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Synthesis and Functionalization of 3,3′-Bis(spirodienone)-Bridged 2,2′-Bithiophene: A New Building Block for Redox-Active Molecular Switching Materials

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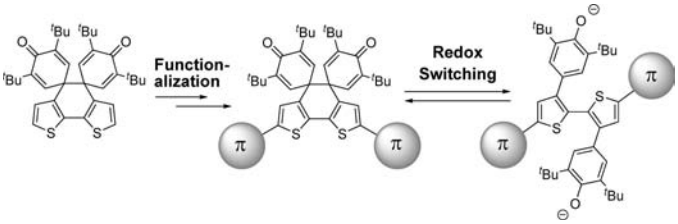
ABSTRACT



Bithiophene derivatives bridged with a bis(spirodienone) unit were synthesized and characterized. Lithiation of the thiophene rings of an unsubstituted derivative proceeded without decomposition of the bis(spirodienone) skeleton. Palladium-catalyzed cross-coupling reactions (Suzuki−Miyaura, Sonogashira) with bromides afforded a variety of π-extended derivatives. Bond breaking and formation under redox conditions were observed by cyclic voltammetry.

Due to the ease of functionalization of thiophene rings, conjugated molecules containing thiophenes are useful building blocks for electrically and optically interesting materials.[1] Some of these molecules show changes in structure and properties in response to external stimuli; these have received much attention as candidates for components of molecular switches.[2] For example, many compounds with a dithienylethene skeleton, which is a commonly used photochromic unit, have been investigated with a view to their application in photochromic switching materials.[3] Furthermore, some oligothiophene derivatives with switching functions have been investigated.[4] In this context, the synthesis of thiophene-

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containing molecules that respond to external stimuli opens the way to the development of new molecular switching materials.

As a part of a study of nonplanar extended quinones,[5] we recently observed the unexpected formation of 3,3′-bis(spirodienone)-bridged 2,2′-bibenzo[*b*]thiophene derivative **1** (Figure 1).[6] Compound **1** showed photo- and redox-active switching properties through a ring-opening/ring-closing process. Inspired by this phenomenon, we designed bis(spirodienone)-bridged 2,2′-bithiophene derivative **2a**, which was logically derived from **1** by removal of the annelated benzene rings, as a potential building block for functionalized π-extended systems with switching properties. Reactive α-positions on the thiophene rings of **2a** were expected to act as “footholds” for π-extension. In addition, compound **2a** has a fixed s-*cis* conformation. Breaking and formation of the bis(spirodienone) bridge would allow control of the conformation of the bithiophene unit,[7] which affects the properties of the molecule.[8] As a first step toward such switchable materials, we here report the synthesis, structure, and functionalization of **2a** to give several derivatives (**2c**−**j**) and describe their redox properties.

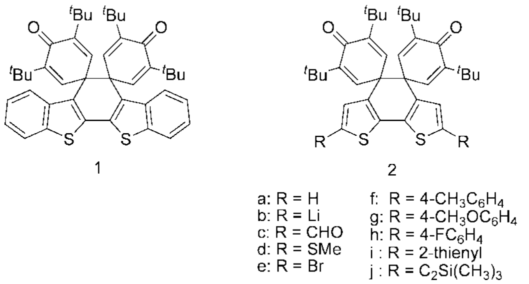
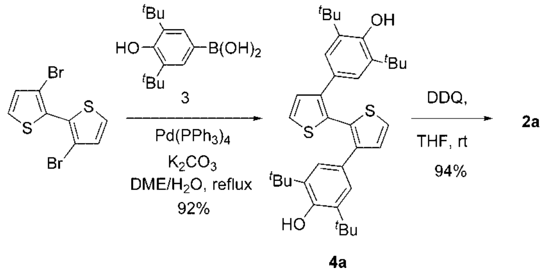


Figure 1. Bis(spirodienone)-bridged bithiophenes **1** and **2**.

The synthesis of **2a** was carried out as shown in Scheme 1. In previous work, 3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)thiophene and its *O*-substituted derivatives have been prepared by Kumada−Tamao coupling of 3-bromothiophene and 3,5-di-*tert*-butyl-4-trimethylsiloxyphenylmagnesium bromide[9] and by Suzuki−Miyaura coupling of 3-thiopheneboronic acid and *O*-substituted 3,5-di-*tert*-butyl-4-bromobenzene derivatives.[10] We recently discovered an efficient synthesis of 3,5-di-*tert*-butyl-4-hydroxyphenylboronic acid **3** directly from 4-bromo-2,6-di-*tert*-butylphenol,[11] and we prepared bisphenol **4a** in 92% yield by Suzuki−Miyaura coupling of 3,3′-dibromo-2,2′-bithiophene[12] with 2.5 equiv of **3**. Oxidation of **4a** with DDQ in tetrahydrofuran at room temperature for 2 h afforded bis(spirodienone) **2a** in 94% yield.

Scheme 1. Synthesis of Bis(spirodienone) **2a**



Compound **2a** was obtained as colorless crystals with air and thermal stability. Recrystallization of **2a** from dichloromethane/hexane afforded good single crystals that allowed characterization of the structure of **2a** by X-ray crystallography.[13] ORTEP drawings of **2a** are shown in Figure 2.

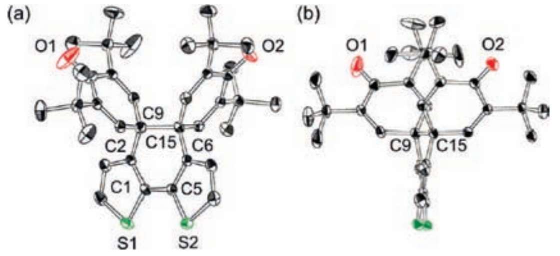


Figure 2. ORTEP drawings of **2a**: (a) front view and (b) side view. Hydrogen atoms are omitted for clarity.

The planes of the cyclohexadienone units lie perpendicular to the thiophene plane and face each other. The dihedral angle formed by C2−C9−C15−C6 is 48.0(2)°. Therefore, the central six-membered ring possesses a twisted-chair conformation. The two thiophene rings are twisted with an S1−C1−C5−S2 dihedral angle of 12.0(4)°. The bond length

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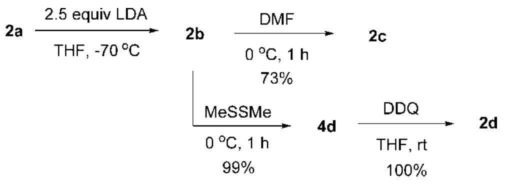
(13) Crystallographic data: $C_{36}H_{44}O_2S_2$, M = 572.86, triclinic, space group $P\bar{1}$ (No. 2), a = 10.1637(1) Å, b = 11.4120(4) Å, c = 17.2254(2) Å, α = 67.23(1)°, β = 71.58(1)°, γ = 65.98(1)°, V = 1652.63(6) Å^3, Z = 2, D_{calc} = 1.151 g cm^{-3}, $F(000)$ = 616.00, μ = 1.90 cm^{-1} (Mo Kα; λ = 0.71070 Å), 16627 reflections measured, 16460 unique, reflection/parameter ratio = 20.60, R = 0.064 for $I > 2\sigma(I)$, wR = 0.206 for all data, GOF = 0.83.

of the two spiro carbons (C9−C15) is 1.609(5) Å, which is slightly shorter than the equivalent in **1** (1.625(5) Å) but longer than a normal sp^3-sp^3 carbon bond (1.54 Å).[14]

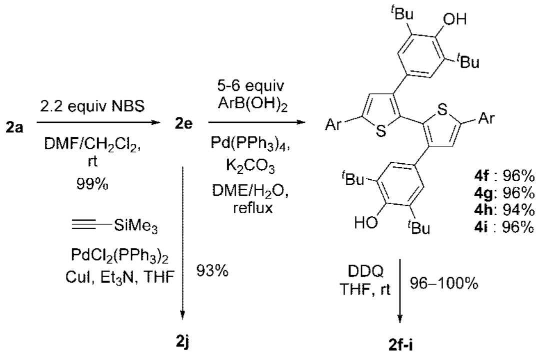
It was considered that if the α-positions of the thiophene rings in **2a** could be lithiated without decomposition of the bis(spirodienone) skeleton, the lithiated intermediate might act as a useful synthon for reaction with electrophiles. Treatment of 2.5 equiv of lithium diisopropylamide with **2a** at −70 °C for 1 h afforded dilithiated derivative **2b**, which was transformed to dialdehyde **2c** by quenching with DMF (Scheme 2). In the reaction of **2b** with dimethyl disulfide, however, ring-opened isomer **4d** was obtained. Compound **4d** was then oxidized by DDQ to afford **2d**. The formation of **4d** is probably based on reduction of **2d** by electron transfer from methyl thiolate species generated in situ. Treatment of **2a** with *n*-BuLi or *t*-BuLi gave complex mixtures.

Scheme 2. Lithiation and Fuctionalization of **2a**



The bromination of **2a** and successive transition-metal-catalyzed cross-coupling reactions are summarized in Scheme 3. Treatment of 2.2 equiv of *N*-bromosuccinimide with **2a** in DMF/CH_2Cl_2 at room temperature afforded **2e** in 99% yield. We examined the Suzuki−Miyaura coupling reactions of **2e** with arylboronic acids. Treatment of **2e** with 2.5 equiv of 4-methylphenylboronic acid under conventional conditions, using $Pd(PPh_3)_4$ as a catalyst and aqueous K_2CO_3 as a base, afforded a mixture of the ring-opened product **4f** (59% yield) and the desired coupling product **2f** (35% yield). The formation of **4f** indicated that reduction occurred under the reaction conditions used. Although the mechanism of reduction was unclear, compound **4f** was obtained selectively in 96% yield by the use of an excess amount of 4-methylphenylboronic acid (5−6 equiv). DDQ-oxidation of **4f** gave **2f** in 96% yield. Similar reactions allowed the preparation of **2g**, **2h**, and **2i** from 4-methoxyphenylboronic acid, 4-fluorophenylboronic acid, and sodium 2-thienylboronate,[15] respectively. We were able to introduce aryl groups in good yield by Suzuki−Miyaura coupling followed by oxidation. Furthermore, Sonogashira coupling of **2e** with trimethylsilylacetylene afforded the desired coupling product **2j** in 93% yield.

Scheme 3. Suzuki−Miyaura and Sonogashhira Couplings of **2e**



The redox properties of **2a** and **2c**−**j** were examined by cyclic voltammetry.[16] The redox potentials are summarized in Table 1, and the cyclic voltammograms of **2a**, **2c**, **2d**, and **2g** are shown in Figure 3.

Table 1. Redox Potentials[a] of Bis(spirodienone) Derivatives **2a**−**j**

compound	$^{ox}E_{p2}$ (V)	$^{ox}E_{p1}$ (V)	$^{red}E_{pc}$ (V)	$^{red}E_{pa}$ (V)
2a	+1.22	+1.00	−2.35	−0.88
2c	nd[d]	nd[d]	−1.49	−0.75
2d	+0.71[b]	+0.45[b]	−2.21	−0.85
2e	+1.34	+1.02	−2.21	−0.82
2f	+1.01	+0.62	−2.29	−0.86
2g	+0.73[b]	+0.44[b]	−2.30	−0.90
2h	+1.10	+0.74	−2.24	−0.86
2i	+1.03	+0.64	−2.15	−0.85
2j	+1.14	+0.96	−2.05	−0.82

[a] Versus Fc/Fc$^+$, in 0.1 M nBu$_4$NClO$_4$/CH_2Cl_2, scan rate 100 mV s^{-1}, at 25 °C. [b] Half-wave potentials. [c] The second reduction wave was observed at +2.18 V as a reversible wave. [d] No peak was observed from 0 to +1.5 V.

All of the compounds except **2c** showed an irreversible reduction wave around −2.0 V, and reoxidation waves were observed around −1.0 V. The large difference in the reduction/reoxidation potentials (known as hysteresis) indicates that electron transfer and subsequent ring opening occurred to afford dianion **6**, as shown in Scheme 4. Such hysteresis is a typical feature of dynamic redox systems.[17]

The substituent effect on the thiophene rings was observed in **2c** and **2d**. Due to the electron-withdrawing properties of the formyl group, the reduction potential of **2c** is remarkably positive than those of the other compounds, and a second

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(14) Recently, a trispiro-conjoined cyclopropane derivative having a similar bis(spirodienone) structure has been reported and the bond length of the two spiro-carbons was 1.595(8) Å. Kiyohara, S.; Ishizuka, K.; Wakabayashi, H.; Miyamae, H.; Kanazumi, M.; Kato, T.; Kobayashi, K *Tetrahedron Lett.* **2007**, *48*, 6877.

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(16) Measurements were carried out in CH_2Cl_2 solution at room temperature using a glassy carbon electronode with nBu$_4$NClO$_4$ (0.1 M) as the supporting electrolyte. Scan rate was 100 mV/s.

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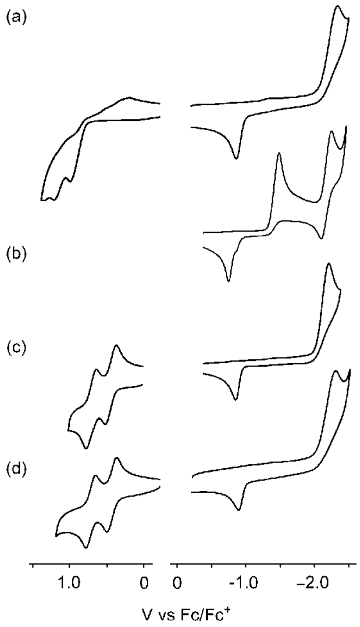
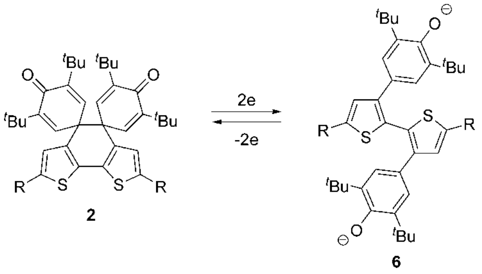


Figure 3. Cyclic voltammograms of (a) **2a**, (b) **2c**, (c) **2d**, and (d) **2g**.

reduction wave was observed (Figure 3b). This potential may be assigned as the formation of tetraanion. Meanwhile, the methylthio derivative **2d** afforded two sets of reversible oxidation waves at relatively low potentials, while the reduction peak potential was similar to that of **2a** (Figure 3c). The high reversibility of the oxidation waves indicates that the cation radical and dication species are stabilized by two methylthio groups.[18] In contrast, the electronic effect of the aryl groups was small; the reduction peaks varied slightly depending on their electron donating/withdrawing properties. Compound **2g** showed reversible oxidation waves similar to those of **2d** (Figure 3d), which corresponds to the redox behavior of 5,5′-bis(4-methoxyphenyl)-2,2′-bithiophene.[19]

Scheme 4. Bond Breaking/Formation Processes of **2** under Redox Conditions



To show formation of ring-opened dianion species, UV−vis spectral changes upon reduction with Na(Hg) in degassed THF were determined for **2a** and **2i** (Figure 4).

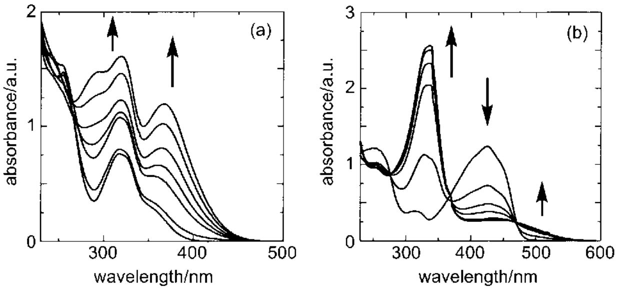


Figure 4. UV−vis spectral changes of (a) **2a** and (b) **2i** upon reduction with Na(Hg) in degassed THF.

The color of the solutions were clearly changed from colorless to yellow for **2a** and pale yellow to orange for **2i**. The spectral change of **2i** was appreciable as a result of its extended π-conjugation, whereas that of **2a** was small. The finally obseved spectra were confirmed as dianions **6a** and **6i** by agreement with the independently measured spectra of **6a** and **6i** generated from **4a** and **4i** by deprotonation with sodium hydride, respectively (Supporting Information).

In conclusion, we have described the synthesis and redox properties of bis(spirodienone)-bridged bithiophene derivatives **2**. Lithiation/fuctionalization of **2a** and transition-metal-catalyzed cross-coupling of **2e** are expected to open the way to the development of new extended π-systems. Conformational change between the s-*cis* and s-*trans* forms of bithiophene under redox conditions will be a key feature of control of the structures and properties of the compounds. Photoresponsive properties of **2a** and **2c−j**, and further investigation of the development of novel switching materials are currently in progress.

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Supporting Information Available: Experimental procedures, spectroscopic data of compounds, and crystallographic data of **2a** in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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