Regioselective Oligomerization of 3-(Alkylsulfanyl)thiophenes with Ferric Chloride

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The action of $FeCl_3$ on 3-(alkylsulfanyl)thiophenes (3-(alkyl*thio*)thiophenes) leads to the one-step formation of regioregular α-conjugated oligothiophenes, from trimer to octamer, depending on the solvent used and on the length of the alkyl chain. The regiochemistry of these oligomers is characterized by one inner *head-to-head* linkage between adjacent rings and by a variable number of lateral *head-to-tail* junctions. The reaction of ferric chloride with the *head-to-head* and *head-to-tail* bis(methylsulfanyl)-2,2′-bithiophenes gives the corresponding tetramers, while the reaction with the *tail-to-tail* counterpart affords a high molecular weight insoluble material. With the aid of theoretical calculations, these results are interpreted on the basis of the joint effects of the orienting power of the substituents and of the stability of the radical cations formed during the oxidative process.

One of the goals of research in the field of new materials is the synthesis of conjugated oligomers of well-defined length and stereochemistry as models for studies aimed at achieving full control of the physical and chemical properties of the correponding polymers.[1] Among conjugated oligomers oligothiophenes have attracted great attention[1,2] for their chemical stability, ease of functionalization, and variety of useful properties, including self-assembly in noncovalently linked supramolecular architectures.[3] Oligothiophenes are also important materials *per se* and are actively studied for applications in transistors, sensors, optical switches, etc.[4]

The synthesis of α-conjugated oligothiophenes is generally achieved by coupling of organotin, organozinc, or Grignard derivatives with the appropriate halogen derivatives, in the presence of Ni^{+2} or Pd^0 catalysts.[5] One of the major problems in the preparation of these compounds is the isolation of the material in pure form. To purify the desired product, repeated sublimations (if insoluble) or long and tedious chromatographic separations (if soluble) are required, and the final reaction yields are generally poor.

We have recently found that functionalization of sexithiophene with alkylsulfanyl groups has the advantage of leading to soluble, polycrystalline materials, in which the loss of π conjugation caused by the steric effect of the β-substituents is compensated by the mesomeric, electron-donating effect exerted by the same substituents.[6a]

We report here that the reaction of ferric chloride with 3-(alkylsulfanyl)thiophenes (3-(alkyl*thio*)thiophenes) affords a mixture of short α-conjugated oligothiophenes, which can be separated by silica gel chromatography. It is known that in the same experimental conditions the reaction of ferric chloride with 3-alkylthiophenes always leads to high molecular weight polymers.[2,7] To account for the present results, this paper also provides theoretical calculations on the coefficients of the HOMO orbitals of 3-(methylsulfanyl)thiophene and of *head-to-head*, *head-to-tail,* and *tail-to-tail* bis(methylsulfanyl)-2,2′-bithiophenes, together with calculations on the coefficients of the SOMO orbitals of the corresponding radical cations.

Results

The reaction of 3-(methylsulfanyl)thiophene **1** with ferric chloride—employing the conditions leading to high molecular weight poly(3-alkylthiophenes) when 3-alkylthiophenes[7] or 3,3′-alkyl-2,2′-bithiophenes are used as starting materials[7a]—gave a mixture of short oligomers, from which we were able to separate and characterize trimer **2**, tetramer **3**, pentamer **4**, and hexamer **5** (Scheme 1). The *syn* or *anti* orientation of the thiophene rings in compounds **2**−**11**, reported in Schemes 1−7, is arbitrary and is only intended to stress the regiochemistry of substitution of these compounds, characterized by one inner *head-to-head* junction and one or more lateral *head-to-tail* linkages between adjacent rings.

Changing the reaction solvent from methylene chloride, in which $FeCl_3$ is soluble, to pentane, in which $FeCl_3$ is insoluble, did not lead to variations in the composition of the reaction mixture, which was always composed of oligomers from trimer to hexamer, with only a minor presence of longer substrates. The change of solvent from chloroform to methylene chloride, to nitromethane, to pentane only affected the relative amount of the different

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[4] (a) Dodabalapur, A.; Torsi, L.; Katz, H. E. *Science* **1995**, *268*, 270. (b) Dodabalapur, A.; Katz, H. E.; Torsi, L.; Haddon, R. C. *Science* **1995**, *269*, 1560. (c) Marsella, M. J.; Newland, R. J.; Carrol, P. J.; Swager, T. M. *J. Am. Chem. Soc.* **1995**, *117*, 9842. (d) Marsella, M. J.; Carrol, P. J.; Swager, T. M. *J. Am. Chem. Soc.* **1995**, *117*, 9832.

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[7] (a) Souto Major, R. M.; Hinkelmann, K.; Eckert, H.; Wudl, F. *Macromolecules* **1990**, *23*, 1268. (b) Daoust, G.; Leclerc, M. *Macromolecules* **1991**, *24*, 455. (c) Pei, Q.; Järvinen, H.; Österholm, J. E.; Inganäs, O.; Laakso, J. *Macromolecules* **1992**, *25*, 4297. (d) Bi, X.; Ying, Q.; Qian, R. *Makromol. Chem.* **1992**, *193*, 2905. (c) Della Casa, C.; Bertinelli, F., Costa Bizzarri, P.; Salatelli, E. *Adv. Mater.* **1995**, *7*, 1005.

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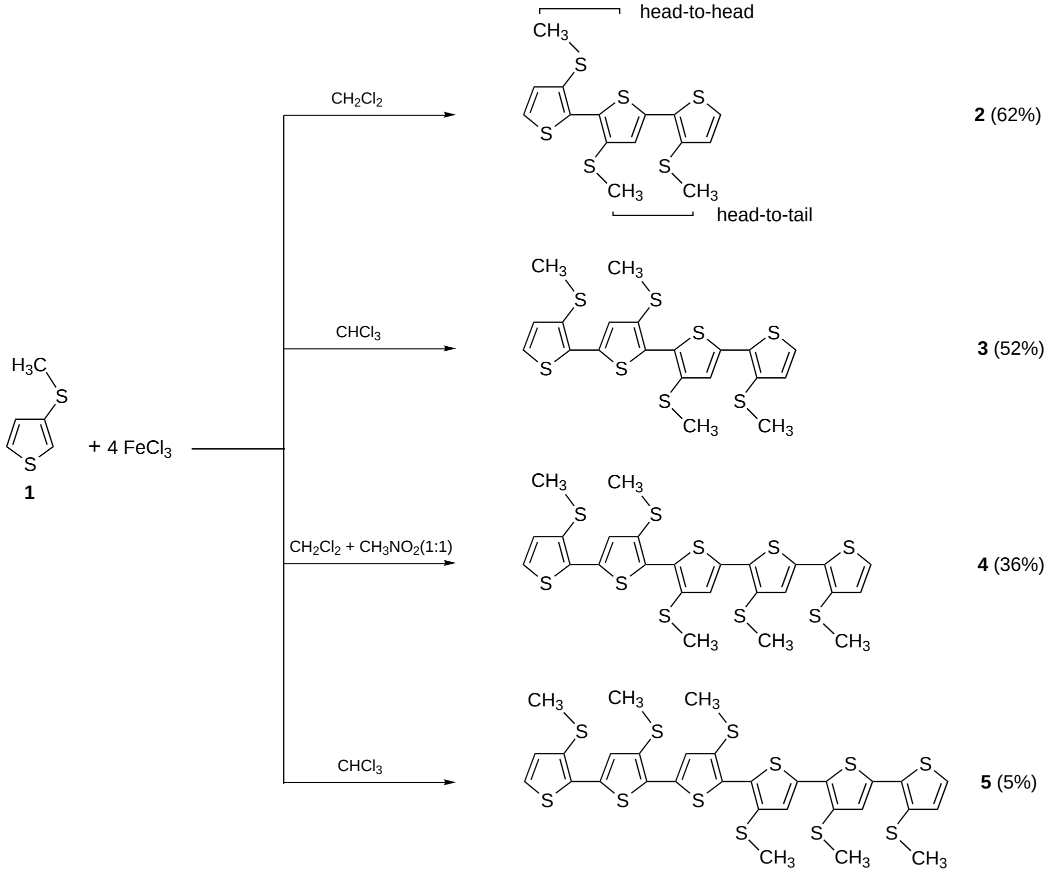
Scheme 1. Products of the Reaction of 3-(Methylsulfanyl)thiophene with Ferric Chloride in Different Solvents[a]



[a] The yields are those obtained after silica gel chromatography of the crude product.

oligomers formed in the reaction. With an appropriate choice of solvent it was possible to obtain the trimer, the tetramer, and the pentamer in such a yield as to make it relatively easy to separate them from the reaction mixture by accurate silica gel chromatographies. However, we were able to separate sexithiophene **5** only from the reaction in chloroform and in very low yield (5%).

Tetramer **3** and hexamer **5** were unambiguously identified by synthesizing both products by an independent pathway. The detailed synthetic pattern for the preparation of **3** and **5** *via* the Stille reaction[8] is reported in ref 6a. The regiochemistry of trimer **2** and pentamer **4** were derived from their ^{1}H and ^{13}C NMR, mass, and UV spectra, compared with those of the tetramer and the hexamer.

Figure 1 gives the proton spectra of compounds **2**−**5**. The ^{1}H NMR spectrum of the tetramer and the hexamer, which are symmetric molecules, is characterized by an AB part due to the hydrogen atoms of the terminal units (four protons) and by one and two singlets (two and four protons, respectively) for the hydrogen atoms of the inner rings. The trimer and the pentamer do not possess any symmetry element; thus, all protons should have different chemical shifts. This is, in fact, the case, for the trimer, as shown in Figure 1, but on increasing the length of the oligomer the chemical shifts of the terminal units, in particular, tend toward the same values. Thus, the spectrum of the pentamer is characterized by an AB part due to the terminal units (four protons) and three singlets (three protons).

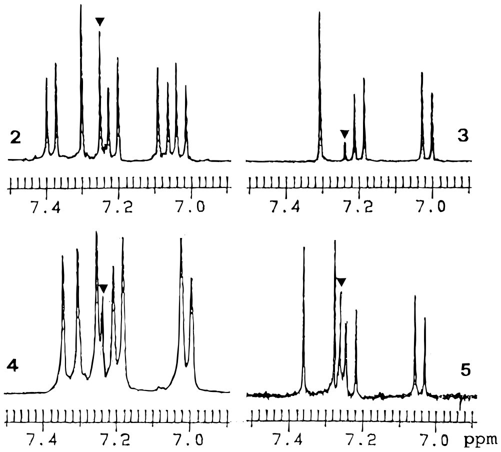


Figure 1. ^{1}H NMR spectrum (in CDCl3) of the aromatic region of compounds **2**−**5**, obtained from the reaction of 3-(methylsulfanyl)thiophene with ferric chloride in different solvents. The peak at 7.25 ppm, marked with a dark triangle, arises from the solvent.

The ^{13}C APT spectrum of compounds **2**−**5** is particularly informative since the quaternary carbons of the aromatic region are well separated and give rise to peaks with different intensities, depending on whether they arise from the carbon−carbon junctions between adjacent rings or between the ring and the substituent[6b] (an example is shown below, in Figure 4).

The reaction of the three regioisomeric bis(methylsulfanyl)-2,2′-bithiophenes **6**−**8** with $FeCl_3$ in chloroform

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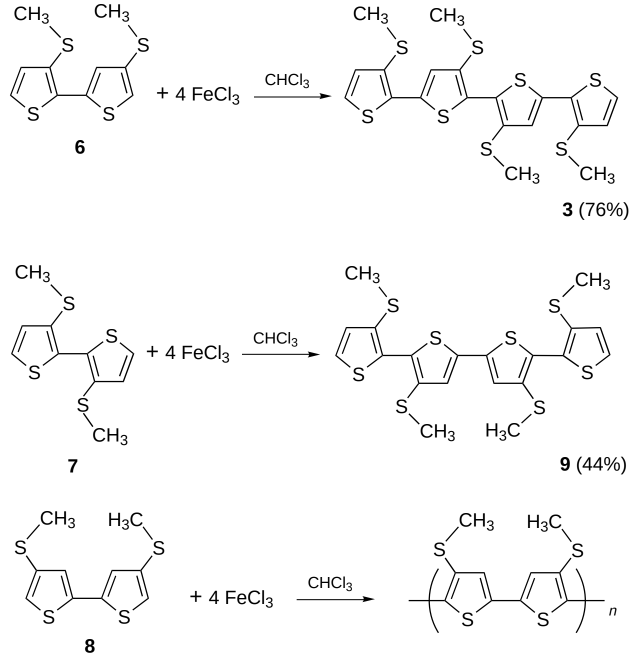
[8] (a) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508. (b) Farina, V. *J. Am. Chem. Soc.* **1991**, *113*, 9585. (c) Farina, V.; Krishnan, B.; Marshall, D. R.; Roth, G. P. *J. Org. Chem.* **1993**, *58*, 5434. (d) Roth, G. P.; Farina, V.; Liebeskind, L. S.; Peña-Cabrera, E. *Tetrahedron Letters* **1995**, *36*, 2191.

Scheme 2. Products of the Reaction of 3,3′-, 3,4′- and 4,4′-Bis(methylsulfanyl)-2,2′-bithiophene with Ferric Chloride in Chloroform[a]



[a] The yields are those obtained after silica gel chromatography of the crude product.

gave different results, depending on the regiochemistry of substitution (see Scheme 2). While the *head-to-head* (**6**) and *head-to-tail* (**7**) dimers afforded the corresponding tetramers (compounds **3** and **9**, respectively), the *tail-to-tail* counterpart (**8**) gave an insoluble poly[4,4′-bis(methylsulfanyl)-2,2′-bithiophene]. It should be noted that poly[(3-methylsulfanyl)thiophene] was recently obtained by catalyzed polycondensation of 2-bromo-5-(bromozincio)-3-(methylsulfanyl)thiophene and was shown to be an insoluble material.[9]

The major product of the reaction of 3,4′-bis(methylsulfanyl)-2,2′-bithiophene (**6**) with ferric chloride is tetramer **3**, *i.e.*, the same product as that obtained from the monomer, however, in greater yield (76% instead of 52%). Tetramer **3**, characterized by one *head-to-head* and two *head-to-tail* inter-ring junctions, is an orange viscous liquid at room temperature,[6a] whereas tetramer **9**, characterized by two *head-to-head* and one *tail-to-tail* inter-ring junctions, has a melting point of 152 °C[6a] and gave monocrystals suitable for X-ray structure determinations. The X-ray structure of this compound has been recently reported by us in a paper describing the synthesis of some soluble hexa(methylsulfanyl)sexithiophenes, including **5**, obtained using tetramers **3** and **9** as the building blocks.[6a]

Increasing the chain length of the alkyl group bonded to the sulfur atom from methyl to dodecyl led to the increase of the degree of oligomerization. Thus, from the reaction of 3-(dodecylsulfanyl)thiophene **10** with ferric chloride a major compound, **11**, was isolated that could be purified by reversed-phase silica gel chromatography (41% yield). The product was solid, mp 39 °C, with polydispersity $M_w/M_n = 1.04$ (see Figure 2). A cast film from chloroform showed a structured absorption band with maxima at $\lambda = 390$, 405, and 430 nm (see Figure 3). Absolute measurements using a multiangle laser light scattering GPC detector[10] gave a molecular weight of 2258, corresponding to an octamer. Scheme 3 gives the structure of octamer **11**, whose regiochemistry was attributed on the basis of proton and carbon-13 NMR spectra, by analogy with that of compounds **2**−**5**. The proton spectrum of this compound is made of an AB part (four protons) and of three singlets (each one corresponding to two protons). The ^{13}C (APT) spectrum of the aromatic region of compound **11** is given in Figure 4, which shows the presence of 11 peaks for the quaternary carbons (in phase signals) and of five peaks (reversed-phase signals) for the CH carbons. Of the 11 peaks of the quaternary carbons, seven are more intense and correspond to the carbons linking adjacent rings, while four are less intense and correspond to the carbons bound to the substituents.

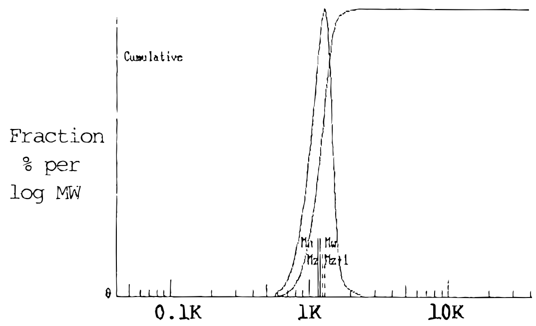


Figure 2. Gel Permeation Chromatography of the compound obtained from the reaction of 3-(dodecylsulfanyl)thiophene with ferric chloride ($M_w/M_n = 1.04$) and identified as octamer **11**.

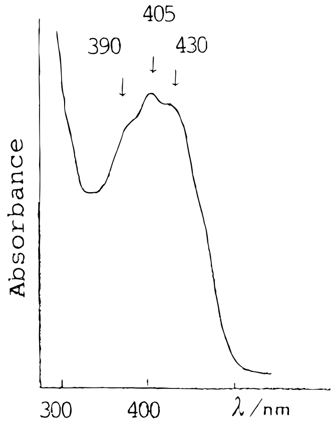


Figure 3. UV spectrum of a cast film of **11** (from chloroform). Absorption maxima are observed at $\lambda_{max} = 390$, 405, and 430 nm.

It is worth noticing that from the mixture of the reaction of 3-(dodecylsulfanyl)thiophene with ferric chloride we were also able to separate by reversed-phase silica gel chromatography a small amount of the quaterthiophene having the same regiochemistry as tetramer **3** (from ^1H and ^{13}C NMR). In the course of the chromatography we expected shorter oligomers to be eluted before the longer ones. However, to our surprise, the tetramer was eluted *after* the octamer. Apparently, the presence of eight dodecyl chains makes the octamer much more soluble than the corresponding tetramer. Thus, when dealing with oligothiophenes bearing long alkyl chains the greatest attention should be paid during the silica gel chromatographies to avoid unpleasant mistakes.

To have insight into the reaction mechanism, we calculated the orbital energies of compounds **1** and **6**−**8**

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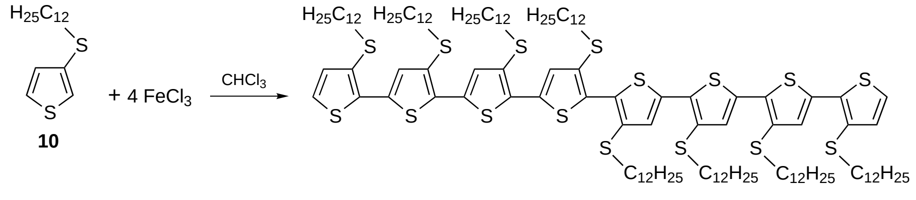
Scheme 3. Major Product Isolated from the Reaction of 3-(Dodecylsulfanyl)thiophene with Ferric Chloride in Chloroform (41% after Reversersed-Phase Silica Gel Chromathography).



10

11

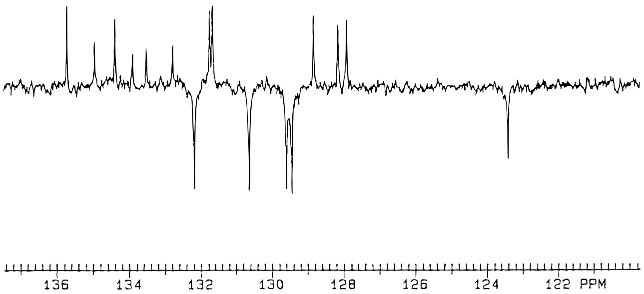
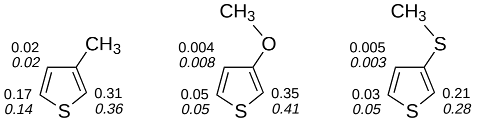


Figure 4. APT ^{13}C NMR spectrum (in $CDCl_3$) of the aromatic region of compound **11**. Reversed-phase signals are those pertaining to protonated carbons.

and of the corresponding radical cations. The calculations showed that the HOMO of the neutral compounds are close in energy to the SOMO of the corresponding radical cations, and consequently, according to the FMO theory, these are the interacting orbitals. The square values of the coefficients of these orbitals are proportional to the electronic densities of the corresponding carbons, and the greater the electronic density at a given atom, the greater the reactivity is at this position. The geometries of the neutral molecules were optimized at the RHF/PM3 level and those of the corresponding radicals at the UHF/MINDO3 level.[11] The coefficients of the frontier orbitals were calculated by a single-point computation at the MINDO3 and CI/MINDO3 level for the neutral molecules and for the corresponding radicals, respectively.[12] The validity of this approach was proven by the fact that calculation of the electronic densities of unsubstituted thiophene and of 3-methylthiophene in this way gave the same values as those derived from hyperfine coupling constants of the same compounds.[13]

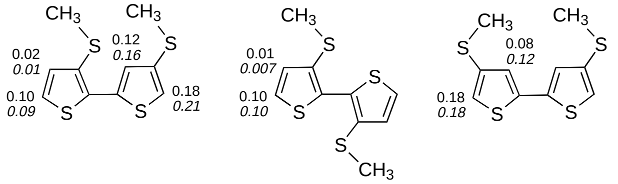
Scheme 4 gives the calculated electronic densities at carbons C-2, C-4, and C-5 of 3-(methylsulfanyl)thiophene and of the corresponding radical cations (in italics). For comparison, the values for 3-methyl- and 3-methoxythiophene were also calculated and are reported in Scheme 4. It can be seen that the trend of variation of the electronic densities is the same in the three substrates and also, for any one of them, is similar for the neutral molecule and its radical cation. For all compounds the greater electronic densities are found for carbons C-2 and C-5, with the former, next to the substituent, displaying the largest electronic density, consequently being the most reactive of all. Interestingly, while in 3-methylthiophene the electronic density at carbon C-2 is nearly twice that of carbon C-5, in 3-methoxy- and 3-(methylsulfanyl)thiophene it is six to eight times that of C-5. Thus, in 3-methoxy- and 3-(methylsulfanyl)thiophene the substituent has a much greater directing power than in 3-methylthiophene. For all compounds, carbon C-4, *β* to the sulfur atom, displays an electronic density that is from 1 to 2 orders of magnitude smaller than that of the α carbons, indicating that formation of α,*β* mislinkages is unlikely.

Scheme 4. Square Values of the Calculated Coefficients of the HOMO of 3-Methyl-, 3-Methoxy- and 3-(Methylsulfanyl)thiophene[a]



[a] Values in italics are those for the SOMO of the corresponding radical cations.

Scheme 5. Square Values of the Calculated Coefficients of the HOMO of 3,3′-, 3,4′- and 4,4′-Bis(methylsulfanyl)-2,2′-bithiophenes[a]



6 **7** **8**

[a] Values in italics are those for the SOMO of the corresponding radical cations.

Scheme 5 gives the calculated electronic densities for dimers **6**−**8** and for the corresponding radical cations (in italics). As in the case of the monomer, there are small variations in electronic densities between the neutral molecule and its radical cation. In 3,3′-bis(methylsulfanyl)-2,2′-bithiophene **7** the α carbons have electronic densities that are still 1 order of magnitude greater than those of the *β* carbons, while for the 3,4′- and 4,4′-regioisomers there is a certain evening out of the difference in electronic densities between the α and *β* carbons, especially in the radical cations.

Of the two α carbons in 3,4′-bis(methylsulfanyl)-2,2′-bithiophene (**6**), the one having the greater electronic density is C-5′, next to the substituent. The terminal carbons of 4,4′-bis(methylsulfanyl)-2,2′-thiophene (**8**) are both next to the substituent, and their electronic densities are greater than those for the 3,3′- isomer **7**, in which the substituents are both in the inner positions.

Discussion

Our results show that the reaction of 3-(alkylsulfanyl)thiophenes with ferric chloride is a useful one-step route to obtain regioregular oligomers, to be used as building blocks for the construction of longer oligothiophenes. The

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(11) Aleman, C.; Vega, M. C.; Perez, J. J. *THEOCHEM* **1993**, *281*, 39.

(12) (a) Jones, D.; Guerra, M.; Favaretto, L.; Modelli, A.; Fabrizio, M.; Distefano, G. *J. Phys. Chem.* **1990**, *94*, 5761. (b) Aleman, C; Brillas, E.; Davies, A. G.; Fajarì, L.; Girò, D.; Jiulià, L.; Perez, J. J.; Rius, J. *J. Org. Chem.* **1993**, *58*, 3091.

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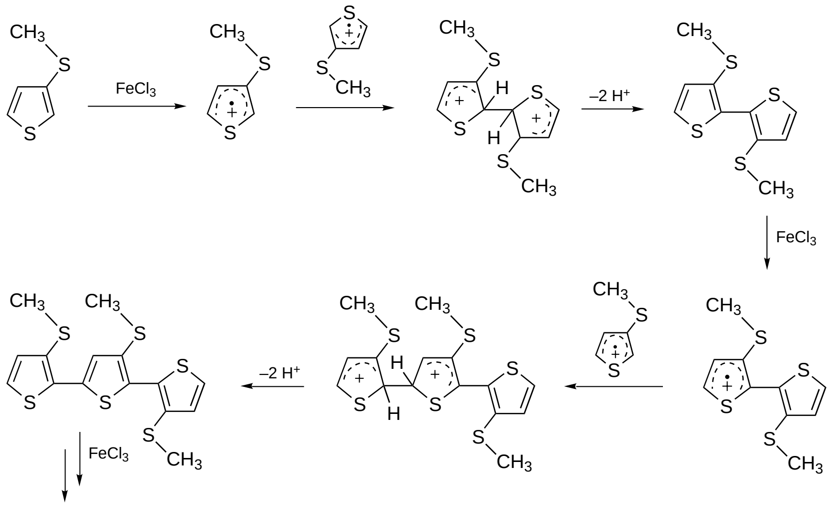
Scheme 6. Possible Mechanism for the Reaction of 3-(Methylsulfanyl)thiophene with Ferric Chloride



reaction yields for the trimer and the tetramer, in particular, are high for these kinds of substrates. The synthesis of oligothiophenes requires a stepwise approach, in which the addition of each repeat unit implies selective brominations and/or lithiations, formation of Grignard or zinc or tin derivatives, coupling in the presence of nickel or palladium catalysts, and accurate purifications at each reaction step. The synthesis of tetramer **3**, for example, required first the preparation of the 3,3′-bis(methylsulfanyl)thiophene, then the synthesis of its dibromo derivative, and finally the palladium(0), catalyzed coupling of this dibromo derivative with the trimethylstannane of the monomer, which was obtained, in turn, through selective bromination, lithiation, and stannylation of 3-(methylsulfayl)thiophene (34% yield for the final cross coupling step[6a]). The reaction of 3-(methylsulfanyl)thiophene with ferric chloride, an inexpensive reagent, affords tetramer **3** in 52% yield in one single step and is, consequently, much more convenient.

There is a drawback, however, in the use of ferric chloride for the oxidative coupling of thiophene derivatives. Indeed, it has recently been reported that unwanted incorporation of even parts per million of $FeCl_3$ into the reaction products (in the form of an octahedral Fe(III) complex) could alter their electric properties.[14] Nevertheless, other important physical properties of these materials such as, for example, their linear and nonlinear optical properties, should not be altered by slight contamination with the metal. Moreover, it should be noted that unwanted contamination by the metals used in the reactants or in the catalysts should always be taken into account, owing to the way oligo- and polythiophenes are synthesized.

The present results raise several questions. Why do 3-alkylthiophenes react with ferric chloride to give high molecular weight polymers[7] while 3-(alkyl*thio*)thiophenes in the same reaction conditions afford short oligomers with the regiochemistry shown in Schemes 1 and 3? What is the role of the solvent? Why in passing from (methylsulfanyl)- to (dodecylsulfanyl)thiophene is the major product of the reaction in chloroform not a tetramer but an octamer?

All these questions are not easy to answer since, despite the large number of papers concerning the polymerization of thiophene derivatives with ferric chloride, the reaction mechanism is still unclear and subject to controversial interpretations. Only recently have the first data on the kinetics of polymerization of thiophene by $FeCl_3$ been reported,[15] which are in contrast, however, with the proposed mechanism for this reaction.[16] Even the reasons why $FeCl_3$ is needed in twice the stoichiometric proportions indicated by equation

$$n\ \text{(3-alkylthiophene)} + 2n\ \mathrm{FeCl_3} \rightarrow \text{(3-alkylthiophene)}_n + 2n\ \mathrm{FeCl_2} + 2n\ \mathrm{HCl}$$

are uncertain. It has been suggested that the evolved HCl consumes the oxidant, probably through formation of the complex $FeCl_4^-$,[16] but clearcut experimental evidence is not yet available on this point.

The reaction of 3-(methylsulfanyl)thiophene with ferric chloride always gives the same mixture of oligomers, whether the reaction takes place in pentane, in which ferric chloride is insoluble, or in methylene chloride, in which $FeCl_3$ is soluble. These results are in contrast with the suggestion according to which the active sites in the polymerization process are the iron(III) ions at the surface of the $FeCl_3$ crystals,[16] a suggestion that is, on the other hand, in contrast with the fact that high weight polythiophenes are also obtained in water.[17]

The isolation of oligomers, from the trimer to the hexamer, having the same regiochemistry and differing only by one single unit (Scheme 1), together with the results of theoretical calculations (Schemes 4 and 5), suggest that the reaction proceeds as illustrated in Scheme 6.

There is no doubt that the first step of the reaction is the formation of a radical cation and the consequent reduction of Fe(III) to Fe(II). During the propagation step there is dimerization of two of these radical cations, elimination of two protons, and consequent rearomatization of the dimer. The dimer that is formed is oxidized to the corresponding radical cation, which can, in turn, react with a radical cation, forming a trimer and so on. According to the calculations reported in Scheme 4, carbon C-2 (next to the substituent) has the largest electronic density in 3-(methylsulfanyl)thiophene as well as in its radical cation. Moreover, in both cases, the electronic density of the β-carbon is much smaller than

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[14] Abdou, M. S. A.; Lu, X.; Xie, Z. W.; Orfino, F.; Deen, M. J.; Holdcroft, S. *Chem. Mater.* **1995**, *7*, 631.

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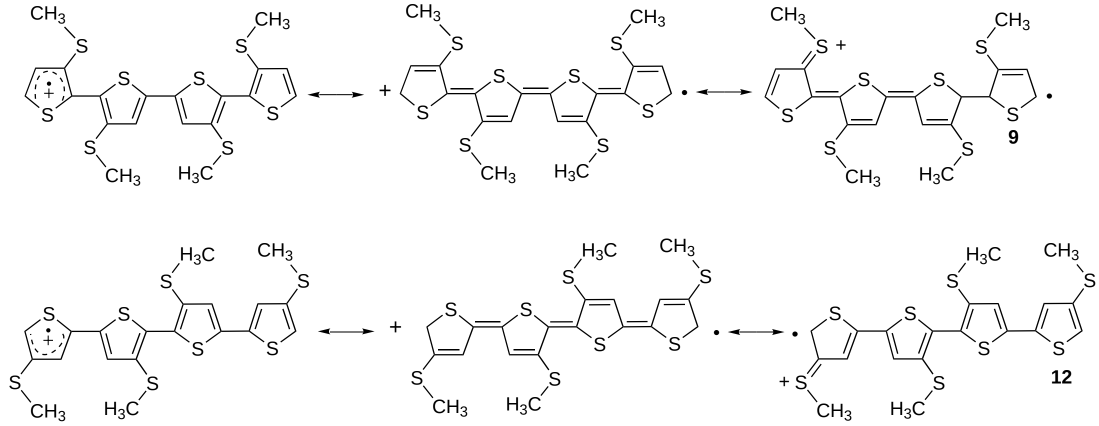
Scheme 7. Some of the Resonance Structures for the Tetramers Obtained from the 3,3′- and 4,4′-Bis(methylsulfanyl)thiophenes (Compounds 9 and 12, Respectively)[a]



[a] In the latter tetramer the lone pairs of the terminal substituents can be delocalized only onto the ring bearing the substituent.

that of the α-carbons. In consequence, the *head-to-head* 3,3′-bis(methylsulfanyl)-2,2′-bithiophene is first formed, which has two equivalent terminal positions. The reaction of the radical cation of this dimer with the radical cation of the monomer leads to the formation of a *head-to-tail* junction and so on, in agreement with the experimental results.

The mechanism in Scheme 6 is similar to that proposed for the electropolymerization of thiophene derivatives[2,18] and is supported by the fact that our data are in agreement with the results of electrochemical polymerization of 3-(methylsulfanyl)thiophene. It has been reported, indeed, that the electropolymerization of **1**, in acetonitrile or nitromethane as the solvents, affords a mixture of oligomers with degrees of polymerization of 7.4 and characterized by a λ_{max} of 415 nm.[19] The λ_{max} values measured in chloroform for compounds **2**, **3**, **4**, and **5** are 360, 395, 415, and 430 nm, respectively.

According to the calculations reported in Scheme 4, the directing power of the methoxy group is similar to that of the methylsulfanyl group. As a consequence, the reaction of 3-methoxythiophene with ferric chloride should occur with the same regiochemistry as that of 3-(methylsulfanyl)thiophene. It is known that the reaction of 3-methoxythiophene with ferric chloride affords a mixture of oligomers, but nothing is known about their regiochemistry. As far as 3-methylthiophene is concerned, the calculations reported in Scheme 4 show that the electronic effect of the substituent on the α-carbons again favors the formation of a head-to-head dimer in the first reaction step. However, the directing power of the methyl group is much smaller than that of the methoxy or methylsulfanyl groups, and the steric effect of the substituent is likely to play a more important role than in the reaction of 3-methoxy or 3-(methylsulfanyl)thiophene with $FeCl_3$. Consequently, the first step of the reaction is not necessarily the formation of a head-to-head dimer since, if the steric effect of the substituent predominates, a head-to-tail dimer could be formed. In both cases the reaction proceeds through the formation of head-to-tail linkages, in agreement with the experimental results.[7]

Turning to the results reported in Scheme 2, the formation of tetramer **3** from dimer **6** (which has two different terminal positions) is explained by the fact that in **6** the carbon with the greater electronic density is C-5′, which is next to the substituent. Dimer **7** has two equivalent terminal positions; thus, only tetramer **9** can be formed. Dimer **8** also has two equivalent terminal positions, however, more reactive than those of dimer **7**, since they are both next to the substituent. Following the addition of $FeCl_3$, a tetramer with two terminal positions more reactive than those of **3** or **9** should first be formed and the reaction should proceed giving a substrate with two terminal reactive positions at any further step. As a consequence, the reaction of **8** with $FeCl_3$ is expected to lead to longer substrates than that of **6** or **7**. In fact, our data show that a polymer is formed. In agreement with these results is the fact that the electropolymerization of 4,4′-dimethoxy-2,2′-bithiophene affords high molecular weight polymers, while that of the 3,3′-counterpart gives only a mixture of oligomers.[20]

At this point the question becomes: when does the reaction stop and what is the role of the solvent in the process? The most obvious answer is that the reaction stops when the radical cation formed (in fact, a salt) becomes insoluble in the reaction solvent. In the case of 3-(alkylsulfanyl)thiophenes this is in agreement with the fact that replacement of *S*-methyl with *S*-dodecyl leads to the formation of an octamer in 41% yield (Scheme 3). But, that the situation must be more complicated is shown by the fact that while CH_2Cl_2 is a better solvent than $CHCl_3$, 3-(methylsulfanyl)thiophene gives the trimer in the former solvent and the tetramer in the latter. Moreover, 4,4′-bis(methylsulfanyl)-2,2′-bithiophene forms a polymer in chloroform. Probably, the factor causing the reaction to stop and, consequently, determining the length of the substrate which is formed, is the stability of the intermediate radical cations, on which the solvent is likely to play a role. In other words, the reaction stops when the radical cation which is formed is too stable to react anymore.

The radical cations derived from alkylsulfanyl thiophenes are strongly stabilized by the mesomeric effect of the substituents. The mesomeric effect of this group, in turn, depends on the regiochemistry of substitution.[21] Scheme 7 shows some of the possible valence bond structures which can be written for the radical cation of tetramer **9** and for that derived from the coupling of two

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4,4′-(bismethylsulfanyl)-2,2′-bithiophene units (let us call it tetramer **12**).

It can easily be seen that in the radical cation derived from **9** the lone pair of all substituents can be delocalized onto the whole molecular skeleton. On the contrary, in the one derived from **12** the lone pairs of the two terminal substituents can only be delocalized onto the ring to which they are bound. In other words, the radical cation of tetramer **9** is more stable than the radical cation of **12**. This suggests that the reaction of ferric chloride with 4,4′-bis(methylsulfanyl)-2,2′-bithiophene leads to substrates which are longer than those obtained from 3,3′- or 3,4′-bis(methylsulfanyl) counterparts not only because the substrates which are formed are always characterized by more reactive terminal positions, but also because their radical cations are less stable. A similar explanation could also apply to the reaction of 3-(dodecylsulfanyl)thiophene with $FeCl_3$ in chloroform, which leads to the formation of an octamer. In this case, indeed, the planarization of the aromatic skeleton—required for the delocalization of the lone pairs of the substituents onto the adjacent rings to take place - is hindered by the steric effect of the bulky chains. Consequently, for the radical cation to be stable enough to be no longer reactive, a longer aromatic skeleton is required. Work is in progress to elucidate this point.

Conclusion

We have shown that in the reaction of 3-(alkylsulfanyl)thiophenes with $FeCl_3$ the strong orienting effect of the substituents combined with the great stability of the intermediate radical cations lead to the regioselective formation of α-conjugated oligomers in rather good yields for these kinds of compounds. Thus, this reaction is an efficient one-step route to obtain regioregular oligomers to be employed as building blocks for a more rapid synthetic construction of longer substrates.

Experimental Section

General Procedures. $FeCl_3$ was purchased from Carlo Erba. All solvents used in reactions and chromatographies were dried by standard procedures. Reactions were carried out under an argon atmosphere. Analytical thin layer chromatographies (TLC) were carried out using 0.2 mm silica gel plates, and the visualization was accomplished by UV light. Flash chromatographies were carried out on silica gel (230−400 mesh ASTM) or reversed-phase RP 18 (230−400 mesh ASTM). Gel permeation chromatography (GPC) was done with a Shodex KF-804L column using a refractive index detector and a multiangle laser light scattering detector in series, with tetrahydrofuran as the eluting solvent. UV spectra were obtained in chloroform. ^{1}H and ^{13}C NMR spectra were run at 200 and 50 MHz, respectively, using $CDCl_3$ as the solvent and TMS as the internal standard.

3-(Methylsulfanyl)thiophene (**1**) and 3,3′- (**7**), 3,4′- (**6**), and 4,4′-bis(methylsulfanyl)-2,2′-bithiophene (**8**) were prepared according to previously published procedures.[22] 3-(Dodecylsulfanyl)thiophene (**10**) was obtained according to the procedures described in ref 23.

Reaction of 3-(Methylsulfanyl)thiophene (1) with $FeCl_3$ in Chloroform. A suspension of 4.98 g (30.7 mmol) of dry $FeCl_3$ in 100 mL of distilled $CHCl_3$ was stirred for about 30 min at room temperature. After this period $FeCl_3$ was only partially dissolved in chloroform giving a dark solution. To this suspension 1.0 g (7.68 mmol) of 3-(methylsulfanyl)thiophene dissolved in 40 mL of $CHCl_3$ were added dropwise over a period of 20 min. The reaction course was followed by thin layer chromatography using hexane:chloroform (85:15) as the eluent. After one hour the TLC showed no traces of the starting material. Then 200 mL of methanol were added. The initially black solution turned red-orange, and a black precipitate was formed. The mixture was filtered, and the solid residue and the filtered solution were worked up separately. The solution was first washed three times with water and then with a 2% hydrazine solution, evaporated, and dried over Na_2SO_4. 0.61 g of a red oil were obtained (fraction 1). The solid was extracted using a Soxhelet apparatus first with methanol, then with acetone, and finally with chloroform as the solvents. The methanol extract was evaporated and the residue dissolved in chloroform. The chloroform solution was washed first with water and then with a 2% hydrazine solution, evaporated, and dried over Na_2SO_4. A red solid (0.1 g) was obtained (fraction 2). The acetone extract was treated as before, and 0.12 g of a deep red oil were obtained (fraction 3). The chloroform extract, after treatment, afforded 0.05 g of red solid (fraction 4). The residual black solid was treated with a 20% hydrazine solution and a red solid (0.05 g) was obtained, which was soluble in chloroform (fraction 5). The maximum UV absorptions of the five fractions in chloroform were $\lambda_{max} = 395$ nm (fraction 1), 395 nm (fraction 2), 415 nm (fraction 3), 430 nm (fraction 4), and 440 nm (fraction 5). The polydispersity of fractions 1 and 2 was $M_w/M_n = 1.18$, and their proton spectrum showed the presence of the same main product. Thus, the mixture of the two fractions was chromatographed on silica gel (neutralized with a 2% triethylamine solution) using cyclohexane:methylene chloride (85:15) as the eluent. A red, viscous oil was isolated (0.52 g, 52% yield): MS m/e 514 ($M^{\bullet+}$). From comparison of the UV, ^{1}H, and ^{13}C NMR spectra with those reported in ref 6a, this product was identified as 3,4′,3″,3‴-tetrakis(methylsulfanyl)-2,2′:5′,2″:5″,2‴-quaterthiophene **3**. Fraction 3 had $M_w/M_n = 1.25$; its $_1$H NMR spectrum showed this fraction to contain mainly hexamer **5** (from comparison with the data reported in ref 6). Fractions 4 and 5 had polydisperties varying between 1.5 and 1.7. Their proton spectrum showed the presence of an unidentified mixture of longer oligomers.

A second preparation was carried out, using the same amount of 3-(methylsulfanyl)thiophene and ferric chloride as before. However, contrary to the above procedure, 400 mL of methanol was directly added to the crude reaction product. In this case, no precipitate was formed. The solution was evaporated and the solid residue dissolved in chloroform. The chloroform solution was washed with water and then with 5% hydrazine, evaporated, and dried over Na_2SO_4. A red solid (0.95 g) was recovered. The product was chromatographed on silica gel (neutralized with a 2% solution of triethylamine) using cyclohexane containing a progressively increasing amount of methylene chloride (85:15, 75:25, 65:35) as the eluent. Three pure products were isolated. The first (0.34 g) was tetramer **3** (34% yield). The second (0.15 g) was a red solid: mp 53 °C; MS m/e 640 ($M^{\bullet+}$). This compound was identified as 3,4′,4″,3‴,3′′′′-pentakis(methylsulfanyl)-2,2′:5′,2″:5″,2‴,5‴:2′′′′-quinquethiophene (**4**): $\lambda_{max} = 415$ nm ($CHCl_3$); ^{1}H NMR ($CDCl_3$, TMS/ppm) 7.37 (s, 1H), 7.33 (s, 1H), 7.28 (s, 1H), 7.21 (d, $J_{AB} = 5.0$ Hz, 2H), 7.03 (d, $J_{AB} = 5.0$ Hz, 2H), 2.52 (s, 3H), 2.49 (s, 3H), 2.48 (s, 9H); ^{13}C NMR ($CDCl_3$, TMS/ppm) 136.0, 135.7, 133.8, 133.6, 133.5, 132.8, 132.7, 132.6, 130.8, 130.65, 130.61, 130.5, 129.0, 127.95, 127.90, 124.0, 123.9. Anal. Calcd for $C_{25}H_{22}S_{10}$: C, 46.69; H, 3.45. Found: C, 46.51; H, 3.45.

The third isolated compound (0.05 g, 5% yield) was a red solid, mp 150 °C. By comparison with the data reported in ref 6, this product was identified as being 3,4′,4″,3‴,3′′′′,3′′′′′-hexa(methylsulfanyl)-2,2′:5′,2″:5″,2‴:5‴,2′′′′:5′′′′,2′′′′′-sexithiophene **5**.

Reaction of 3-(Methylsulfanyl)thiophene (1) with $FeCl_3$ in CH_2Cl_2. Dry ferric chloride (2.49 g, 15.3 mmol) was dissolved in 60 mL of distilled CH_2Cl_2. The mixture was stirred for about 30 min at room temperature. Then 0.5 g (3.84 mmol) of 3-(methylsulfanyl)thiophene dissolved in 20 mL of CH_2Cl_2 was added dropwise over a period of 20 min. The reaction course was followed by thin layer chromatography. After 1 h 200 mL of methanol was added. No precipitate was

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formed. The solution was evaporated and the solid residue dissolved in chloroform. The chloroform solution was washed with water and then with 5% hydrazine, evaporated, and dried over Na_2SO_4. A red solid (0.45 g) was obtained. The product was chromatographed on silica gel (neutralized with a 2% triethylamine solution) using cyclohexane:methylene chloride (85:15, 75:25, 65:35) as the eluent. 3,3′,3″-Tris(methylsulfanyl)-2,2′:5′,2″-terthiophene (**2**) (0.31 g) as a brown oil was isolated (62% yield): $\lambda_{max} = 375$ nm ($CHCl_3$); MS *m/e* 386 ($M^{\bullet+}$); ^1H NMR ($CDCl_3$, TMS/ppm) 7.40 (d, $J_{AB} = 5.0$ Hz, 1H), 7.31 (s, 1H), 7.23 (d, $J_{AB} = 5.0$ Hz, 1H), 7.09 (d, $J_{AB} = 5.0$ Hz, 1H), 7.04 (d, $J_{AB} = 5.0$ Hz, 1H), 2.48 (s, 3H), 2.45 (s, 3H), 2.44 (s, 3H); ^{13}C NMR ($CDCl_3$, TMS/ppm) 136.0, 133.7, 133.6, 133.0, 130.7, 130.4, 129.5, 127.8, 126.3, 124.0. Anal. Calcd for $C_{15}H_{14}S_6$: C, 46.60; H 3.65. Found: C, 46.65; H, 3.64.

Reaction of 3-(Methylsulfanyl)thiophene (1) with $FeCl_3$ in CH_2Cl_2:CH_3NO_2 (1:1 v:v). The reaction was carried out as before, using a 1:1 (v:v) mixture of CH_2Cl_2:CH_3NO_2 as the solvent. Following addition of 200 mL of methanol, a precipitate was formed. Work up of the crude product afforded three fractions. Fraction 1 (soluble in methanol, 0.21 g) and fraction 2 (soluble in methylene chloride before treatment with hydrazine, 0.05 g) contained tetramer **3** with different amounts of pentamer **4** (from^1H NMR). Fraction 3 (soluble in methylene chloride after treatment with hydrazine, 0.17 g, 36% yield) contained only pentamer **4** (from^1H NMR).

Reaction of 3-(Methylsulfanyl)thiophene (1) with $FeCl_3$ in CH_3NO_2. The reaction was carried out as before, using CH_3NO_2 as the solvent. Following addition of 200 mL of methanol a precipitate was formed. Work up of the crude product afforded three fractions. Fraction 1 (soluble in methanol, 0.2 g) and fraction 2 (0.02 g, soluble in methylene chloride before treatment with hydrazine) contained different mixtures of tetramer **3** and pentamer **4** (from ^1H NMR). Fraction 3 (soluble in methylene chloride after treatment with hydrazine, 0.1 g) had $\lambda_{max} = 430$ nm (in $CHCl_3$) and contained a mixture of oligomers including hexamer **5** (from^1H NMR).

Reaction of 3-(Methylsulfanyl)thiophene (1) with $FeCl_3$ in Pentane. The reaction was carried out as before, using pentane as the solvent. Ferric chloride is insoluble in pentane. After the usual workup three fractions were obtained. Fraction 1 (soluble in methanol, 0.2 g) contained mainly trimer **2** with a nonnegligible proportion of tetramer **3** (from^1H NMR). Fraction 2 (soluble in methylene chloride before treatment with hydrazine, 0.13 g, $M_w/M_n = 1.64$) displayed $\lambda_{max} = 405$ nm (in $CHCl_3$) and was made of a mixture of oligomers **3**−**5** together with a minor amount of longer oligomers. Fraction 3 (soluble in methylene chloride after treatment with hydrazine, 0.085 g, $M_w/M_n = 1.73$) had $\lambda_{max} = 435$ nm (in $CHCl_3$) and was also composed of an unidentified mixture of oligomers.

Reaction of 3-(Dodecylsulfanyl)thiophene (10) with $FeCl_3$ in Chloroform. A suspension of 1.71 g (10.5 mmol) of $FeCl_3$ in 50 mL of distilled $CHCl_3$ was stirred for about 30 min at room temperature. To this suspension were added dropwise 0.75 g (2.64 mmol) of 3-(dodecylsulfanyl)thiophene in 30 mL of $CHCl_3$ over a period of 20 min. After 1 h 200 mL of methanol was added. No precipitate was formed. The solution was washed with water and then with 5% hydrazine, evaporated and dried over Na_2SO_4. The crude product was chromatographed on reversed-phase silica gel RP 18 using MeOH/CH_2Cl_2 in different proportions (up to 40:60 v/v) as the eluent. A brown crystalline compound (0.31 g, 41% yield), mp 39 °C, was isolated. From gel permeation chromatography the polidispersity of this fraction was found to be $M_w/M_n = 1.04$. Absolute measurements using a multiangle laser light scattering GPC detector gave a molecular weight of 2258, corresponding to the octamer, **11**: $\lambda_{max} = 390$ nm (in CH_2Cl_2); ^1H NMR ($CDCl_3$, TMS/ppm) 7.36 (s, 2H), 7.26 (s, 2H), 7.19 (d, $J_{AB} = 5.0$ Hz, 2H), 7.04 (d, $J_{AB} = 5.0$ Hz, 2H), 6.86 (s, 2H), 2.85 (m, 16H), 1.50 (m, 16H), 1.25 (m, 144H), 0.85 (m, 24H); ^{13}C NMR ($CDCl_3$, TMS/ppm) 135.8, 135.1, 134.5, 134.0, 133.6, 132.9, 132.3 (−CH−), 131.9, 131.8, 130.8 (-CH-), 129.7 (-CH-), 129.6 (-CH-), 128.9, 128.3, 128.0, 123.5 (-CH-), 36.4, 36.3, 32.0, 29.7, 29.6, 29.4, 29.3, 29.2, 28.0, 22.7, 14.1 (−CH_3). Anal. Calcd for $C_{128}H_{210}S_{16}$: C, 67.96; H, 9.36. Found: C, 68.21; H, 10.02.

Reaction of 3,3′-Bis(methylsulfanyl)-2,2′-bithiophene (7) with $FeCl_3$ in Chloroform. A suspension of 1.25 g (7.7 mmol) of dry ferric chloride in 40 mL of distilled $CHCl_3$ was stirred for about 30 min at room temperature under an argon atmosphere. To this suspension 0.5 g (1.9 mmol) of 3,3′-bis(methylsulfanyl)-2,2′-bithiophene dissolved in 20 mL of $CHCl_3$ was added dropwise over a period of 15 min. The mixture was stirred overnight. Then 100 mL of methanol was added, and a black precipitate was formed. The precipitate (0.38 g, 76% yield) was filtered and redissolved in $CHCl_3$, washed with water and then with a 2% hydrazine solution, evaporated, and dried over Na_2SO_4. A brown solid, mp 152 °C, was obtained: MS *m/e* 514 ($M^{\bullet+}$). The single-crystal X-ray structure (see ref 6c) showed this compound unambiguously to be 3,3′,4″,3‴-tetrakis(methylsulfanyl)-2,2′:5′,2″:5″,2‴-quaterthiophene (**9**). The methanol solution was first washed with water and then with 5% hydrazine, evaporated, and dried over Na_2SO_4. A brown oil (0.1 g), was obtained, containing a mixture of the dimer and the tetramer (from ^1H NMR).

Reaction of 3,4′-Bis(methylsulfanyl)-2,2′-bithiophene (6) with $FeCl_3$ in Chloroform. A suspension of 1.25 g (7.7 mmol) of dry ferric chloride in 40 mL of distilled $CHCl_3$ was stirred for about 30 min at room temperature under an argon atmosphere. To this suspension was added 0.5 g (1.9 mmol) of 3,4′-bis(methylsulfanyl)-2,2′-bithiophene dissolved in 20 mL of $CHCl_3$ dropwise over a period of 15 min. The mixture was stirred overnight. Then 200 mL of methanol were added. A black precipitate was formed. The solution was washed with water and then with 2% hydrazine, evaporated, and dried over Na_2SO_4. A red oil (0.22 g, 44%) was obtained (fraction 1), $\lambda_{max} = 395$ nm in $CHCl_3$. ^1H and ^{13}C NMR showed this fraction to be tetramer **3**. The black solid was first treated with a 20% hydrazine solution and then partially dissolved in chloroform. The chloroform solution was treated as usual, and 0.19 mg of a red solid was obtained (fraction 2), $\lambda_{max} = 440$ nm in CH_2Cl_2. Gel permeation chromatography gave polydispersity $M_w/M_n = 2.33$ for this fraction, which, according to ^1H and ^{13}C NMR, contained an unidentified mixture of oligomers.

Reaction of 4,4′-Bis(methylsulfanyl)-2,2′-bithiophene (8) with $FeCl_3$ in Chloroform. A suspension of 1.25 g (7.7 mmol) of dry ferric chloride in 50 mL of distilled $CHCl_3$ was stirred for about 30 min at room temperature under an argon atmosphere. To this suspension 0.5 g (1.9 mmol) of 4,4′-bis(methylsulfanyl)-2,2′-bithiophene dissolved in 20 mL of $CHCl_3$ was added dropwise over a period of 15 min. The mixture was stirred overnight. Then 200 mL of methanol was added, and a black precipitate was formed. The methanol solution was treated as usual, and 0.1 g of a red oil was obtained: $\lambda_{max} = 440$ nm in CH_2Cl_2. Gel permeation chromatography gave polydispersity $M_w/M_n = 2.08$, and ^1H NMR showed this fraction to contain an unidentified mixture of oligomers. The solid was insoluble in common organic solvents even after repeated treatment with a 20% hydrazine solution.

Theoretical Calculations. All calculations were performed with a Microvax 3500 using the integrated MOPAC 6.0 package.[24]

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