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Cyclization of 1,4-Phenylenediacrylic Acid with Thionyl Chloride and Subsequent Suzuki–Miyaura Reactions Revisited. The Products are Benzo[1,2-*b*;5,6-*b*′]dithiophenes and not Benzo[1,2-*b*;4,5-*b*′]dithiophenes

Zahid Hassan,[a] Sebastian Reimann,[a,b] Kai Wittler,[c] Ralf Ludwig,[b,c] Alexander Villinger,[a] and Peter Langer[a,b,*]

[a] Institut für Chemie, Universität Rostock, Albert Einstein Str. 3a, 18059 Rostock, Germany
E-mail: peter.langer@uni-rostock.de
[b] Leibniz-Institut für Katalyse an der Universität Rostock e.V., Albert Einstein Str. 29a, 18059 Rostock, Germany
[c] Institut für Chemie, Physikalische und Theoretische Chemie, Universität Rostock, Dr.-Lorenz-Weg 1, 18059 Rostock, Germany

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Abstract: The reaction of 1,4-phenylenediacrylic acid with thionyl chloride was reinvestigated. In earlier reports [*Liebigs Ann. Chem.* **1980**, 1172; *Heterocycles* **1995**, *41*, 2691; *Adv. Synth. Catal.* **2009**, *351*, 2683] it was claimed that 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes were formed in these reactions. Herein, we provide unambiguous evidence that the assignment of these structures is wrong and that, in contrast, 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes are formed. As a consequence, the structures of these parent molecules and of numerous aryl-substituted derivatives prepared by Pd-catalyzed cross-coupling reactions have to be revised. As many of these dithiophenes were reported to show interesting optical, thermal and electronic properties, the theoretical explanations for these properties have to be reconsidered in the light of the corrected structures reported herein. Our structural assignments are based on X-ray crystal structure analyses of the parent molecules and on NMR spectroscopic studies of the first unsymmetrical derivatives. Besides, mechanistic investigations based on quantum chemical calculations have been carried out which support the formation of the 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene isomers.

Keywords: catalysis; cyclization; dithiophenes; heterocycles; palladium; regioselectivity; structure revision

Introduction

Benzo[*b*]thiophenes show a wide range of pharmacological activities, such as estrogen receptor modulating activity, tubulin binding activity, activity as MRP1, angiogenesis and thrombin inhibitors, anti-inflammatory activity, and antifungal activity.[1] More complex, annulated thiophene derivatives often contain a low singlet-triplet energy gap and are important core structures of magnetic and electronic materials,[2] such as organic ferromagnets, conductors, transistors, photovoltaic cells and organic light-emitting diodes (OLEDs).[3] Therefore, the synthesis and properties of rigid benzothiophene-fused aromatic compounds has been extensively studied in recent years.

Miura and co-workers have recently reported the synthesis of various 3,7-diarylbenzo[1,2-*b*;4,5-*b*′]dithiophenes[4] by two-fold Suzuki–Miyaura and Sonogashira cross-coupling reactions of 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes. The latter compounds were first prepared by Ried[5] and Karminski-Zamola[6] and their co-workers by cyclization of 1,4-phenylenediacrylic acid (**1**) with thionyl chloride and subsequent addition of a nucleophile. The basic methodology, the cyclization of thionyl chloride with cinnamic acids to give benzophenones, was first reported by Krubsack and Higa[7a] and later improved by Ried and co-workers.[7b]

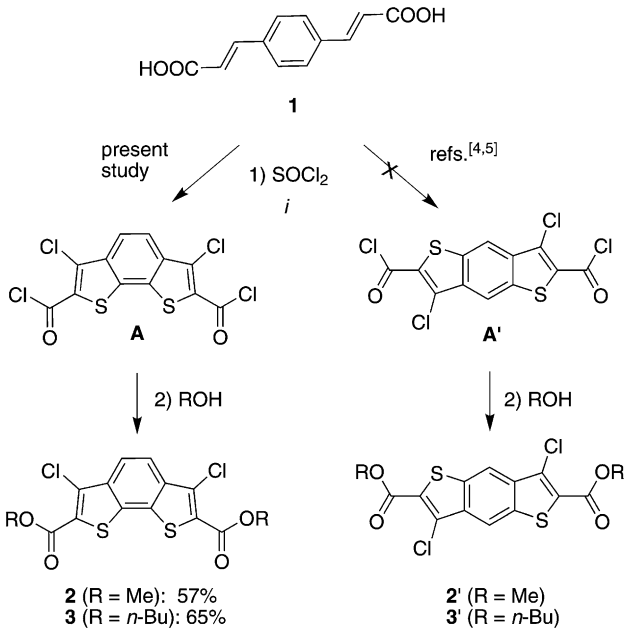
During our studies related to regioselective cross-coupling reactions of polyhalogenated heterocycles, we reinvestigated the cyclization of **1** with thionyl chloride. Herein, we provide unambiguous evidence that several of the earlier reported structures, 3,7-di-

chlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes, are wrong and that, in contrast, 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes are formed. As a consequence, the structures of numerous arylated dithiophenes prepared by Pd-catalyzed cross-coupling reactions of the parent chlorinated derivatives have to be revised as well. Many of these products were reported to show interesting optical, thermal and electronic properties. The theoretical explanations for these properties have to be carefully reconsidered in the light of the correct structures reported herein. Indeed, our results are also important for the future design of related molecules and materials. Our structural assignments are based on X-ray crystal structure analyses of the parent chlorinated dithiophenes and on NMR spectroscopic studies of unsymmetrical derivatives which were prepared for the first time. Besides, mechanistic studies based on quantum chemical calculations have been carried out which are in agreement with the observed formation of 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes.

Results and Discussion

In 1980, Ried and Oremek reported[5] that the reaction of 1,4-phenylenediacrylic acid (**1**) with thionyl chloride, in the presence of catalytic amounts of pyridine, afforded the diacid dichloride **A′** as a reactive intermediate which was subsequently trapped with methanol as a nucleophile to give the 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene **2′** (Scheme 1). In their original report,[5] Ried and co-workers characterized their product by ^{1}H NMR, IR and mass spectroscopy as well as by elemental analysis. They considered that, alternatively, the isomeric 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene **2** could have been formed. But they decided that isomer **2'** is more likely based on an analysis of the IR bands in the fingerprint region because more reliable methods were not available at that time. In 1995, Karminski-Zamola referred to the original report of 1980 and reported the employment of anilines as the nucleophile and formation of 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene-diamides. In 2009, Miura used *n*-butanol as the nucleophile and reported the synthesis of diester **3′**.[4] This product was transformed into various symmetrical 3,6-diarylated benzo[1,2-*b*;5,6-*b*′]dithiophenes by two-fold Suzuki–Miyaura cross-coupling reactions. None of these structures reported were unambiguously confirmed by X-ray crystal structure analyses or detailed NMR studies.

Our original plan was to study whether unsymmetrical benzo[1,2-*b*;4,5-*b*′]dithiophenes can be prepared by mono-Suzuki reactions of **2′** and related molecules. Therefore, we reinvestigated the work of Ried and Miura and their co-workers. We have found that the reaction of 1,4-phenylenediacrylic acid (**1**) with thionyl chloride (5 h, 140 °C), in the presence of catalytic amounts of pyridine, and subsequent addition of methanol (2 h, reflux), following the conditions reported by Ried,[5] afforded a yellow crystalline solid. To our surprise, an X-ray crystal structure analysis revealed that the product was 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene **2** instead of the expected isomeric 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene **2′** (Scheme 1, Figure 1).[8] To confirm that product **2′** does not simply represent a by-product which crystallized in the presence of **2**, special attention was given to the work-up procedure. The crude product mixture showed only one major spot by TLC which was isolated by chromatography and examined by NMR and X-ray crystal structure analysis. The NMR data of the crystals were identical with the rest of the material. The moderate isolated yield of **2** (57%) can be ex-



Scheme 1. Synthesis of **2** and **3**. *Reaction conditions:* 1) $SOCl_2$, pyridine, 5 h, 140 °C; 2) ROH, 2 h, reflux.

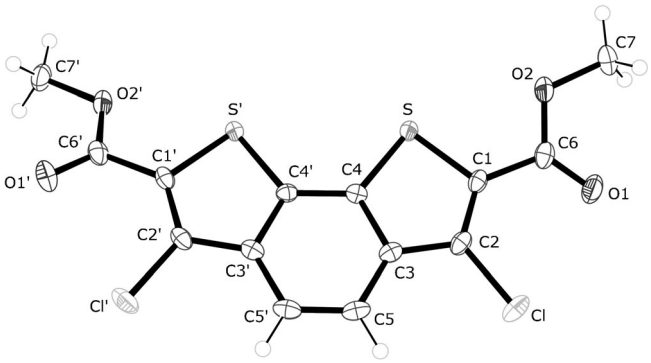
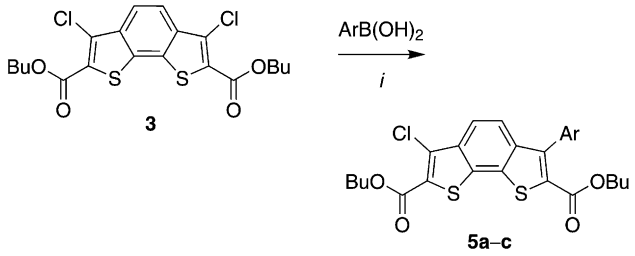


Figure 1. ORTEP plot of **2**

plained by losses during the chromatographic purification. The isomeric product **2′** was not formed which was confirmed by NMR measurements of the crude product (before chromatographic purification). The ^{1}H NMR shifts of the aromatic protons of **2** and **2′** were calculated by DFT computations (B3LYP level of theory using a 6-31G* basis set, see the Supporting Information). The calculated chemical shifts of both isomers are very similar (0.22 ppm difference) and are, thus, not diagnostic for the structural assignment of the product by comparison of the calculated with the experimental data.

We also repeated the synthesis of di(butyl)ester **3′** which was reported by Miura in 2009.[4] The cyclization of **1** with $SOCl_2$ and subsequent reaction with *n*-butanol (instead of methanol) again afforded a yellow solid. The structure, which was unambiguously confirmed by X-ray crystal structure analysis, turned out to be 3,6-dichlorobenzo[1,2-*b*;5,6-*b′*]dithiophene **3** instead of 3,7-dichlorobenzo[1,2-*b*;4,5-*b′*]dithiophene **3′** (see the Supporting Information).[8] Because of the importance of this finding, we aimed to obtain an additional structural proof by NMR. The NMR data of our product were identical with those reported by Miura and co-workers. Due to the symmetrical structures of dithiophenes **3** and **3′**, similar NMR data are expected and a structural elucidation by NMR is not possible. The aromatic protons H_a appear as a singlet with the integration of two protons. However, this observation is compatible with both isomers **3** and **3′**, since no coupling between the two aromatic protons H_a is expected (the protons are equivalent) (Figure 2).

To solve the problem, we decided to transform the symmetrical product **3** to an unsymmetrical derivative. The mono-Suzuki–Miyaura cross-coupling reaction[9] of **3** (symmetrical substrate) with 1.2 equivalents of arylboronic acids **4a–c** afforded the 3-aryl-6-chlorobenzo[1,2-*b*;5,6-*b′*]dithiophenes **5a–c** in very good yields (Scheme 2, Table 1). The best yields were obtained when $Pd(PPh_3)_4$ (5 mol%) and K_3PO_4



Scheme 2. Synthesis of **5a–c**. *Reaction conditions: i*, **3** (1.0 equiv.), $ArB(OH)_2$ (1.2 equiv.), $Pd(PPh_3)_4$ (5 mol%), K_3PO_4 (2.0 equiv.), dioxane, 120 °C, 4 h.

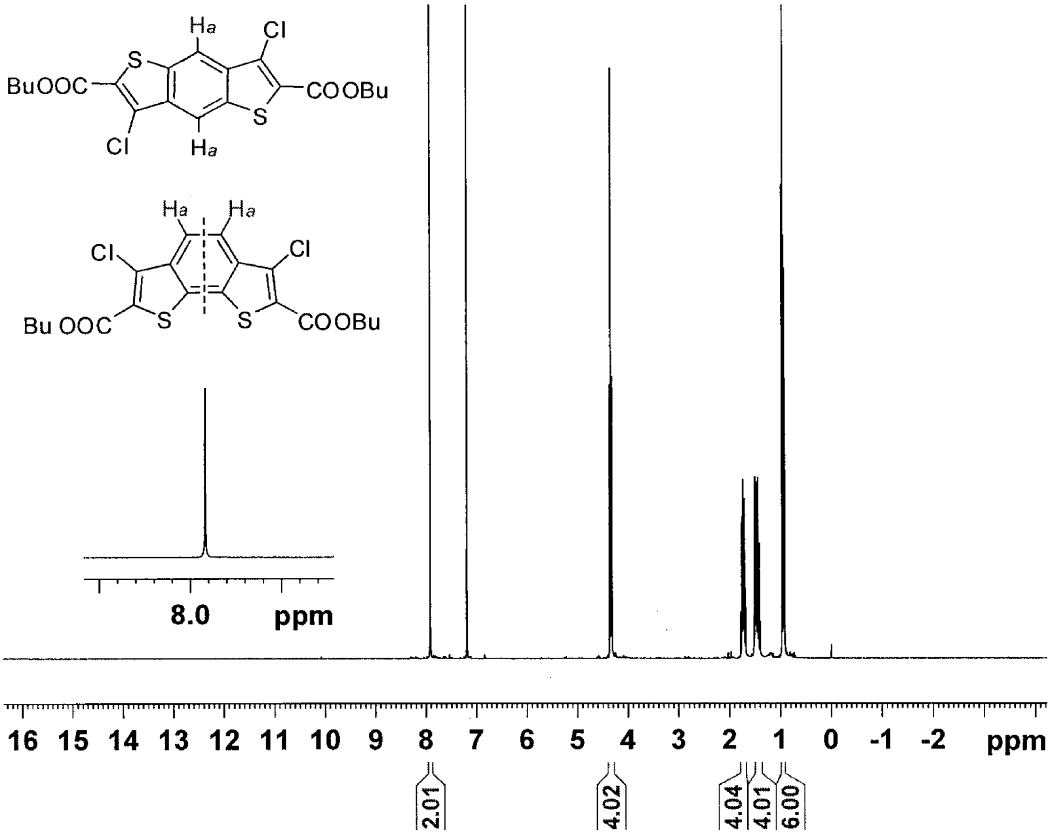


Figure 2. ^{1}H NMR spectrum of compound **3** in $CDCl_3$ at 300 MHz.

Table 1. Synthesis of **5a–c**.

4	Ar	Yield [%] of **5**[a]
a	2-MeO-5-F-C_6H_3	82
b	2-MeO-5-Cl-C_6H_3	87
c	2-(MeO)-C_6H_4	80

[a] Yields of isolated compounds.

(1.5 equiv.) were used as the catalyst and base, respectively. The reactions were carried out in dioxane (120 °C, 4 h). The arylboronic acids were chosen in the sense that their ^{1}H NMR signals would not disturb the structure elucidation of the aromatic core structure (*vide infra*).

Inspection of the ^{1}H NMR spectra of **5a–c** clearly showed that the two aromatic protons H_a and H_b are, as expected, chemically different and resonate as characteristic doublets at approx. $\delta = 7.74$ and 7.36 ppm with coupling constants of about 8.8 Hz (Figure 3). These results are only compatible with the structures of 3-aryl-6-chlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes **5a–c**, but not with the corresponding isomeric 3-aryl-8-chlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes. In the latter case, no significant coupling is possible for the aromatic protons H_a and H_b. As a consequence, the NMR experiments of **5a–c** clearly confirm the structure of dichlorodithiophene **3** as well, as no change of the aromatic core can be expected during the Suzuki reactions.

Due to the striking difference between our results and those reported earlier, the cyclization reaction of **1** with thionyl chloride, pyridine and methanol or *n*-butanol was repeated five times under the original conditions and always the same result was observed (formation of **2** and **3** as the main products, respectively). The reaction was also carried out in the absence of pyridine, but no significant change of the product distribution was observed.

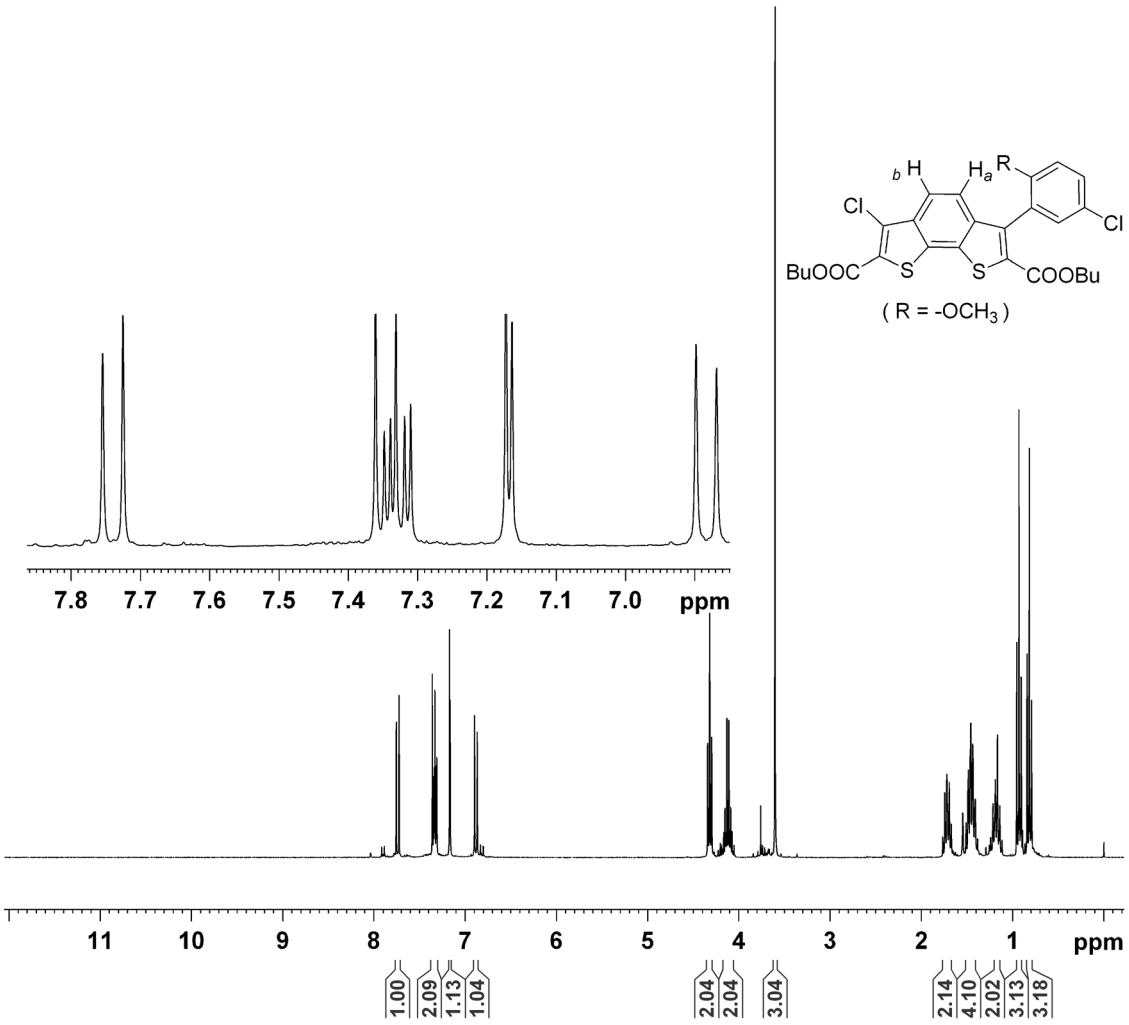


Figure 3. ^{1}H NMR spectrum of **5b** in $CDCl_3$ at 300 MHz.

Computations

To get some rationalization of the observed selectivity in favour of 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene **A** instead of 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene **A′** (Scheme 1), the cyclization of **1** with thionyl chloride was studied by density functional theory calculations (DFT) at the B3LYP level of theory using a 6-31G* basis set. The DFT calculations show that isomer **A** is thermodynamically more stable than isomer **A′** (by 5.5 kJ mol^{-1}, Table 3). However, the thermodynamic stability is unlikely to be the reason for the selectivity of the reaction because the reaction is irreversible. Therefore, possible mechanistic intermediates were studied by DFT calculations. The calculations were carried out for analogues of the mechanistic intermediates suggested by Krubsack et al. for the reaction of *trans*-cinnamic acid with thionyl chloride.[7a]

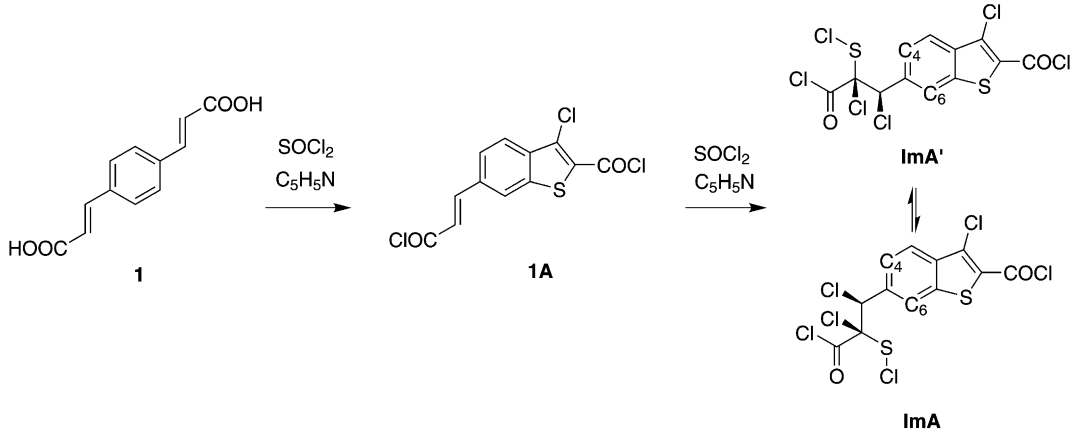
We assumed that the two cyclization reactions of diacrylate **1** occur sequentially and not at the same time. Thus, the first cyclization of **1** with thionyl chloride afforded the planar intermediate **1A** which reacts with a second equivalent of thionyl chloride to give the rotamers **ImA** and **ImA′** (Scheme 3). In principle, two diastereomers can be formed for each rotamer. However, only one diastereomer was considered because the energetic difference between the two diastereomers is low.

In analogy to the mechanistic studies of Krubsack et al. for *trans*-cinnamic acid, three possible paths for the transformation of **ImA** and **ImA′** to **A** and **A′** can be proposed, respectively (Scheme 4 and Scheme 5). This includes a direct electrophilic substitution (path 1), or electrophilic substitution *via* intermediate **ImBA** which could be formed by 1,2-elimination of hydrogen chloride (path 2), or rearrangement of intermediate **ImBA** to episulfide **ImA3** (path 3).

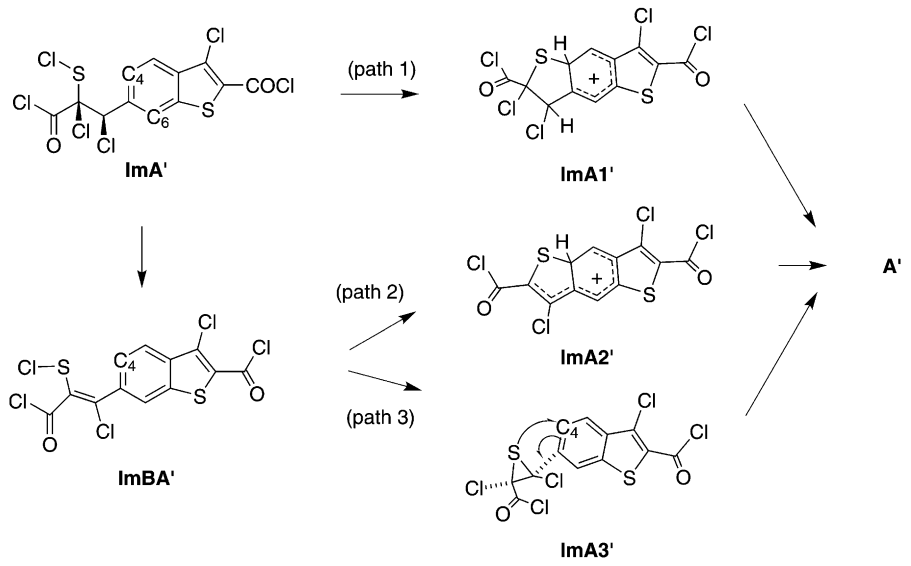
The energies of the open-chain intermediates **ImA**, **ImBA**, **ImA3** were compared with the energies of their rotamers **ImA′**, **ImBA′**, **ImA3′**, respectively. In general, the rotamers, in which the aromatic carbon atom C-6 is more close to the sulfur atom, are slightly energetically favoured (by 0.8 kJ mol^{-1}–2.1 kJ mol^{-1}). In addition, position 6 of the arene moiety has a higher electron density as compared to position 4. Based on these calculations, the sulfur atom of the S–Cl moiety is expected to preferentially attack at carbon C-6 (Table 2). In addition, we computed the energies of the cationic cyclic intermediates **ImA1**, **ImA1′**, **ImA2** and **ImA2′** (Table 3). Interestingly, intermediate **ImA1** is considerably more stable than **ImA1′** (by 16.15 kJ mol^{-1}). Likewise, **ImA2** is more stable than **ImA2′** (by 12.63 kJ mol^{-1}). The calcula-

Table 2. Energies of the optimized structures, the energy differences between the conformers, natural (NBO) charges and distances (S-C) of **ImA**, **ImA′**, **ImBA**, **ImBA′**, **ImA3, ImA3′** calculated at the B3LYP/6-31G* level for optimized structures.

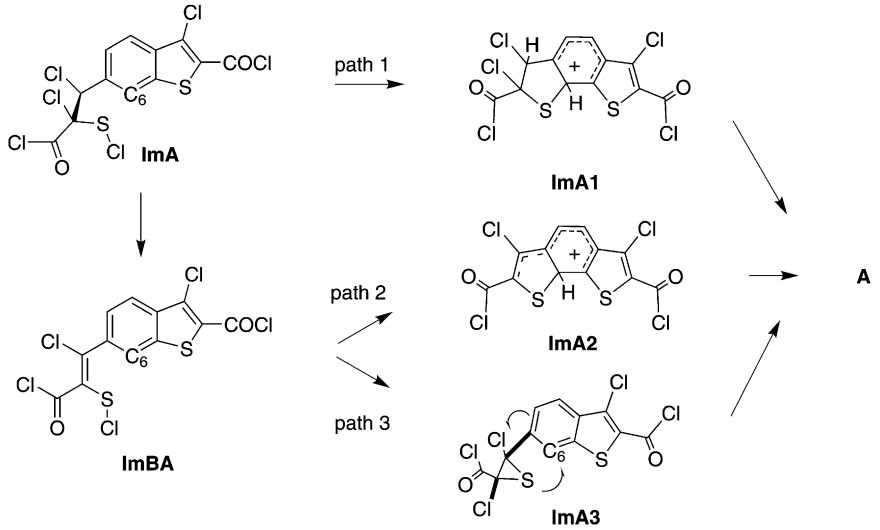
Intermediate		ImA	ImA′	ImBA	ImBA′	ImA3	ImA3′
Energy [a.u.]		−4167.66135	4167.66105	−3706.85652	−3706.85603	−3706.85263	−3706.85185
ΔE [kJ mol^{-1}]		−0.785129		−1.28786		−2.06798	
Charge [a.u.]	C-6	−0.21715	−0.19980	−0.19426	−0.19107	−0.20603	−0.18995
	C-4	−0.20714	−0.22368	−0.19969	−0.20087	−0.19660	−0.20846
	S	0.33445	0.33571	0.33339	0.33321	0.31805	0.32131
r(S–C) [Å]	C-6	3.33400	3.89695	3.24921	4.33132	3.20363	4.13341
	C-4	3.87239	3.31937	4.35374	3.26222	4.17400	3.22313



Scheme 3. Formation of **ImA** and **ImA′**.



Scheme 4. Proposed mechanism for the formation of 3,8-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene **A′**.



Scheme 5. Proposed mechanism for the formation of 3,8-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene **A**.

Table 3. Energies of the optimized structures, the energy differences between the conformers of **ImA1, ImA1′, ImA2, ImA2′, A** and **A′** calculated at the B3LYP/6-31G* level for optimized structures.

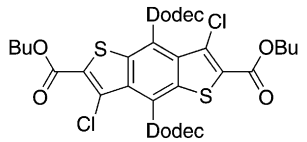
Intermediate	ImA1	ImA1′	ImA2	ImA2′	A	A′
Energy [a.u].	−3707.16569	−3707.15954	−3246.38173	−3246.37692	−3246.10058	−3246.09848
ΔE [kJ mol^{-1}]	−16.15168		−12.6282		−5.5161	

tions rationalize the fact that isomer **A** instead of **A′** is formed.

Conclusions

We have reinvestigated the cyclization of 1,4-phenylenediacrylic acid (**1**) with thionyl chloride and alcohols and provided evidence that the earlier reported structures, 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes, are wrong and that, in contrast, 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes are formed. The first report related to the reaction of **1** with $SOCl_2$, published by Ried et al. and using methanol as a trapping agent, provided a wrong structural assignment of diester **2** based on IR experiments.[5] In 1995, Karminski-

Zamola reported the use of anilines as the nucleophile and the formation of 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene-diamides.[6] The authors refer to the original report of 1980, but unfortunately did not provide an unambiguous structural proof. In 2009, Miura et al. referred to the work of 1995, again without providing an unambigious structural proof, and thus misinterpreted the structure of diester **3** which they believed would be **3′**.[4] As a consequence, the structures of a variety of symmetrical arylated dibenzothiophenes, prepared from **3** by Suzuki–Miyaura cross-coupling reactions, were not correctly assigned. Very recently, the synthesis of dialkylated 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene **6** has been reported by Miura (Figure 4).[10] In this case, only the formation of product **6** is possible because two aromatic positions are blocked by the alkyl groups.



6

Figure 4. Dialkylated 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophene **6** reported by Miura.

The formation of benzo[*b*]thiophenes starting from 3-phenylpropanoic acid with thionyl chloride and a small amount of pyridine was mechanistically discussed by Krubsack et al. in 1975.[7a] Based on his investigations we carried out quantum chemical calculations for several possible mechanistic intermediates. The calculations support the experimental findings and indicate that the formation of 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes is considerably more favored than the formation of 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes.

The misinterpretation of the structures of many benzo[1,2-*b*;5,6-*b*′]dithiophenes by several authors is presumably based on the fact that all of them relied on previously published reports without providing an independent unambiguous structural proof, such as an X-ray crystal structure analysis, 2D NMR or preparation of non-symmetrical derivatives. Several of the 3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophenes, which were earlier misinterpretated as 3,7-dichlorobenzo[1,2-*b*;4,5-*b*′]dithiophenes, show extremely interesting optical, thermal and electronic properties.[4] Theoretical explanations for these properties and comparisons with other molecules were provided by the authors. These theories and models have to be reconsidered in the light of the correct structures reported herein. In addition, the results reported herein are expected to be important for the future design of related molecules and materials.

Experimental Section

General Procedure for the Synthesis of 2 and 3

Thionyl chloride (6 mL, 80 mmol) was added portionwise to a mixture of 1,4-phenylene-diacrylic acid (**1**) (2.00 g, 9.16 mmol) and a catalytic amount of pyridine (0.2 mL). The reaction mixture was heated for 5 h at 140 °C. Upon cooling, the product solidified and the excess of thionyl chloride was removed under reduced pressure to give a greenish solid. This solid was dissolved in 50 mL of benzene and to the solution 10 mL of methanol were added. The mixture was heated at reflux for 2 h to give crude **2**. The same procedure was applied using *n*-butanol to give the crude butyl ester **3**. The residue was purified by flash column chromatography (silica gel, heptanes/ethyl acetate = 9:1). The spectroscopic data of **3** are identical with those reported in the literature.[4]

2,8-Bis(methoxycarbonyl)-3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene (2): Starting with **1** (2.00 g, 9.16 mmol), $SOCl_2$ (6 mL, 80 mmol), pyridine (0.2 mL), **2** was isolated as a yellow crystalline solid; yield: 1.94 g (57%); mp 147–149 °C. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 3.93$ (s, 6H, OCH_3), 7.95 (s, 2H, Ar); ^{13}C NMR (75.5 MHz, $CDCl_3$): $\delta = 52.7$ (OCH_3), 121.3 (CH), 126.2, 128.5, 133.1, 137.0, 160.7 (C); IR (KBr): $\nu = 3434$, 2960, 2842, 1727 (s), 1650, 1643, 1633, 6113, 1509, 1434 (m), 1322, 1306, 1250, 1238, 1010, 1090, 1038 (s), 973, 940, 910, 817, 759, 736, 611 cm^{-1} (m); GC-MS (EI, 70 eV): *m/z* (%) = 374 (M^+, $2\times^{35}$Cl, 100), 343 (89), 315 (43), 256 (29); HR-MS (EI, 70 eV): *m/z* = 373.9274, calcd. for $C_{14}H_8Cl_2O_4S_2$ ($2\times^{35}$Cl) $[M]^+$: 373.9276. The spectroscopic data are identical with those previously reported.[5]

2,7-Bis(butoxycarbonyl)-3,6-dichlorobenzo[1,2-*b*;5,6-*b*′]dithiophene (3): Starting with **1** (2.00 g, 9.16 mmol), $SOCl_2$ (6 mL, 80 mmol) and pyridine (0.2 mL), **3** was obtained as a yellow crystalline solid; yield: 2.73 g (65%); mp 95–97 °C. ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.94$ (t, $J = 7.3$ Hz, 6H, CH_3), 1.39–1.46 (m, 4H, CH_2), 1.68–1.77 (m, 4H, CH_2), 4.34 (t, $J = 6.5$ Hz, 4H, OCH_2), 7.91 (s, 2H, Ar); ^{13}C NMR (75.5 MHz, $CDCl_3$): $\delta = 13.7$ (CH_3), 19.2, 30.6 (CH_2), 65.9 (OCH_2), 121.2 (CH), 126.2, 128.2, 132.9, 137.1, 160.8 (C); IR (KBr): $\nu = 3418$, 2956, 2931, 2872 (s), 2736 (w) 1726, 1708, 1510, 1494 (s), 1476, 1406, 1380, 1301 (m), 1235, 1211, 1095, 1082, 1060, 1045, 1017, 964 (s), 932, 850, 804, 756 (m), 756, 734, 715 cm^{-1} (s); GC-MS (EI, 70 eV): *m/z* (%) = 458 (M^+, $2\times^{35}$Cl, 100), 346 (78), 329 (41), 257 (33); HR-MS (EI, 70 eV): *m/z* = 458.0171, calcd. for $C_{20}H_{20}Cl_2O_4S_2$ ($2\times^{35}$Cl) $[M]^+$: 458.0280.

General Procedure for Suzuki–Miyaura Reactions

A 1,4-dioxane solution (5 mL) of K_3PO_4 (2.0 equiv.), $Pd(PPh_3)_4$ (5 mol%) and arylboronic acids (1.0–1.2 equiv.) was stirred at 110–120 °C for 4 h. After cooling to 20 °C, H_2O was added. The organic and the aqueous layers were separated and the latter was extracted with CH_2Cl_2 (15 × 3 mL). The combined organic layers were dried (Na_2SO_4), filtered and the filtrate was concentrated under vacuum.

The residue was purified by column chromatography (flash silica gel, heptanes/dichloromethane = 1:1).

2,7-Bis(butoxycarbonyl)-3-(5-fluoro-2-methoxyphenyl)-6-chlorobenzo[1,2-*b*;5,6-*b*′]dithiophene (5a): Starting with **3** (200 mg, 0.43 mmol), 5-fluoro-2-methoxyphenylboronic acid **4a** (1.2 equiv., 88 mg, 0.53 mmol), $Pd(PPh_3)_4$ (25 mg, 5 mol%), K_3PO_4 (2.0 equiv., 185 mg, 0.85 mmol), and 1,4-dioxane (5 mL), **5a** was isolated as a white solid; yield: 195 mg (82%); mp 108–110 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.79 (t, J = 7.3 Hz, 3H, CH_3), 0.92 (t, J = 7.3 Hz, 3H, CH_3), 1.11–1.38 (m, 2H), 1.40–1.48 (m, 4H), 1.66–1.74 (m, 2H), 3.61 (s, 3H, OCH_3), 4.10 (t, J = 6.3 Hz, 2H), 4.31 (t, J = 6.3 Hz, 2H), 6.86–6.95 (m, 2H), 7.04–7.10 (td, J = 8.1, 3.1 Hz, 1H), 7.36 (d, J = 8.8 Hz, 1H), 7.74 (d, J = 8.8 Hz, 1H); ^{19}F NMR (282.4 MHz, $CDCl_3$): δ = −124.0; ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = 13.3, 13.7 (CH_3), 19.0, 19.2 (CH_2), 30.5, 30.6 (CH_2), 56.1 (OCH_3), 65.4, 65.7 (OCH_2), 111.9 (d, $J_{F,C}$ = 8.3 Hz, CH), 115.9 (d, $J_{F,C}$ = 22.5 Hz, CH), 117.9 (d, $J_{F,C}$ = 23.6 Hz, CH), 120.5, 122.5 (CH), 124.6 (d, $J_{F,C}$ = 8.2 Hz, CH), 128.2, 130.5, 133.0, 134.2, 136.3, 139.2, 139.8, 153.5 (C), 156.1 (d, $J_{F,C}$ = 237.7 Hz, CF), 161.0, 162.0; IR (KBr): ν = 2958, 2932, 1872, 2836, 1718, 1697 (s), 1493, 1463, 1414, 1334, 1311 (m), 1273, 1255, 1227, 1206, 1180, 1155, 1125, 1085, 1069, 1029 (s), 992, 940, 907, 877 (m), 807, 757, 729 cm^{-1} (s); GC-MS (EI, 70 eV): *m/z* (%) = 548 (M^+, ^{35}Cl, 97), 475 (48), 461 (41), 447 (13) 405 (32), 391 (22), 381 (34), 359 (31), 325 (21); HR-MS (EI, 70 eV): m/z = 548.8890, calcd. for $C_{27}H_{26}ClFO_5S_2$ (^{35}Cl) $[M]^+$: 548.0889.

2,7-Bis(butoxycarbonyl)-3-(5-chloro-2-methoxyphenyl)-6-chlorobenzo[1,2-*b*;5,6-*b*′]dithiophene (5b): Starting with **3** (200 mg, 0.43 mmol), 5-chloro-2-methoxyphenylboronic acid **4b** (1.2 equiv., 96 mg, 0.51 mmol), $Pd(PPh_3)_4$ (25 mg, 5 mol%), K_3PO_4 (2.0 equiv., 185 mg, 0.85 mmol), and 1,4-dioxane (5 mL), **5b** was isolated as a light green solid; yield: 211 mg (87%); mp 77–99 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.81 (t, J = 7.3 Hz, 3H, CH_3), 0.93 (t, J = 7.3 Hz, 3H, CH_3), 1.14–1.21 (m, 2H), 1.38–1.42 (m, 4H), 1.44–1.48 (m, 2H), 3.60 (s, 3H, OCH_3), 4.13 (t, J = 6.5 Hz, 2H), 4.32 (t, J = 6.5 Hz, 2H), 6.88 (d, J = 8.8 1H), 7.16 (d, J = 2.6 Hz, 1H), 7.30–7.36 (m, 2H), 7.73 (d, J = 8.8 Hz, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = 13.7, 13.8 (CH_3), 19.1, 19.2 (CH_2), 30.5, 30.6 (CH_2), 55.8 (OCH_3), 65.5, 65.7 (OCH_2), 112.1, 120.5, 122.5 (CH), 124.9, 125.3, 125.4, 128.2 (C), 129.6, 130.6 (CH), 130.7, 133.0, 134.2, 136.3, 138.9, 139.8, 155.9, 161.0, 162.0 (C); IR (KBr): ν = 2974, 2961, 2930, 2911, 2825, 1721, 1686 (s), 1675, 1663, 1582, 1561 (w), 1481, 1479, 1461, 1411, 1403, 1338, 1334 (m), 1289, 1261, 1251, 1182, 1134, 1127, 1025 (s), 802, 769, 684, 667 cm^{-1} (s); GC-MS (EI, 70 eV): *m/z* (%) = 564 (M^+, ^{35}Cl, 100), 491 (24), 477 (36), 463 (11), 421 (31), 381 (37) 325 (24); HR-MS (EI, 70 eV): *m/z* = 564.0594, calcd. for $C_{27}H_{26}Cl_2O_5S_2$ (^{35}Cl) $[M]^+$: 564.0593.

2,7-Bis(butoxycarbonyl)-3-(2-methoxyphenyl)-6-chlorobenzo[1,2-*b*;5,6-*b*′]dithiophene (5c): Starting with **3** (200 mg, 0.43 mmol), 2-methoxyphenylboronic acid **4c** (1.2 equiv., 78 mg, 0.52 mmol), $Pd(PPh_3)_4$ (25 mg, 5 mol%), K_3PO_4 (2.0 equiv. 185 mg, 0.85 mmol), and 1,4-dioxane (5 mL), **5c** was isolated as a light green highly viscous oil; yield: 180 mg (80%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.79 (t, J = 7.3 Hz, 3H, CH_3), 0.92 (t, J = 7.3 Hz, 3H, CH_3), 1.11–1.20 (m, 2H), 1.40–1.46 (m, 4H), 1.66–1.74 (m, 2H), 3.61 (s, 3H, OCH_3), 4.10 (t, J = 6.3 Hz, 2H), 4.31 (t, J = 6.5 Hz, 2H), 6.95 (d, J = 8.3, 1H), 7.01 (td, J = 7.4, 1.2 Hz, 1H), 7.17 (dd, J = 7.4, 1.7 Hz, 1H), 7.34–7.39 (m, 2H), 7.71 (d, J = 8.8 Hz, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = 13.7, 13.8 (CH3), 19.1, 19.2 (CH_2), 30.5, 30.6 (CH_2), 55.8 (OCH_3), 65.5, 65.7 (OCH_2), 110.9, 120.2, 120.5 (CH), 123.2, 125.2 (CH), 128.2 (C), 129.9 (CH), 130.1 (C), 130.9 (CH), 133.0, 134.1, 136.1, 140.2, 140.7, 157.1, 161.0, 162.2; IR (KBr): ν = 2957, 2930, 2872, 1716, 1698 (s), 1547, 1531, 1501, 1486, 1462, 1413, 1337, 1311 (m), 1274, 1228, 1175, 1123, 1114, 1071 (s) 906, 875, 727 cm^{-1} (s); GC-MS (EI, 70 eV): *m/z* (%) = 530 (M^+, ^{35}Cl, 100), 457 (49), 443 (33), 381 (37), 325 (21); HR-MS (EI, 70 eV): *m/z* = 530.0981, calcd. for $C_{27}H_{27}ClO_5S_2$ (^{35}Cl) $[M]^+$: 530.0982.

Calculations

Geometry optimizations have been carried out using the Gaussian 09[11,12] program package. We used the B3LYP method including the Becke-3-parameter gradient corrected exchange functional combined with the gradient-corrected correlation LYP functional by Lee, Yang and Parr and the 6–31G* basis sets to calculate the structures of the compounds. No imaginary frequencies were found indicating that all geometries represent at least local minimum structures on the potential energy surface. Additionally we calculated the natural atomic charges by applying the NBO program as implemented in Gaussian 09. All calculations have been carried out on the HPC-Cluster in Rostock.

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