

# C–C bond formation through oxidatively induced elimination of platinum complexes—A novel approach towards conjugated macrocycles†

Gerda Fuhrmann,<sup>a</sup> Tony Debaerdemaeker<sup>b</sup> and Peter Bäuerle<sup>\*a</sup>

<sup>a</sup> Department Organic Chemistry II (Organic Materials and Combinatorial Chemistry), Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany. E-mail: peter.baeuerle@chemie.uni-ulm.de

<sup>b</sup> Division of X-ray and Electron Diffraction, Ulm University, Albert-Einstein-Allee 11, 89081 Ulm, Germany

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A novel and effective method for the synthesis of conjugated macrocycles is described. By the self-assembly of conveniently accessible building blocks to a metalla-macrocycle, and subsequent C–C bond formation through elimination of transition metal units, the strained cyclodimeric terthiophene-diyne **4**—as a precursor for cyclo[8]thiophene **5**—was synthesized in a good overall yield.

The field of nano-sized and shape-persistent cycles is growing rapidly and today various systems have become available due to considerable efforts in developing new strategies for cyclization reactions.<sup>1</sup> Few recent examples, such as the zirconocene-coupling<sup>2</sup> or the supramolecular formation of macrocycles containing transition metals as tectons,<sup>3</sup> are reported to give high yields. This is due to the ideal geometric factors of the building blocks and the reversibility of the reactions under thermodynamic equilibrium conditions. However, the facile accessibility of rigid, all-carbon perimeter macrocycles on a larger scale still remains a major challenge.

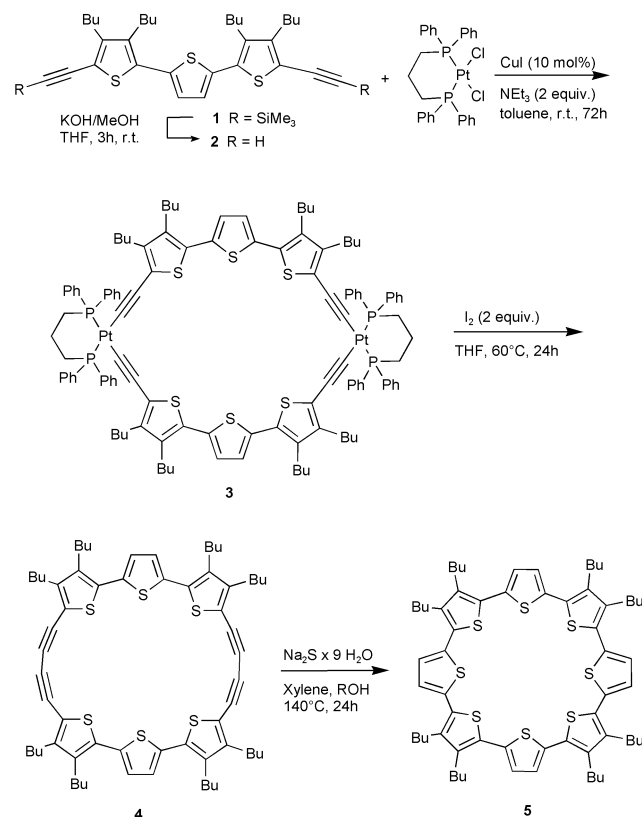
We recently obtained a set of 39- to 133-membered conjugated thiophene-derived macrocycles which represent a novel topology and class of compounds in the area of conducting polymers and oligomers.<sup>4</sup> Due to their highly symmetrical circular structures completely new properties have been discovered.<sup>5</sup> Terthiophene-diyne **2** and a corresponding pentamer were oxidatively coupled in a random cyclization approach under pseudo high dilution conditions to give mixtures of macrocyclic oligothiophene-diyne in expected modest total yields (8.5%, 13.5%) which were then separated into the individual macrocycles by preparative HPLC in yields of 3.9 to <0.5%. In a second step, by reacting the butadiyne units in the cyclo(oligothiophene-diyne)s with sulfide anions the fully conjugated cyclo[*n*]thiophenes (*n* = 12,16,18) were obtained in yields of 7–27% only on a milligram scale.

In this respect, we have now developed a novel and effective protocol for the synthesis of conjugated macrocycles in which conveniently accessible diyne building blocks and transition metal precursor complexes self-assemble to form a stable, coordinatively bound metalla-macrocycle. Subsequently and most importantly, the transition metal units are expelled under simultaneous formation of C–C bonds leading to the conjugated macrocycle.

Thus, by reaction of *cis*-Pt(dppp)Cl<sub>2</sub> and terthiophene-diyne **2** in the presence of 10 mol% CuI and 2 eq. of NEt<sub>3</sub> at room temperature bisplatinum-macrocycle **3** was isolated after chromatography as a stable orange-brown powder in 91% yield (Scheme 1). <sup>1</sup>H and <sup>31</sup>P NMR spectra suggest the formation of a cyclic bisplatinum σ-acetylide complex. In the <sup>1</sup>H NMR spectrum of **3**, signals for terminal acetylenic protons are completely lacking and only those belonging to the phenyl protons of the dppp-ligand (7.90, 7.38 ppm) and to the β protons of the terthiophene unit (6.98 ppm) are visible in the aromatic part of the spectrum. The <sup>31</sup>P NMR spectrum of **3** exhibits a

single peak at –5.59 ppm with a set of <sup>195</sup>Pt satellites (<sup>1</sup>J<sub>Pt–P</sub> = 2243 Hz). Ultimate proof of the cyclodimeric structure of **3** comes from MALDI-TOF mass spectrometry revealing molecular ions at *m/z* = 2249.5. IR spectra corroborate the structure of **3** by showing typical ν(C≡C–Pt) stretches at 2362 and 2106 cm<sup>–1</sup> and by the lack of ν(C≡C–H) stretches at 3308 cm<sup>–1</sup> which appear for precursor **2**. These results are in full accordance with other recently published platinum σ-acetylide macrocycles.<sup>6</sup>

Reductive 1,1-eliminations for C–C coupling products from Pd σ-acetylide complexes are well known to effectively proceed in the catalytic cycle of the Sonogashira-Hagihara reaction<sup>7</sup> or the Pd-catalyzed version of the Glaser coupling.<sup>8</sup> While stabilized *cis*-(R'<sub>3</sub>P)<sub>2</sub>PdR<sub>2</sub> complexes allow the thermal elimination of C–C coupling products to be controlled and followed<sup>9</sup> the corresponding Pt complexes are very stable toward reductive elimination and only few examples of *cis*-(R'<sub>3</sub>P)<sub>2</sub>PtAr<sub>2</sub> are known where the pyrolytic formation of biaryls is accounted.<sup>10</sup> Generally, an increase in the oxidation state of a complexed transition metal facilitates its reductive elimination. An example for oxidatively induced reductive elimination of Pt(II) complexes, but only promoted by a ferrocenyl group, has been reported.<sup>11</sup>



Scheme 1 Synthesis of macrocycles **3–5**.

† Electronic supplementary information (ESI) available: experimental section. See <http://www.rsc.org/suppdata/cc/b3/b300542a/>

In a newly developed reaction, we could achieve 1,1-reductive elimination of the Pt(dppp) "corners" from bismetallacycle **3** under simultaneous C–C bond formation and preservation of the cyclic structure by treatment of **3** with 2 eq. of iodine. 100% conversion of the starting material took place at an optimum temperature of 60 °C and a reaction time of 24 hours in THF. After chromatographic separation from polymeric by-products and Pt(dppp)<sub>2</sub> the cyclodimeric terthiophene-diyne **4** was isolated in 54% yield as a stable red microcrystalline solid (Scheme 1). It represents the smallest (26-memb.) macrocycle in the homologous series which, however, could never be detected in the previous random cyclooligomerization reactions. Due to the highly symmetrical structure, <sup>1</sup>H and <sup>13</sup>C NMR spectra consist of only few signals which are directly comparable to those of the corresponding higher members in the series. The cyclic structure of **4** is finally, unambiguously proven by a molecular mass of  $m/z = 1036.7$  in the MALDI-TOF mass spectra.

A more detailed characterization of **4** was possible by X-ray structure analysis of single crystals which could be obtained by slow evaporation from chloroform solutions.<sup>12</sup> The top view of an individual molecule (including atomic labelling) shows a nearly perfect circular shape comprising all-*syn*-oriented terthiophene moieties which are connected by concavely bowed butadiyne units indicating considerable ring strain (Fig. 1). The bond angles of the butadiyne fragments (C1'–C19–C17 163.2°, C19–C17–C15 167.7°, C17–C15–C13 167.4° and C15–C13–C11 160.3°) are severely distorted and largely deviate from the normal linear geometry. They are under the smallest values reported for strained dehydroannulenes<sup>13</sup> or cyclophanes.<sup>14</sup> The alternating carbon–carbon bond lengths are quite typical for strained macrocycles (C1'–C19 1.416 Å, C19–C17 1.205 Å, C17–C15 1.368 Å, C15–C13 1.203 Å, C13–C11 1.417 Å). Due to the steric interactions of the butyl side chains adjacent thiophene rings are distorted by 13.80° (T1, T2) and –29.09° (T2, T3), a phenomenon which was also detected in the X-ray structure analyses of the less strained next larger members in the homologous series, the cyclotrimeric<sup>5a</sup> and cyclotetrameric terthiophene diynes.<sup>4a</sup> The nonbonding distances S1...S1' and S1'...S3 are 11.04 Å (largest) and 8.06 Å (smallest), respectively. The space filling model of the 26-membered ring suggests an interior cavity of about 35 Å<sup>2</sup>. Despite the distortion of the thiophene rings and the butadiyne units, the 32 $\pi$ -electron perimeter shows remarkable conjugation. In the <sup>1</sup>H-NMR spectrum a substantial up-field shift of the thiophene  $\beta$ -protons in comparison to those of the next larger members in the series ( $\Delta\delta = \geq 0.2$  ppm) shows antiaromatic behaviour.

Cyclodimeric terthiophene-diyne **4** was finally reacted with disodium sulfide in xylene/2-methoxyethanol at 140 °C to give octabutyl-cyclo[8]thiophene **5** which after chromatography was isolated in 19% yield as a stable red microcrystalline solid. The modest yield in this reaction might be due to the ring strain in **4** and the high reaction temperature which cause partial destruction of the cycle. Structural proof of this smallest member of

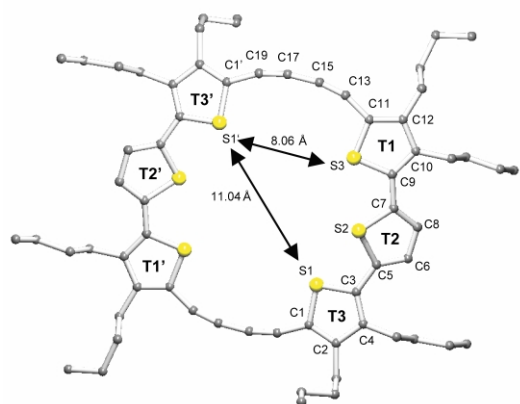


Fig. 1 POVray top view of cyclodimeric terthiophenediyne **4**.

conjugated cyclo[*n*]thiophenes came from <sup>1</sup>H and <sup>13</sup>C NMR spectra, which are very simple due to the high symmetry of the molecule, and MALDI-TOF mass spectra exhibiting molecular ions at  $m/z = 1104.5$ . Very recently, the synthesis and structural characterization of a comparable cyclo[8]pyrrole have been reported.<sup>15</sup>

In summary, we have developed a very effective method for the synthesis of conjugated macrocycles involving supramolecular formation of platino-macrocycles and subsequent C–C bond formation through elimination of the transition metal units by means of an oxidant. In the meanwhile, we successfully used this protocol for the synthesis of other macrocyclic systems, indicating a more general applicability of the method.

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‡ CCDC 201462. See <http://www.rsc.org/suppdata/cc/b3/b300542a/> for crystallographic data in .cif or other electronic format.

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- X-Ray single-crystal diffraction data for **4** were collected on a STOE-IPDS image-plate diffractometer. Crystal data: C<sub>64</sub>H<sub>76</sub>S<sub>8</sub>,  $M = 1037.6$ , monoclinic, space group  $P2_1/a$ ,  $a = 9.073(1)$ ,  $b = 20.222(2)$ ,  $c = 16.503(2)$  Å,  $\beta = 104.87(2)^\circ$ ,  $V = 2926.6(6)$  Å<sup>3</sup>,  $Z = 2$ ,  $\rho_{\text{calcd}} = 1.177$  g cm<sup>-3</sup>,  $\mu(\text{MoK}\alpha) = 0.272$ . Least square refinement based on 3949 reflections with  $I \geq 2\sigma(I)$  and 468 parameters led to convergence, with a final  $R1 = 0.0331$ ,  $wR2 = 0.0755$ , and  $\text{GOF} = 0.945$ . ‡
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