Optically responsive switches
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Chapter 3

Synthesis and photochemical behavior of an asymmetric dithienylcyclopentene photoswitch

In this chapter, a new synthetic strategy towards substituted symmetric and asymmetric dithienylethenes is presented and used to synthesize an asymmetric perhydrogenated dithienylethene photoswitch. This dithienylethene is found to exhibit photochemical properties similar to its previously reported perfluoro analogue, such as the ability to ring open photochemically at low temperatures. However, the efficiency of photochemical ring closing was found to be lower. Quantum chemical calculations indicate that the lower efficiency is the result of the parallel and antiparallel conformations of the open form lying close in energy, hence a significant proportion of the molecules in the open form is present in unreactive conformations.*

* Part of the synthesis described in this chapter has been published as: Pijper, T. C.; Kudernac, T.; Browne, W. R.; Feringa, B. L. J. Phys. Chem. C 2013, 117, 17623–17632.
3.1 Introduction
Photochromic molecular switches are a versatile class of organic compounds. Their chemical structure can be alternated by photoirradiation at specific wavelengths between (at least) two isomers of the compound with unique UV/vis absorption spectra. One class of photochromic switches that has received substantial attention are diarylethenes, which consist of two aromatic units connected by a central olefin. Irradiation of the ‘open form’ isomers of these compounds, usually in the UV region, triggers a photochemical electrocyclization in which a covalent bond is formed directly between the two aromatic units, resulting in the formation of a ‘closed form’ isomer (see Scheme 3.1 for examples). This closed form typically absorbs strongly in the visible and can be switched back to the open form by irradiation with visible light. A common choice for the aromatic unit is thiophene; the corresponding photochromic systems are generally referred to as dithienylethenes. Dithienylethenes are currently investigated for various applications, examples being fluorescence modulation, conductance switching, and providing control over the properties of gels and liquid crystalline phases.

One of the most common designs for dithienylethenes employs a perfluoro- or perhydrocyclopentene central part and an identical substitution pattern for both thiophene moieties, resulting in a symmetric design (Scheme 3.1a). These photochromic molecules convert readily from the open form to the closed form by UV irradiation. However, the reverse process suffers from low quantum yields and has been shown to be inhibited at low temperatures. This has been attributed to the presence of a conjugated π system in the closed form isomer which stabilizes this form and presents a barrier to conversion to the open form. Recently, in an attempt to reduce the stabilization of the closed form, a dithienylethene with an asymmetric design was reported (Scheme 3.1b). This system was found to exhibit a higher quantum yield for photochemical ring opening and displayed a very low activation energy for this process (2.3 kJ/mol, compared to 9.3 kJ/mol for its symmetric analogue), enabling bidirectional switching even at 115 K.

A question that arises, however, is whether the improved photochemistry of the asymmetric dithienylperfluorocyclopentene will also be displayed by a perhydro analogue of this compound. For symmetric compounds, perfluoro and perhydrodithienylethenes usually display similar photochemical behavior, the only significant difference being that the perfluoro species are less subject to switching fatigue. However, it is not a priori to be assumed that this relation will hold for asymmetric systems – a perhydrocyclopentene will withdraw much less
electron density from the \( \pi \) system and, as such, may result in different photochemical behavior. For this reason, the synthesis and photochemical properties of 3.1, a phenyl-substituted asymmetric dithienylperhydrocyclopentene, were investigated in the present study (Scheme 3.1c). It was found that the photochemical behavior of 3.1 is substantially different from that of its perfluoro analogue. In addition, a new, convergent synthesis towards symmetric and asymmetric dithienylethenes is presented.

Scheme 3.1 Phenyl-substituted \( a \) symmetric and \( b \) asymmetric dithienylperfluorocyclopentenes.\(^8\) \( c \) Dithienylethene 3.1, a phenyl-substituted asymmetric dithienylperhydrocyclopentene.

3.2 Results and discussion

3.2.1 Synthesis

A convergent synthetic strategy was developed for the synthesis of dithienylethene 3.1 that was expected to provide dithienylethenes with different substitution patterns and functionalities. It should allow one to prepare dithienylethenes that are either symmetric or asymmetric, that contain either an perhydro- or perfluorocyclopentene central part, and that are terminated with aromatic side groups (Scheme 3.2, in which the side groups are chosen to be substituted phenyls). The two central building blocks in this synthesis are 3,5-dibromo-2-methylthiophene, which can be prepared from commercially available 2-methylthiophene in a single step, and 2-chloro-5-iodo-3-methylthiophene, which can be prepared from commercially available 2-chloro-3-methylthiophene. Both thiophenes can be connected to an aromatic side
group, for example by means of a transition metal mediated cross-coupling reaction. The substituted thiophenes can then be connected to the central cyclopentene. For 1,2-dibromocyclopentene, this can be achieved by a second cross-coupling reaction while, for octafluorocyclopentene, an addition-elimination reaction can be employed.

**Scheme 3.2 Convergent synthetic strategy used for the synthesis of 3.1.**

The synthesis of 3.1 is described in Scheme 3.3. Thiophene 3.2 was synthesized in 68 % yield through the double bromination of 2-methylthiophene with bromine.\(^{10}\) The bromine at the 5-position was then substituted for a phenyl group by lithiation and boration, followed by a Suzuki–Miyaura cross-coupling reaction with iodobenzene. This provided the substituted thiophene 3.3 in 88 % yield. NOESY NMR spectroscopy was used to confirm that the substitution pattern was as expected. Thiophene 3.4 was synthesized by the iodination of 2-chloro-3-methylthiophene by iodine and (diacetoxyiodo)benzene, which provided the expected product in good yield.\(^{11}\) Lithiation and boration of bromobenzene, followed by coupling to thiophene 3.4, provided thiophene 3.5 in 58 % yield. Dibromocyclopentene 3.6 was prepared in a three-step, one-pot procedure beginning with cyclopentanone.\(^{12}\) Thiophene 3.3 was then coupled to 3.6, which provided olefin 3.7 in 61 % yield. It was found that 3.7 decomposed completely within one day of its preparation. Therefore, 3.7 was used in the next synthetic step immediately after purification. Coupling of 3.7 and 3.5 finally provided dithienylethene 3.1 in 65 % yield.
**Scheme 3.3 Synthesis of dithienylethene 3.1.**

### 3.2.2 Photochemical behavior

UV/vis spectroscopy of dithienylethene 3.1 showed an absorption maximum at 320 nm and no significant absorption at > 400 nm (Figure 3.1). Irradiation of 3.1 at 365 nm resulted in the appearance of a new absorption band with a maximum at 459 nm, which is indicative of the formation of the closed form, 3.1c. In addition, a decrease in intensity of the band at 320 nm was observed. When the photostationary state (PSS) was reached by irradiation at 365 nm, the spectrum could be changed further by irradiating at 312 nm. This indicates that the open/closed equilibrium at PSS312nm lies further towards the closed form than at PSS365nm, which is attributed to differences in the absorption spectra of 3.1 and 3.1c at the two irradiation wavelengths employed. Irradiation with visible light caused the spectrum to change back to its initial state. The quantum yields for ring closing and ring opening (Φc and Φo) were found to be 0.20 (measured at 365 nm) and 0.25 (measured at 436 nm), respectively. These values indicate that ring closing and ring opening are approximately equally favorable and thus explain the open/closed ratio at PSS that was observed. They also show
differences between 3.1 and its the perfluoro analogue (Scheme 3.1) – for 3.1, the photochemical equilibrium slightly favors the open form, while for its perfluoro analogue the closed form is favored. This difference is also reflected in the open/closed ratios at PSS. For 3.1, the open/closed ratio at PSS_{312nm} was determined to be 36 : 64 while for the perfluoro analogue a ratio of 17 : 83 at PSS_{365nm} has been reported.⁸

Figure 3.1 UV/vis absorption spectra of 3.1₀ (solid), 3.1_{PSS365} (dashed), and 3.1_{PSS312} (dotted) at 1.0 × 10⁻⁵ M in n-hexane.

The fluorescence spectrum of dithienylethene 3.1₀ is shown in Figure 3.2. The emission spectrum of 3.1₀ showed a single maximum at 430 nm. The excitation spectrum showed two excitation maxima, at 267 nm and 310 nm. The fluorescence quantum yield, measured at an excitation wavelength of 310 nm, was determined to be 0.004. The fluorescence lifetime was determined to be < 1 ns.
The photochemical switching of dithienylethene 3.1 was also investigated by $^1$H NMR spectroscopy (Figure 3.3). Irradiation of 3.1o at 312 nm resulted in several spectral changes. The signals originating from the hydrogens of the two thiophene moieties shifted from 7.09 and 6.99 ppm to 6.47 and 6.06 ppm, which is attributed to the loss of aromaticity in the thiophenes upon photochemical ring closing. Similarly, the signals of the two methyl groups attached to the thiophenes shifted from 2.06 and 1.81 ppm to 1.71 and 1.66 ppm. Finally, the signals from the central cyclopentene shifted from 2.94–2.83 (2 × CH₂) and 2.16–2.08 ppm to 2.55–2.46, 2.34–2.28, and 1.96–1.85 ppm. The splitting of the signal at 2.94–2.83 ppm into two separate signals is attributed to the loss of rotational freedom around the two thiophene-alkene bonds upon photochemical cyclization. Irradiation with visible light reverted the spectrum to its original form.
Finally, the presence of a thermal barrier for the ring opening process of 3.1 was investigated. First, a sample of 3.1\textsubscript{o} in i-pentane was irradiated at 365 nm until the PSS was reached. The sample was then cooled to 120 K and irradiated in the visible region using a Xe arc lamp (Newport) equipped with a 480 nm long pass filter. The ring opening was monitored by UV/vis spectroscopy at set time intervals. In the experiment, it was found that 3.1\textsubscript{PSS365} converts to 3.1\textsubscript{o} fully within 4 s. This is in contrast to that found for the symmetric dithienylethene 4.1\textsubscript{PSS365} (see chapter 4), which did not undergo observable ring opening even after 60 s of irradiation. This experiment shows that the thermal barrier for the photochemical ring opening of 3.1 is significantly lower than that of a structurally similar symmetric dithienylethene, as was also found earlier for the perfluoro analogue of 3.1.

3.2.3 Discussion of photochemistry and quantum chemical calculations
Comparing the photochemical behavior of dithienylethene 3.1 with that of its perfluoro analogue, it is apparent that the photochemical ring closing of 3.1 is somewhat less efficient in that the ring closing quantum yield is lower (0.20, against 0.35 for the perfluoro analogue). The efficiency of the ring opening for the two dithienylethenes, on the other hand, is comparable – their ring opening
quantum yields are similar (0.25 against 0.23) and both molecules ring open readily at 120 K.

In order to investigate this difference in efficiency of photocyclization, ground state energies and vertical excitation energies of the two dithienylethenes were calculated using density functional theory (DFT), the results of which are shown in Figure 3.4. From these calculations, it was found that the relative energies of the vertically excited S\textsubscript{1} states of the two dithienylethenes are similar. For both, the energy difference between the S\textsubscript{1} state of the open isomer and S\textsubscript{1} state of the closed isomer is \( \sim 40 \text{ kJ/mol} \). Taken together with the minor differences in the S\textsubscript{0}\textrightarrow S\textsubscript{1} excitation energies, this suggests that no significant difference in reactivity is to be expected (assuming that the substitution pattern on the cyclopentene moiety does not affect the location of the conical intersections involved in the photochemical reactivity\textsuperscript{13}). However, an important difference between the two dithienylethenes is seen for the relative Gibbs energies of the two antiparallel (O-AP1 and O-AP2) and the two parallel (O-P1 and O-P2) open form isomers. These four isomers interconvert readily, however, only isomer O-AP1 is able to undergo photocyclization. For the perfluoro analogue, the relative Gibbs energies of these four open form isomers were found to be 0.0 kJ/mol (O-AP1), 11.9 kJ/mol (O-AP2), 8.6 kJ/mol (O-P1), and 8.2 kJ/mol (O-P2). According to Maxwell-Boltzmann statistics, this corresponds to a distribution of 92.9 % O-AP1, 0.8 % O-AP2, 2.9 % O-P1, and 3.5 % O-P2, which signifies that a large proportion of the open form is present in the reactive conformation. However, for 3.1, the relative Gibbs energies of the four open form isomers were found to be 0.0 kJ/mol (O-AP1), 12.5 kJ/mol (O-AP2), 3.3 kJ/mol (O-P1), and –0.1 kJ/mol (O-P2), which corresponds to a distribution of 42.9 % O-AP1, 0.3 % O-AP2, 11.4% O-P1, and 45.5 % O-P2 and signifies that a much smaller proportion of the open form consists of the reactive O-AP1 isomer. These findings provide a rationale for the observed reduced efficiency in photochemical ring closing of 3.1.
Figure 3.4 Relative ground state energies and excitation energies of the conformational and constitutional isomers of 3.1 and its perfluoro analogue. C = closed isomer, O-AP = open antiparallel isomer, O-P = open parallel isomer. Ground state energies were calculated at the DSD-PBEP86-D3BJ/cc-pVTZ//B3LYP-D3/6-311G(2d,2p) level with solvation effects calculated at the B3LYP/6-31G(d)/SMD(n-hexane) level. Vertical excitation energies were calculated at the CAM-B3LYP/6-311+G(2d,2p)/gas-phase level using TDDFT. Arrows and dashed lines denote relevant connections between the various isomers and states. The relative Gibbs energies of the five ground state isomers are given.

3.3 Conclusions
A general, convergent synthetic strategy towards substituted symmetric and asymmetric perfluoro- and perhydrodithienylethenes is presented in this chapter and is employed to synthesize a phenyl-substituted asymmetric
dithienylperhydrocyclopentene. Compared to its perfluoro analogue, the switching behavior of this dithienylethene is similar though the efficiency of the photochemical ring closing process was found to be lower. Quantum chemical calculations suggest that this lowered efficiency is the result of parallel and antiparallel conformations of the open form lying close in energy. This leads to a significant proportion of the open form being in unreactive conformations, thus lowering the quantum yield of photocyclization.

3.4 Experimental section

General experimental

NMR spectra were recorded on a Varian VXR-300 or a Varian Unity AS 400, operating at 299.97 and 399.93 MHz for $^1$H NMR, respectively. Chemical shifts are denoted in $\delta$-unit (ppm) relative to CDCl$_3$ (7.26) or CD$_2$Cl$_2$ (5.32) for $^1$H NMR and relative to CDCl$_3$ (77.16) for $^{13}$C NMR. The splitting parameters for $^1$H NMR are denoted as follows: s (singlet), d (doublet), t (triplet), q (quartet), dd (double doublet), dt (double triplet), m (multiplet), and b (broad). For $^{13}$C NMR, peaks are assigned as q (primary carbon), t (secondary carbon), d (tertiary carbon), and s (quaternary carbon). Infrared spectra were recorded with a PerkinElmer Spectrum 400 FT-IR spectrometer equipped with a universal diamond ATR sampling pod. Raman spectra were recorded with a PerkinElmer RamanStation 400F spectrometer at 785 nm. Melting points were determined with a Büchi B-545 melting point apparatus. Low resolution mass spectra were obtained with a Hewlett-Packard HP 6890 Series GC system in combination with a HP 5973 mass spectrometer. High resolution mass spectra were obtained using a Orbitrap XL (Thermo Fisher Scientific) HR/MS with an APPI (Kr lamp) or APCI ionization source. UV-vis spectra were recorded at room temperature using a JASCO V-630 spectrophotometer with 1 cm pathlength quartz cuvettes. Fluorescence excitation and emission spectra were recorded at room temperature using a JASCO FP-6200 spectrofluorometer with 1 cm pathlength quartz cuvettes. UV irradiation experiments were performed with a Spectroline ENB-280C/FE UV lamp (range at ‘365 nm’: 320–380 nm with a maximum at 365 nm; range at ‘312 nm’: 285–370 nm with a maximum at 312 nm). Irradiation experiments with visible light were performed with a Thorlabs OSL1-EC fiber illuminator together with a 420 nm long pass filter. All reactions were carried out under a nitrogen atmosphere with the exception of lithium-halogen exchange reactions and Suzuki–Miyaura cross-coupling reactions, which were carried out under an argon atmosphere. Column chromatography was performed on SiO$_2$ (SiliCycle SiliaFlash, 230-400 mesh) using methodology described by Still and coworkers.¹⁴
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All reagents were of commercial grade and were used as received. Solvents for spectroscopic measurements were UVASOL (Merck) grade.

**Determination of the ratio of open to closed forms at PSS**
A $2 \times 10^{-5}$ M solution of dithienylethene in ethanol in a quartz cuvette was irradiated at 312 nm. When the PSS was reached (as confirmed by UV/vis absorption spectroscopy), the sample was concentrated \textit{in vacuo}, redissolved in a 99:1 mixture of heptane and isopropanol, and submitted for HPLC analysis. Separation of $3.1_o$ and $3.1_c$ was achieved with Chiralcel OD-H (flow rate: 0.5 mL min$^{-1}$) and Chiralpak AD (flow rate: 1.0 mL min$^{-1}$) columns using a 99:1 mixture of heptane/isopropanol as the mobile phase. Retention times on OD-H column: $t_R = 6.0$ min ($3.1_o$ and $3.1_c$ enantiomer 1), $t_R = 7.5$ min ($3.1_c$ enantiomer 2). Retention times on AD column: $t_R = 10.7$ min ($3.1_c$ enantiomer 1), $t_R = 13.1$ min ($3.1_o$), $t_R = 14.1$ min ($3.1_c$ enantiomer 2).

**Determination of photochemical switching quantum yields**
Quantum yields were determined using a JASCO FP-6200 spectrofluorometer (5 nm bandwidth) as the irradiation source. An aqueous solution of potassium ferrioxalate was used as actinometer.$^{15}$ A 6.0 mM solution of the actinometer was used at 365 nm and a 0.30 M solution at 436 nm. The absorption spectra of irradiated samples were recorded with an Analytik Jena Specord S 600 UV/vis absorption spectrophotometer.

**Determination of the fluorescence quantum yield**
Fluorescence quantum yields were determined for a sample of $3.1_o$ in $n$-hexane using an excitation wavelength of 310 nm. Anthracene in ethanol was used as a reference ($\Phi = 0.27$).$^{15}$

**Quantum chemical calculations**
Ground state geometries were optimized with DFT using the B3LYP hybrid functional$^{16}$ (with VWN 1 RPA correlation$^{16c}$) in combination with the DFT-D3 dispersion correction scheme$^{17}$ and a 6-311G(2d,2p) basis set.$^{18}$ Thermochemical corrections to the ground state SCF energies were calculated at the same level with $T = 298.15$ K and $p = 1$ atm. Ground state SCF energies were calculated with DFT using the DSD-PBEP86 functional$^{19}$ in combination with the DFT-D3BJ dispersion correction scheme$^{17,20}$ and a cc-pVTZ basis set.$^{21}$ The Gibbs energy of solvation was calculated with the SMD model$^{22}$ (solvent: $n$-hexane) by calculating the molecular geometry, SCF energy, and thermochemical correction to the energy, both in the gas phase and in solution, after which the difference of the resulting energies was taken. For these calculations, the B3LYP functional
and the 6-31G(d) basis set were used as recommended by Marenich, Cramer, and Truhlar. Vertical excitation energies were calculated using linear response TDDFT with the CAM-B3LYP functional and a 6-311+G(2d,2p) basis set. The TDDFT and B3LYP/6-31G(d) calculations were performed with Gaussian 09 rev. C.01. All other calculations were performed with Firefly 8.0.0 RC, which is based partially on GAMESS (US) source code.

3,5-Dibromo-2-methylthiophene (3.2). Br₂ (18.1 g, 113 mmol, 5.8 mL) was slowly added to a stirred solution of 2-methylthiophene (5.00 g, 50.9 mmol) in acetic acid (120 mL). The resulting mixture was stirred for 20 h, after which diethylether (300 mL) was added. The mixture was repeatedly washed with saturated aqueous Na₂CO₃ (200 mL each time) until neutralized. The combined aqueous layers were extracted with diethyl ether (200 mL), after which the combined organic layers were dried over Na₂SO₄ and concentrated in vacuo.

Column chromatography (SiO₂, pentane, Rf = 0.75) afforded thiophene 3.2 as a colorless liquid (8.87 g, 68 %); ¹H NMR (300 MHz, CDCl₃) δ 6.86 (s, 1H), 2.34 (s, 3H); ¹³C NMR (75 MHz, CDCl₃) δ 136.0 (s), 132.0 (d), 108.8 (s), 108.6 (s), 14.9 (q); IR (neat) νmax 3097, 2919, 1533, 1449, 1378, 1304, 1143, 1022, 950, 814, 783, 691, 625, 586 cm⁻¹; Raman (neat) νmax 3098, 2919, 1533, 1449, 1378, 1304, 1143, 1022, 950, 814, 783, 691, 625, 586 cm⁻¹; m/z (EI, %): 258 (M⁺, 45), 256 (M⁺, 43), 177 (93), 175 (100), 96 (56); HRMS (EI): calcd for C₅H₄Br₂S: 253.8395, found: 253.8394.

3-Bromo-2-methyl-5-phenylthiophene (3.3). A stirred solution of 3,5-dibromo-2-methylthiophene (3.2, 2.00 g, 7.81 mmol) in THF (80 mL) was cooled to –80 °C. n-BuLi (1.6 M solution in hexane, 8.60 mmol, 5.4 mL) was added dropwise, after which stirring was continued for 30 min. Tributyl borate (1.98 g, 8.60 mmol, 2.3 mL) was added dropwise and stirring was continued for 30 min, after which the reaction mixture was allowed warm to rt slowly. At rt, the mixture was stirred for 1 h. Meanwhile, in a separate flask, a stirred mixture of iodobenzene (4.78 g, 23.4 mmol, 2.6 mL), tetrakis(triphenylphosphine)-palladium(0) (271 mg, 0.234 mmol), ethylene glycol (0.6 mL), aqueous Na₂CO₃
(2 M, 20 mL), and THF (24 mL) was heated to 70 °C. The crude boronic ester was added and the resulting mixture was heated at 80 °C for 16 h. The mixture was diluted with diethyl ether (200 mL) and washed with water (2 × 150 mL). The combined aqueous layers were extracted with diethyl ether (200 mL), after which the combined organic layers were dried over Na₂SO₄ and concentrated in vacuo. Column chromatography (SiO₂, heptane, Rf = 0.45) provided thiophene 3.3 as a white solid (1.75 g, 88 %); mp 73.9–74.0 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.51 (d, J= 7.1 Hz, 2H), 7.37 (t, J= 7.5 Hz, 2H), 7.28 (d, J= 7.5 Hz, 1H), 7.11 (s, 1H), 2.42 (s, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 141.1 (s), 133.6 (s), 133.4 (s), 128.9 (d), 127.7 (d), 125.5 (d), 125.2 (d), 109.9 (s), 14.8 (q); IR (neat) νmax 3064, 3023, 2919, 2871, 1539, 1498, 1468, 1444, 1327, 1299, 1072, 1032, 1007, 947, 827, 791, 753, 686 cm⁻¹; Raman (neat) νmax 3063, 2919, 1600, 1539, 1498, 1468, 1444, 1327, 1299, 1072, 1032, 1007, 947, 827, 791, 753, 686 cm⁻¹; m/z (EI, %): 254 (M⁺, 100), 252 (M⁺, 99), 173 (65); HRMS (APPI): calcd for C₁₁H₁₀BrS ([M + H⁺]: 252.9681, found: 252.9678.

2-Chloro-5-iodo-3-methylthiophene (3.4). 2-Chloro-3-methylthiophene (1.00 g, 7.54 mmol) was dissolved in dichloromethane (20 mL) and the resulting solution was cooled to 0 °C. Iodine (1.06 g, 4.18 mmol) and (diacetoxyiodo)benzene (1.47 g, 4.55 mmol) were added successively, after which the mixture was shielded from light and stirred for 4 h at rt. Diethyl ether (100 mL) was added and the mixture was washed with 10 % aqueous Na₂S₂O₃ (2 × 50 mL). The combined aqueous layers were extracted with diethyl ether (50 mL), after which the combined organic layers were dried over Na₂SO₄ and concentrated in vacuo. Column chromatography (SiO₂, cyclohexane, Rf = 0.8) provided thiophene 3.4 as a light yellow liquid (1.60 g, 82 %); ¹H NMR (400 MHz, CDCl₃) δ 6.96 (s, 1H), 2.15 (s, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 138.6 (d), 136.4 (s), 128.1 (s), 68.3 (s), 13.4 (q); IR (neat) νmax 2920, 1550, 1441, 1408, 1379, 1337, 1188, 1069, 1042, 1002, 961, 901, 824, 732, 685, 584, 574 cm⁻¹; Raman (neat) νmax 3067, 2920, 1443, 1408, 1379, 1337, 1189, 685, 574, 491, 344, 267, 241, 211, 137, 87 cm⁻¹; m/z (EI, %): 260 (M⁺, 36), 258 (M⁺, 100), 223 (33), 133 (7), 131 (21).
2-Chloro-3-methyl-5-phenylthiophene (3.5). A stirred solution of bromobenzene (1.74 g, 11.1 mmol) in THF (110 mL) was cooled to -80 °C. n-BuLi (1.6 M solution in hexane, 12.2 mmol, 7.6 mL) was added dropwise, after which stirring was continued for 30 min. Tributyl borate (2.80 g, 12.2 mmol, 3.3 mL) was added dropwise and stirring was continued for 30 min, after which the reaction mixture was allowed warm to rt slowly. At rt, the mixture was stirred for 1 h. Meanwhile, in a separate flask, a stirred mixture of 2-chloro-5-iodo-3-methylthiophene (3.4, 3.00 g, 11.6 mmol), tetrakis(triphenylphosphine)-palladium(0) (383 mg, 0.332 mmol), ethylene glycol (0.75 mL), aqueous Na₂CO₃ (2 M, 27 mL), and THF (33 mL) was heated to 70 °C. The crude boronic ester was added and the resulting mixture was heated at reflux for 16 h. The mixture was diluted with diethylether (150 mL) and washed with water (2 × 150 mL). The combined aqueous layers were extracted with diethylether (100 mL), after which the combined organic layers were dried over Na₂SO₄ and concentrated in vacuo. Column chromatography (SiO₂, heptane, Rf = 0.6) provided thiophene 3.5 as a white solid (1.35 g, 58 %); mp 76.7–76.9 °C; ¹H NMR (400 MHz, CDCl₃) δ 7.49 (d, J = 7.1 Hz, 2H), 7.36 (t, J = 7.5 Hz, 2H), 7.28 (d, J = 7.5 Hz, 1H), 6.99 (s, 1H), 2.20 (s, 3H); ¹³C NMR (101 MHz, CDCl₃) δ 140.4 (s), 135.4 (s), 133.9 (s), 129.1 (d), 127.8 (d), 125.4 (d), 124.7 (d), 124.2 (s), 13.8 (q); IR (neat) ν max 2921, 1598, 1560, 1495, 1455, 1432, 1355, 1231, 1205, 1160, 1032, 999, 715, 576, 498, 282, 219 cm⁻¹; m/z (EI, %): 210 (M⁺, 36), 208 (M⁺, 100), 173 (50); HRMS (APPI): calcd for C₁₁H₁₀ClS ([M + H]⁺): 209.0186, found: 209.0183. Anal. Calcd for C₁₁H₉ClS: C, 63.30; H, 4.35. Found: C, 63.41; H, 4.31.

1,2-Dibromocyclopentene (3.6).¹² Cyclopentanone (20.2 g, 0.240 mmol, 21.2 mL) was added slowly to a stirred solution of phosphorus pentachloride (55.0 g, 0.264 mol) in toluene (120 mL) over a period of 30 min. The mixture was cooled to -20 °C after which bromine (31.3 g, 0.196 mol, 10.0 mL) was added slowly over a period of 30 min. Volatiles were removed by concentration in vacuo. The residue was dissolved in hexane (40 mL) and cooled to -25 °C. A solution of
potassium tert-butoxide (27.8 g, 0.248 mol) in THF (120 mL) was added slowly over a period of 30 min after which the mixture was allowed to warm to rt. Celite (16 g), water (120 mL), and hexane (80 mL) were added and the resulting suspension was filtered over a plug of Celite. The layers were separated, and the organic layer dried over MgSO₄ and concentrated *in vacuo*. Purification by vacuum distillation (65 °C at 1.2 mmHg) provided olefin 3.6 as a colorless liquid (19.1 g, 35%) which was of suitable purity for further reactions. Analytically pure 3.6 was obtained by preparative TLC (SiO₂, heptane); ¹H NMR (300 MHz, CDCl₃) δ 2.63 (d, J = 7.5 Hz, 4H), 2.12–2.01 (m, 2H); ¹³C NMR (101 MHz, CDCl₃) δ 121.8 (s), 39.0 (t), 22.4 (t); IR (neat) ν max 2924, 2853, 1724, 1622, 1442, 1309, 1200, 1106, 1059, 840 cm⁻¹; m/z (EI, %): 228 (M⁺, 24), 226 (M⁺, 48), 224 (M⁺, 26), 147 (49), 145 (55), 65 (100).

3-(2-Bromocyclopent-1-enyl)-2-methyl-5-phenylthiophene (3.7). A stirred solution of 3-bromo-2-methyl-5-phenylthiophene (3.3, 1.75 g, 6.91 mmol) in THF (70 mL) was cooled to –80 °C. n-BuLi (1.6 M solution in hexane, 7.60 mmol, 4.8 mL) was added dropwise, after which stirring was continued for 30 min. Tributyl borate (1.75 g, 7.60 mmol, 2.1 mL) was added dropwise and stirring was continued for 30 min, after which the reaction mixture was allowed to warm to rt slowly. At rt, the mixture was stirred for 1 h. Meanwhile, in a separate flask, a stirred mixture of 1,2-dibromocyclopentene (3.6, 6.23 g, 27.7 mmol), tetrakis(triphenylphosphine)palladium(0) (240 mg, 0.207 mmol), ethylene glycol (0.7 mL), aqueous Na₂CO₃ (2 M, 25 mL), and THF (38 mL) was heated to 70 °C. The crude boronic ester was added and the resulting mixture was heated at 80 °C for 16 h. The mixture was diluted with diethylether (10 mL) and washed with water (2 × 10 mL). The combined aqueous layers were extracted with diethylether (10 mL), after which the combined organic layers were dried over Na₂SO₄ and concentrated *in vacuo*. Column chromatography (SiO₂, heptane, Rᵣ = 0.5) provided thiophene 3.7 as a colorless liquid (1.34 g, 61 %); ¹H NMR (300 MHz, CDCl₃) δ 7.55 (d, J = 7.4 Hz, 2H), 7.35 (t, J = 7.6 Hz, 2H), 7.24 (t, J = 7.2 Hz, 1H), 7.13 (s, 1H), 2.86–2.78 (m, 2H), 2.69–2.62 (m, 2H), 2.43 (s, 3H), 2.14–2.03 (m, 2H); ¹³C NMR (101 MHz, CDCl₃) δ 140.1 (s), 136.7 (s), 135.6 (s), 134.6 (s), 134.5 (s), 128.9 (d), 127.2 (d), 125.6 (d), 123.7 (d), 118.9 (s), 41.1 (t), 37.0 (t), 22.6 (t), 15.1 (q); IR (neat) ν max 2916, 2849, 1597, 1498, 1442, 1308, 1223, 1154, 1073, 1030, 947, 894, 838, 754, 708, 689 cm⁻¹; Raman (neat) ν max 3058, 2917,
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2850, 1644, 1598, 1552, 1500, 1468, 1443, 1377, 1241, 1185, 1157, 1033, 1001, 765, 709, 378 cm⁻¹; m/z (EI, %): 320 (M⁺, 100), 318 (M⁺, 97), 239 (22). It was found that 3.7 decomposed with time. Therefore, 3.7 was used in the next reaction step within 24 h of preparation.

2-Methyl-3-(2-(3-methyl-5-phenylthiophen-2-yl)cyclopent-1-enyl)-5-phenylthiophene (3.1). 2-Chloro-3-methyl-5-phenylthiophene (3.5, 876 mg, 4.20 mmol) was dissolved in THF (45 mL). n-BuLi (1.6 M solution in hexane, 4.62 mmol, 2.9 mL) was added dropwise, after which stirring was continued for 45 min. Tributyl borate (1.06 mg, 4.62 mmol, 1.2 mL) was added dropwise and stirring was continued for 45 min. Meanwhile, in a separate flask, a stirred mixture of 3-(2-bromocyclopent-1-enyl)-2-methyl-5-phenylthiophene (3.7, 1.34 mg, 4.20 mmol), tetrakis(triphenylphosphine)palladium(0) (146 mg, 0.126 mmol), ethylene glycol (0.45 mL), aqueous Na₂CO₃ (2 M, 18 mL), and THF (26 mL) was heated to 70 °C. The crude boronic ester was added and the resulting mixture was heated at reflux for 16 h. The mixture was diluted with pentane (100 mL) and washed with water (2 × 100 mL). The combined aqueous layers were extracted with pentane (100 mL), after which the combined organic layers were dried over Na₂SO₄ and concentrated in vacuo. Column chromatography (SiO₂, heptane/ethyl acetate 200:1, Rf = 0.4) provided dithienylethene 3.1 as a colorless oil (1.13 g, 65 %); ¹H NMR (400 MHz, CDCl₃) δ 7.54–7.49 (m, 4H), 7.33 (t, J = 7.8 Hz, 4H), 7.22 (t, J = 7.4 Hz, 2H), 7.06 (s, 1H), 6.96 (s, 1H), 2.93–2.84 (m, 4H), 2.14–2.06 (m, 2H), 2.06 (s, 3H), 1.79 (s, 3H); ¹H NMR (300 MHz, CD₂Cl₂) δ 7.54–7.49 (m, 4H), 7.33 (t, J = 7.6 Hz, 4H), 7.22 (t, J = 7.3 Hz, 2H), 7.09 (s, 1H), 6.99 (s, 1H), 2.94–2.83 (m, 4H), 2.16–2.08 (m, 2H), 2.06 (s, 3H), 1.81 (s, 3H); ¹³C NMR (75 MHz, CDCl₃) δ 141.7 (s), 139.9 (s), 136.7 (s), 135.8 (s), 135.4 (s), 135.3 (s), 135.0 (s), 134.7 (s), 134.6 (s), 132.4 (s), 128.88 (d, 4C), 127.2 (d), 127.1 (d), 126.4 (d, 4C), 124.2 (d), 39.8 (t), 39.1 (t), 23.0 (t), 15.3 (q), 14.5 (q); IR (neat) νmax 2914, 1597, 1498, 1436, 1314, 1199, 1155, 1072, 1030, 903, 836, 752, 687 cm⁻¹; Raman (neat) νmax 3060, 2914, 1623, 1598, 1550, 1499, 1462, 1438, 1234, 1199, 1000 cm⁻¹; HRMS (APPI): calcd for C₂₇H₂₄S₂: 413.1392, found: 413.1384.
Chapter 3

Dithienylethene 3.1e. $^1$H NMR (400 MHz, CD$_2$Cl$_2$) $\delta$ 7.55–7.48 (m, 4H), 7.41–7.29 (m, 6H), 6.47 (s, 1H), 6.06 (s, 1H), 2.55–2.46 (m, 2H), 2.34–2.28 (m, 2H), 1.96–1.85 (m, 2H), 1.71 (s, 3H), 1.66 (s, 3H); Raman (neat) $\nu_{max}$ 1572, 1535, 1305, 1261, 1000 cm$^{-1}$.

3.5 Full IR, Raman, and NOESY spectra
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NOESY spectrum, recorded at 400 MHz

Zoom-in of aromatic region
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3.6 References


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