, W.; Tian, J. *Tetrahedron Lett.* **1995**, *36*, 665−668.
(13) Nakayama, J.; Nakamura, Y.; Tajiri, T.; Hoshino, M. *Heterocycles* **1986**, *24*, 637−640.
(14) Barbarella et al. and Rozen et al. have previously reported direct oxidation of quaterthiophenes in references 2a and 4, respectively.

(15) For example, see ref 10 and the following: (a) Yoon, M.-H.; Facchetti, A.; Stern, C. E.; Marks, T. J. *J. Am. Chem. Soc.* **2006**, *128*, 5792−5801. (b) Facchetti, A.; Mushrush, M.; Katz, H. E.; Marks, T. J. *Adv. Mater.* **2003**, *15*, 33−38. (c) Bader, M. M.; Custelcean, R.; Ward, M. D. *Chem. Mater.* **2003**, *15*, 616−618. (d) Pappenfus, T. M.; Chesterfield, R. J.; Frisbie, C. D.; Mann, K. R.; Casado, J.; Raff, J. D.; Miller, L. L. *J. Am. Chem. Soc.* **2002**, *124*, 4184−4185. (e) Pappenfus, T. M.; Raff, J. D.; Hukkanen, E. J.; Burney, J. R.; Casado, J.; Drew, S. M.; Miller, L. L.; Mann, K. R. *J. Org. Chem.* **2002**, *67*, 6015−6024.

UV−vis absorption, emission, and cyclic voltammetry data of methyl-capped oligomers are summarized in Table 1. The

Table 1. Spectroscopic and Electrochemical Data of the Oligomers

oligomer	abs_{max}, nm[a]	em_{max}, nm[a]	E^0_{ox}, V[b]	E^0_{red}, V[b]
$Me_2$3T	345	426, 445	0.82, 1.32[c]	*d*
$Me_2$3T-O_2	426	529	1.17, 1.44[c]	−1.55
$Me_2$6T	418	522, 554	0.72, 0.85	*d*
$Me_2$6T-O_4	496	617	1.09, 1.23	−1.32

[a] Measured in dry dichloromethane. [b] Potentials vs Ag/AgCl in 0.1 M $TBAPF_6$/dichloromethane solution. [c] Irreversible process; E_{pa} value provided. [d] No observable reduction processes.

electronic spectra of the oligomers were recorded in dichloromethane solutions (Supporting Information Figures S16−S17). Consistent with previously reported oligothiophene sulfones, a red shift in the electronic spectra is observed upon oxidation. For example, the parent oligomer **$Me_2$3T** (λ_{max} = 345 nm) is shifted 81 nm upon oxidation (**$Me_2$3T-O_2**, λ_{max} = 426 nm). This behavior has been attributed to the large stabilization of the LUMO upon oxidation of one or more thiophene rings.[5] Similar red shifts are also observed in the emission spectra of the oligomers.

The redox properties of all oligomers were investigated by cyclic voltammetry (Table 1, Supporting Information Figures S18−S19). All oligomers displayed oxidative processes. Only the sulfones, however, display reductions under the experimental conditions. Both **$Me_2$3T-O_2** and **$Me_2$6T-O_4** have reversible reductions on the CV time scale. This redox behavior is consistent with data from previously reported oligothiophene sulfones.[2,4,6] Furthermore, upon oxidation, the oligomers display oxidations at more positive potentials. For example, the first oxidation of **$Me_2$6T** (E^0 = 0.72 V) is shifted 0.37 V in relation to **$Me_2$6T-O_4** (E^0 = 1.09 V).

Positional isomers of oxidized products are determined by which ring reacts fastest and deactivation of adjacent rings. Except the bithiophene example with both rings activated by TBDMS, no other instances of adjacent *S*,*S*-dioxide rings are observed unless a more powerful oxidant is used.[4] Fast end ring oxidation in **(TBDMS)$_2$3T**, likely promoted by TBDMS, deactivates the center ring.[2a] The other end ring may oxidize, but the inner ring cannot. In quaterthiophenes, end ring oxidation predominates, but reaction of inner rings becomes significant and gives additional products. Our study finds that fast center ring oxidation in **$Me_2$3T** deactivates the terminal rings, precluding other products. Reaction of the analogous rings in **$Me_2$6T** is preferred with deactivation of adjacent rings to provide **$Me_2$6T-O_4** as the major product. Oxidation of terminal rings in the hexamer, however, cannot be excluded, but these products are likely present in lower yield than **$Me_2$6T-O_4**.

In summary, we have demonstrated reverse selectivity in the oxidation of alkyl-substituted oligothiophenes with *m*-CPBA. This method has been applied to oligomers of up to six rings, and the selectivity has been confirmed with X-ray crystal structure analyses. This synthetic technique is a convenient way to alter the electronic properties of preexisting thiophene-based oligomers. Given the numerous reports of alkyl-substituted oligothiophenes similar to ours,[17] we feel our method should appeal to those who wish to maximize the utility of their materials.

Acknowledgment. T.M.P. and J.H.M. acknowledge the Morris Academic Partnership Program funded by the University of Minneosta, Morris (UMM), Dean's Office. T.M.P. acknowledges UMM Faculty Research Enhancement Funds supported by the University of Minnesota Office of the Vice President for Research and the UMM Division of Science and Mathematics for financial assistance. UMTC acknowledges financial support from the National Science Foundation Materials Research Science and Engineering Center Program (DMR-0212302) and the X-ray crystallographic laboratory in the UMTC Department of Chemistry.

Supporting Information Available: Experimental procedures, characterization data, crystallographic CIF files, and plots of physical data. This material is available free of charge via the Internet at http://pubs.acs.org.

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(16) Antolini, L.; Tedesco, E.; Barbarella, G.; Favaretto, L.; Sotgiu, G.; Zambianchi, M.; Casarini, D.; Gigli, G.; Cingolani, R. *J. Am. Chem. Soc.* **2000**, *122*, 9006−9013.

(17) For example, see the following references: (a) Schulze, K.; Uhrich, C.; Schuppel, R.; Leo, K.; Pfeiffer, M.; Brier, E.; Reinold, E.; Bauerle, P. *Adv. Mater.* **2006**, *18*, 2872−2875. (b) Knoblock, K. M.; Silvestri, C. J.; Collard, D. M. *J. Am. Chem. Soc.* **2006**, *128*, 13680−13681. (c) Zotti, G.; Zecchin, S.; Vercelli, B.; Pasini, M.; Destri, S.; Bertini, F.; Berlin, A. *Chem. Mater.* **2006**, *18*, 3151−3161. (d) Chisholm, M. H.; Epstein, A. J.; Gallucci, J. C.; Feil, F.; Pirkle, W. *Angew. Chem., Int. Ed.* **2005**, *44*, 6537−6540.