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# Construction and Elucidation of the Properties of Oligothiophene-Based Three-Dimensional Systems

(オリゴチオフェンを基盤とする三次元パイ電子系の構築と物  
性の解明)

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2015

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# Chapter 1

## General Introduction

### 1.1. General purpose of this thesis

Chemistry is one of the discipline of science. It deals with "molecule", which is defined as "*an electrically neutral entity consisting of more than one atom*" in IUPAC Gold book.<sup>[1]</sup> Molecules have discrete shapes by chemical bonds, which represent how the atoms are connected in the individual molecule and provide intuitive images of the molecular shapes. Once the structure of each molecule is revealed, especially in the case of unique one, the properties of the molecule always attract the significant interests of chemists. With the aid of such structural modeling, chemists have always devoted themselves to creation of novel molecular architecture and elucidation of the unique properties based on the structures

It is one of the task of chemistry to design and synthesize new molecules since the breakthrough in chemistry should be brought about, regardless of serendipity or not, creation or discovery of new molecules. It might take sometimes long time to evaluate the utilities or characters of such the new molecules, but I believe that all of them must have potentials to provide new research field. Among them, organic compounds, carbon-based materials, have been produced uncountable number of molecular structures owing to the diversity of bonding pattern of carbon. Especially,  $\pi$ -electron systems,  $sp^2$ - or  $sp$ -hybridized carbon-based compounds, electronic properties deeply correlate to the structure, which define how the  $\pi$ -electrons are interacted in the conjugation systems. Although myriad of compounds have been produced and studied by means of various spectroscopic analysis, there still exist numerous uncreated compounds, which will expand or change the existing philosophy. The structure of such molecules are often hard to realize so that the elucidation of structure-property relationships for such molecule will give important experimental evidence for the nature of  $\pi$ -electron systems. In addition, synthetic strategy employed for the creation of such molecules would be applicable to production of other new compounds. In this regard, development of the field of  $\pi$ -conjugated systems should bring growth and success to both physical chemistry and synthetic chemistry.

My purpose of this study is to create and elucidate the "unusual" structured molecules. I believe that such novel molecular motifs will show new direction of the synthesis and design concepts. One of the greatest goals on this study is to seek and find the seeds in chemistry, which can stimulate other chemists and become a milestone for the research field.

### 1.2. Oligothiophene-based materials

Since discovery of thiophene in 1882 by Victor Meyer, thiophene and its derivatives are one of well-known and widely-used heterocyclic aromatic compounds.<sup>[2]</sup> Oligomers or polymers of thiophene, so-called oligothiophenes or polythiophenes, are one of well-known organic semiconducting materials and successfully applied to in organic field effect transistors and organic photovoltaics and various organic devices. There are mainly two reason of such wide-spread use of oligothiophenes. One is the high stability and electron conductivity in oxidized or doped state, which play an important role for charge transport in conjugated chains. The other is facile and regioselective functionalization by various transition metal catalyzed cross-coupling reactions. The latter

allows us to develop various series of oligothiophenes for controlling their electronic properties. Cheap and printable polymers would have advantages for the application in organic devices,<sup>[3]</sup> however, oligothiophenes have also gained attention in organic semiconducting materials because they afford high-purity and well-defined materials that can be easily modified with a variety of functional groups. In addition, oligothiophenes have been considered to be as model systems of polythiophenes, so that structurally defined oligomers have been synthesized and studied to obtain the insight into the structure-property relationships of those systems.

Thiophene connection at the  $\alpha$ -position produces one-dimensional (1D) thiophene chains. Various 1D oligothiophenes have been employed for electronic devices and shown excellent properties.<sup>[4]</sup> However, simple 1D system limits their topological feature to linear system. For example, such linear materials exhibit anisotropic charge transport and optical properties, which implies that the precise control of thiophene interaction or orientation are required for high performance and hence demands complicated fabrication process. To address this limitation from chemical point of view, an expansion of 1D linear systems to higher dimensional systems have been applied to construct more sophisticated molecular structures for exploration of unique properties.<sup>[5]</sup>

One structural motif of such structurally characteristic oligothiophenes is macrocyclic compounds. Thiophene-containing macrocycles can be considered as sulfur bridged annulene derivatives, so that the electronic properties should be interesting research object in addition to host-guest interaction, aggregation and self-assembly properties arising from the cyclic structures. Early reported thiophene macrocycles are contained  $\beta$ -linkage (**1.1**, **1.2**)<sup>[6]</sup> and the first report of the macrocycles connecting only through  $\alpha$ -position is reported Bäerle and co-workers (**1.3**).<sup>[7]</sup> They used a sequence of coupling reactions of bisethynylated ter- or quaterthiophenes followed by reaction with  $\text{Na}_2\text{S}$ . The compounds exhibited unusual absorption behavior resulted from their characteristic cyclic structure,<sup>[8]</sup> which finally revealed by X-ray diffraction analysis.<sup>[9]</sup> After this synthesis, Iyoda and co-workers reported synthesis, aggregation properties and thiophene-ethynylene or vinylene linked macrocycles (**1.4**), which exhibited unique aggregation behavior and large two photon absorption depended on their ring size.<sup>[10]</sup>

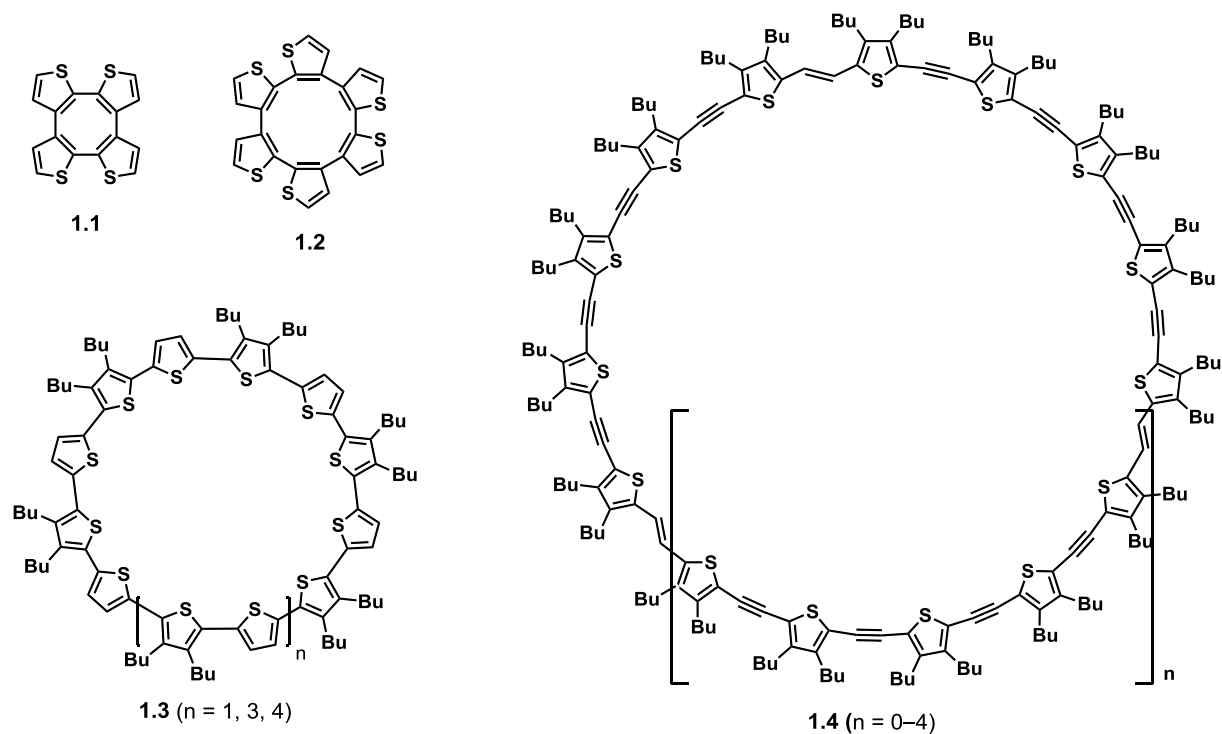


Chart 1.1.

An alternative idea for structural expansion of oligothiophene dimension is bridging two oligothiophene chains by appropriate linker, which would be model system of  $\pi$ -dimer in doped polythiophenes. For this end, Otsubo and Aso prepared double-decker type oligothiophene **1.5** by Glaser-type homocoupling of bis(ethynylated)thiophene chains followed by the reaction with  $\text{Na}_2\text{S}$ .<sup>[11]</sup> UV-vis spectroscopic and cyclic voltammetry measurements suggested the radical cation-radical cation (polaron-polaron) interaction, which depended on the length of the bridging alkyl chains. Tour and co-workers reported terthiophene dimer bridged by bicyclo[4.4.1]undecane (**1.6**), which exhibited the radical cation stabilization at the one electron oxidation state.<sup>[11]</sup> Another hinge was employed in Tour's research group by replacing with calix[4]arene (**1.7**)<sup>[12]</sup>, or xanthene (**1.8**)<sup>[13]</sup> both of which showed facile  $\pi$ -dimer formation at the oxidized state. These results demonstrate that oligothiophene interaction can be controlled by utilizing appropriate linker, which will give a possibility to create more oligothiophene congested system toward higher oligothiophene dimensionality, or 3D-expanded oligothiophenes.

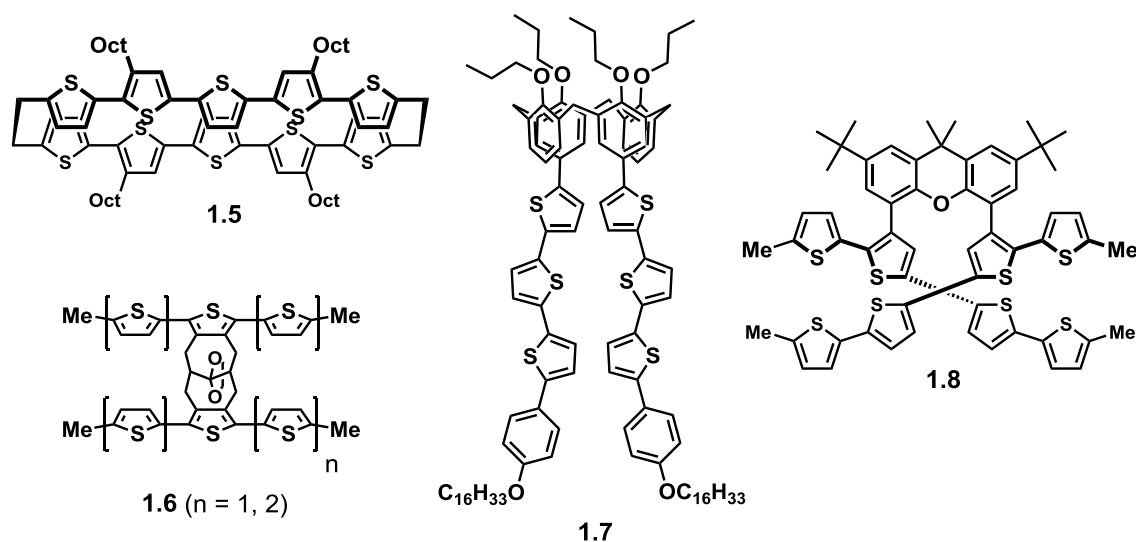


Chart 1.2

### 1.3. Thiophene-based three-dimensional systems

Creation of higher dimensional conjugated compounds or 3D  $\pi$ -systems have been also challenged. Such systems are aimed at realization of isotropic electronic properties, which will provide good chemical solution of anisotropic effect as is often observed in lower dimensional systems. It has been adopted a strategy of utilizing various branched 3D molecular architectures, such as dendrimer<sup>[14]</sup>, star-shaped,<sup>[15]</sup> and tetrahedral<sup>[16]</sup> oligothiophenes have been synthesized and characterized (e.g. **1.9–1.11** in Chart 1.3). In this respect, both "intermolecular" and intramolecular" interactions are important to realize isoelectronic properties or 3D electronic transport properties. The former is mainly depends on how they packed or aggregated in solid state and the latter affected by how the branched oligothiophene chromophore are placed in individual molecule. Based on these design strategy, a large number of 3D oligothiophenes are synthesized and measured their device performances. However, most of these compounds have focused on improvement their electronic properties and the research on the 3D oligothiophenes in a single molecular level are still rare. To disclose the electronic properties of these 3D



molecules will give valuable information especially on the intramolecular interaction of such the systems, which will feed back to molecular design concept for 3D oligothiophenes. Therefore, creation and elucidation of the properties of novel 3D oligothiophene models will contribute to the development of this field of chemistry and should be examined with one possessing unprecedented structural features.

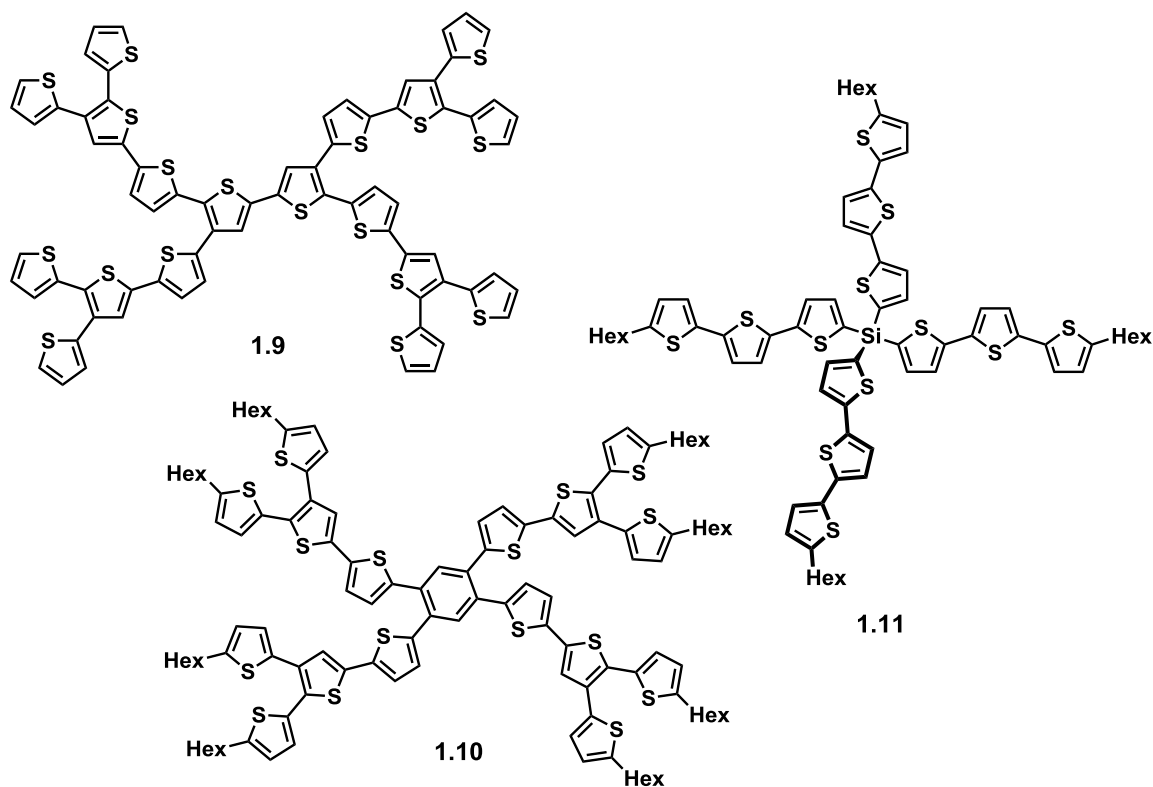
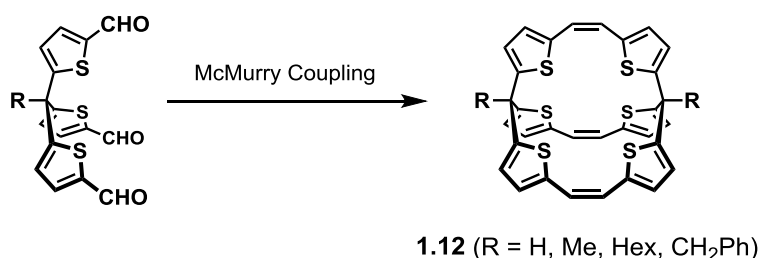


Chart 1.3.

#### 1.4 Three-dimensional $\pi$ -conjugated cage-shaped compounds

Tris(2-thienyl)methane<sup>[17]</sup> is one of the three-dimensional structural motifs, but has been little developed<sup>[18]</sup> compared to thiophene-branched tris(aryl)amines,<sup>[19]</sup> tetrakis(2-thienyl)methanes<sup>[20]</sup> or silanes.<sup>[21]</sup> This is probably because attachment of larger number of thiophene units will be advantageous for construction of 3D  $\pi$ -systems. However, a facile preparation of parent tris(2-thienyl)methane and possibility of thereafter three-fold  $\pi$ -expansion will provide new direction to develop novel 3D molecular systems. In addition, construction of molecular skeleton mainly by robust C–C bonds will lead to product stability as well as tailoring functionalized materials by various synthetic methodology. After pioneering work for functionalization of tris(2-thienyl)methane by Nakayama and co-workers, Kurata and Oda reported tris(2-thienyl)methane-based three-dimensional cage-shaped compounds **1.12** by three-fold McMurry reaction (Scheme 1.1).<sup>[22]</sup> The authors have expanded their strategy various tris(2-thienyl)methanes and produced a series of thiophene-based cage-shaped compounds (**1.13–1.15**, Chart 1.5). The notable feature of these compounds are three-fold symmetric structure in solution as well as in solid state. The chemistry of tris(2-thienyl)methane-based cages have been expanded in the same research group and they successfully prepared cage-shaped cation/anion species<sup>[23]</sup>, the largest bicycloalkane, bicyclo[10.10.10]dororiacontane (**1.14**),<sup>[24]</sup> complexes with hexane or silver metals,<sup>[25]</sup> and fluorescent bithiophe-

ethynylene-bridged cage (**1.15**). These results demonstrate the utilities of employment of tris(2-thienyl)methane as a key building block for 3D  $\pi$ -systems and motivate exploration of more functionalized cage compounds, or more  $\pi$ -extended cage compound. From this viewpoint, all-oligothiophene-bridged cage compound, so-called "cage-shaped oligothiophenes (**1.16**)" was newly designed. Such the cage is expected to possess sufficient intramolecular interactions because the fixation of three  $\pi$ -bridges attached to a single atom will lead to efficient orbital overlap. Therefore, I assumed that the cage **1.16** will represent one of the novel class of 3D molecular platforms. In addition to the electronic properties, the bridged oligothiophenes would be interesting from the viewpoint of structural organic chemistry because they should adopt curved conformation and be placed on closed position. The electronic properties of such fixed and neighbored oligothiophenes should make a deep effect on the optical and/or electronic behavior of such "cage-shaped oligothiophenes". Furthermore the sulfur-rich inner cavity is expected to exhibit unprecedented accommodation behavior, which will contribute to host-guest or supramolecular chemistry. In order to clarify listed above, I decided to challenge the synthesis and characterization of the oligothiophene cage **1.16**.



Scheme 1.1

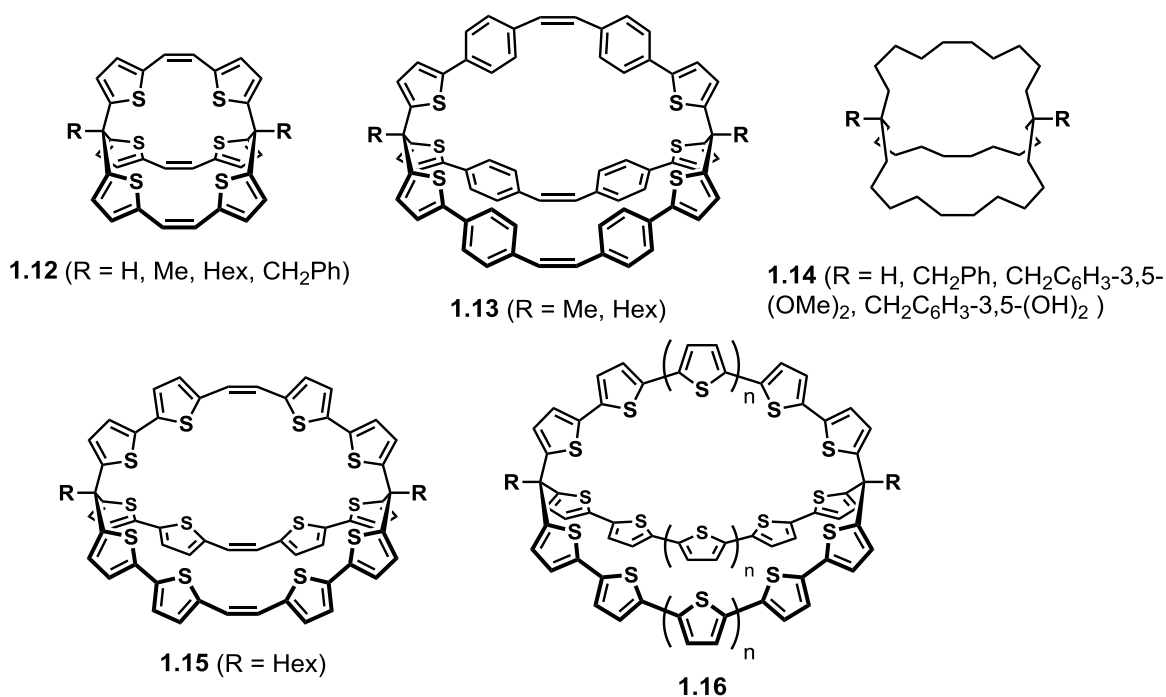
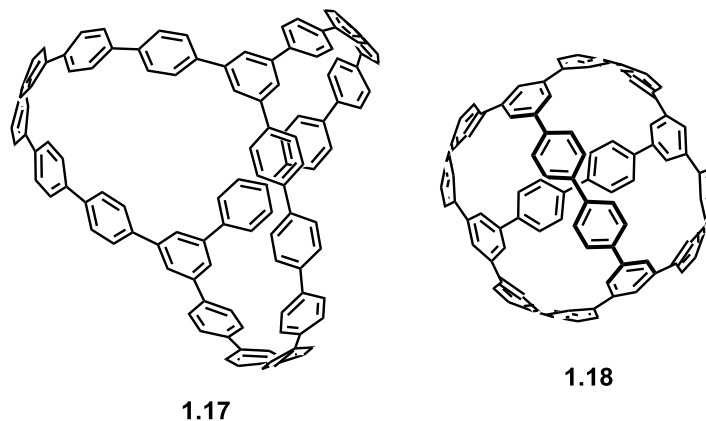


Chart 1.5.

Although there are numerous reports of the synthesis of  $\pi$ -based cage-shaped compounds, it was quite recently that the syntheses of cage-shaped compound composed of fully conjugated aromatic rings were achieved (**1.17** and **1.18**, Chart 1.6). These compounds are expected to exhibit unique optical or complexation behavior owing to the curved  $\pi$ -systems. However, as long as I know, there is no report on the all-thiophene-based cage-shaped compounds, so that the synthesis and properties of such oligothiophene-based cage-shaped compounds could give significant impact on the not only oligothiophene chemistry but also such little developed chemistry of  $\pi$ -conjugated cage compounds.

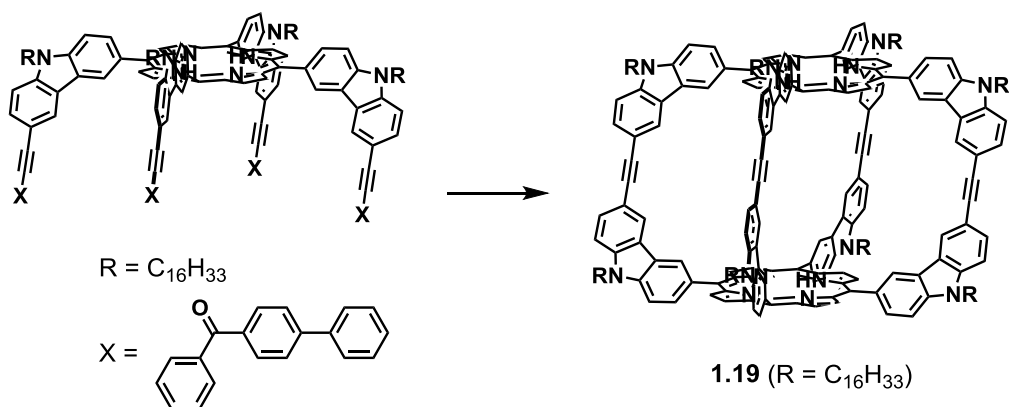


**Chart 1.6.**

### 1.5 Synthesis of shape-persistent $\pi$ -conjugated cage compounds

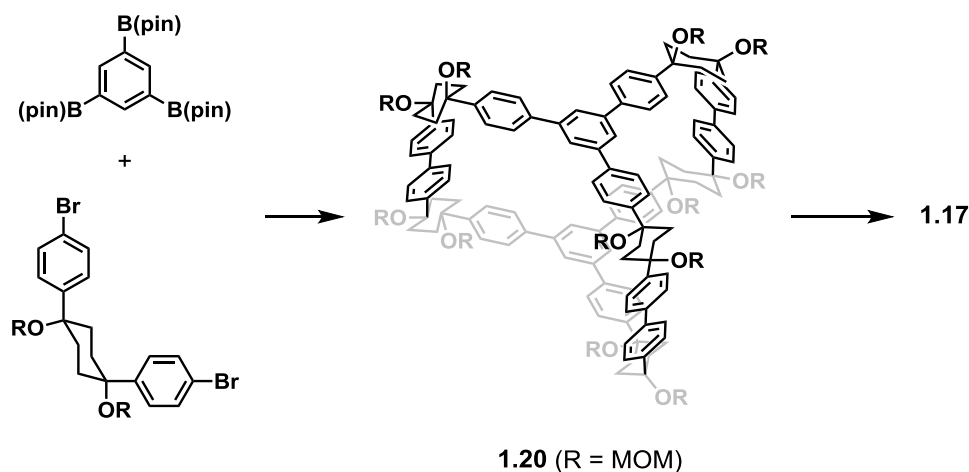
It has been always considered as a challenges to create shape-persistent 3D molecular architecture. Classical but reliable approach would be stepwise construction toward 3D molecular topologies. The reactions are kinetically controlled, so that the cage structure formation reactions have been conducted under high dilution condition.<sup>[26]</sup> This methodology have produced sophisticated cage compounds usually poor yield. Involvement of templates<sup>[27]</sup> or metal-organic coordination<sup>[28]</sup> have employed to overcome such a low yielding problem. However, necessity of coordination site in the components or instability of metal-ligand to acid/base condition do not make these methods general solutions yet. Another approach is using dynamic covalent bonds for cage construction.<sup>[29]</sup> Thus, transesterification of boronic ester or imine condensation have been utilized to construct molecular composite in high yield.<sup>[30]</sup> Although the resulting 3D molecular architectures are constructed by covalent bond, these bonds are susceptible to water, or decomposed by hydrolysis. Thus, development of 3D systems based on robust C–C bond based materials will offer an opportunity to create stable molecular framework.

Metathesis reaction have undoubtedly brought breakthrough in synthetic organic chemistry.<sup>[31]</sup> The reversible bond formation mechanism enable to prepare thermodynamically controlled products. This efficient and versatile methodolgy could have been applied to the synthesis of highly complicated molecules including cage compounds, but the resulting bonds are only composed of carbons. This means that the involvement of metathesis reaction will leads to the creation of robust cage compounds in high product yield. There are some examples of cage construction using olefin<sup>[32]</sup> or alkyne metathesis reactions (Scheme 1.3).<sup>[33]</sup>

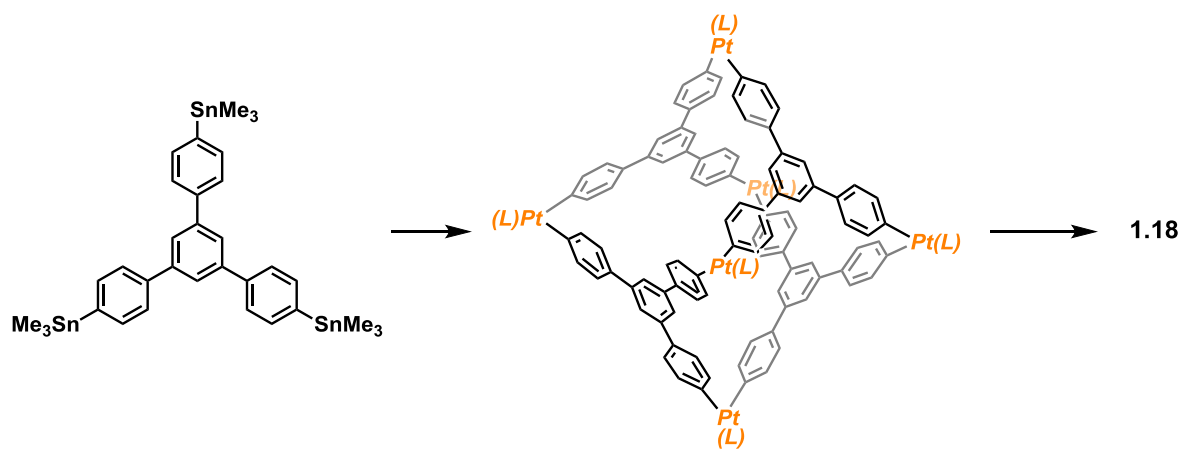


**Scheme 1.3.**

An additional important viewpoint for construction of  $\pi$ -conjugated carbon-based cages is employment of flexible or less-strained precursor than desired rigid cage architecture. Especially, due to the rigidity and linearity of oligoarenes, the synthesis of cage compounds composed of fully aromatic rings were synthesized quite recently. Thus, Itami's<sup>[34]</sup> and Ymago's research group<sup>[35]</sup> independently reported cage compounds composed of all-benzene rings **1.17** and **1.18**, by applying their cyclo-*p*-phenylene synthesis 1,3,5-trisubstituted benzenes for 3D expansion. However, the synthesis of strained oligothiophene  $\pi$ -systems is still rare so that exploit of efficient synthetic strategy toward oligothiophene cage will give can offer an opportunity to was achieved by Bäuerle and co-workees by involving a Pt(II)-thiophene complex as a precursor for cyclic oligothiophenes (**1.3**).<sup>[9]</sup> However, the use of an equimolar amount of expensive platinum complex is required and development of alternative way for construction of strained oligothiophenes should be desired and required.



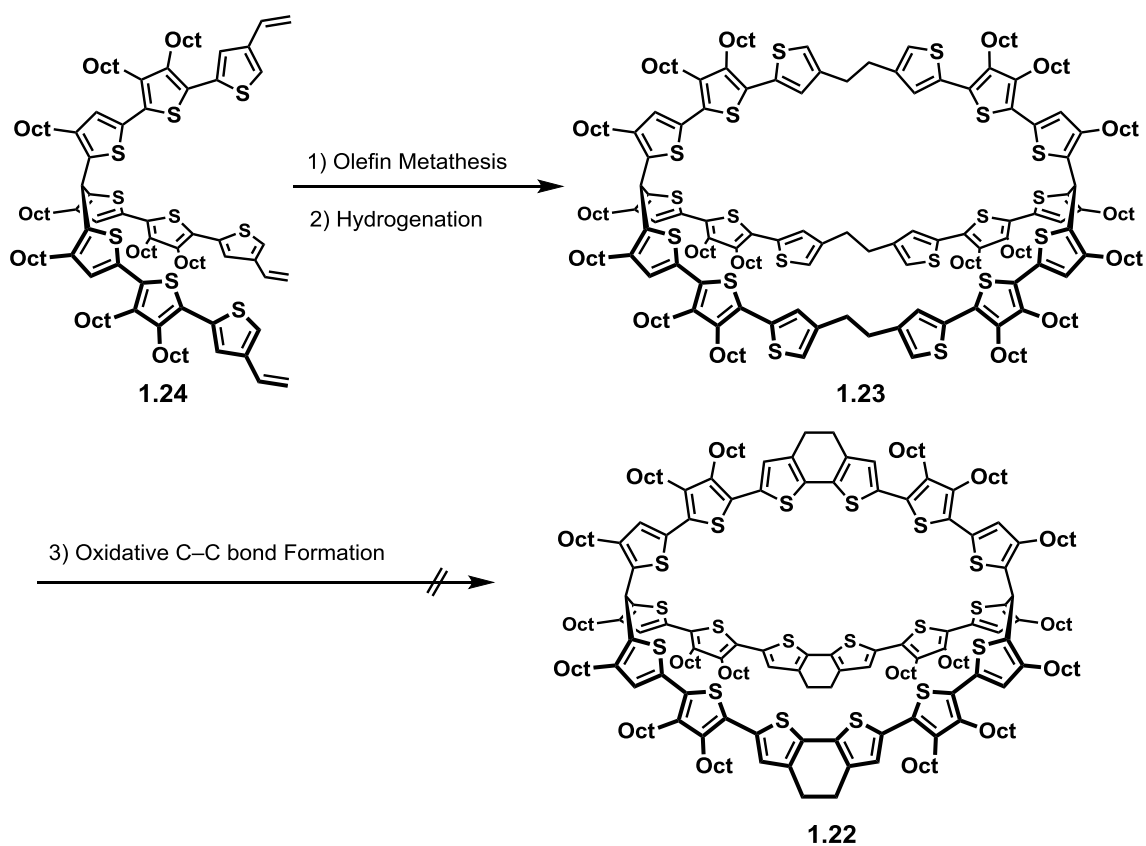
**Scheme 1.4.**



1.21 (L = cod or dppf)

Scheme 1.5.

In these in mind, I previously attempted preparation of oligothiophene-based cage (**1.22**) and succeeded in isolating cage-shaped molecule that consists of thiophene chains tethered by C2 bridges at the  $\beta$ -position (**1.23**),<sup>[36]</sup> (Scheme 1.6). Thus, starting tris(2-thienyl)methane **1.24**, in which vinyl functional groups are present on the  $\beta$ -position of the terminal, Grubbs' olefin metathesis reaction gave ethylene linked dimeric cage, which could be converted into ethano-linked cage by hydrogenation. The efficient preparation of **1.23** should be due to the flexibility of the alkylene linker, which lessens the molecular strain in cage form. This demonstrates the potential utility of this synthetic methodology for cage-shaped oligothiophene construction, or more generally, strained oligothiophene preparation. However, it has not been successful to formation C–C bonds between the neighboring  $\alpha$ -positions yet. Therefore, it should be required to find how to accomplish this synthetic sequence, which would provide efficient synthetic tool in oligothiophene chemistry



**Scheme 1.6.**

## 1.6. Contents of this thesis

This thesis contains five chapters. Chapter 2 describes various synthetic attempts toward sexithiophene-bridged cage compound. First procedure was involving Sholl-type oxidative coupling reaction, which could have successfully given corresponding linear sexithiophene. However, the after structural modification and reaction condition refinement, that is, replacement of hydrogen at the bridgehead carbons with methyl group and employment of reaction sequence of Cu-mediated coupling reaction of lithiated thiophenes are found to be effective to afford desired cage **1.25** (Chart 1.7). The spectral characterization as well as X-ray structure is also presented. In addition, structural analogue of the cage, or cyclic and linear sexithiophenes **1.26** and **1.27** were synthesized by applying the same synthetic protocol.

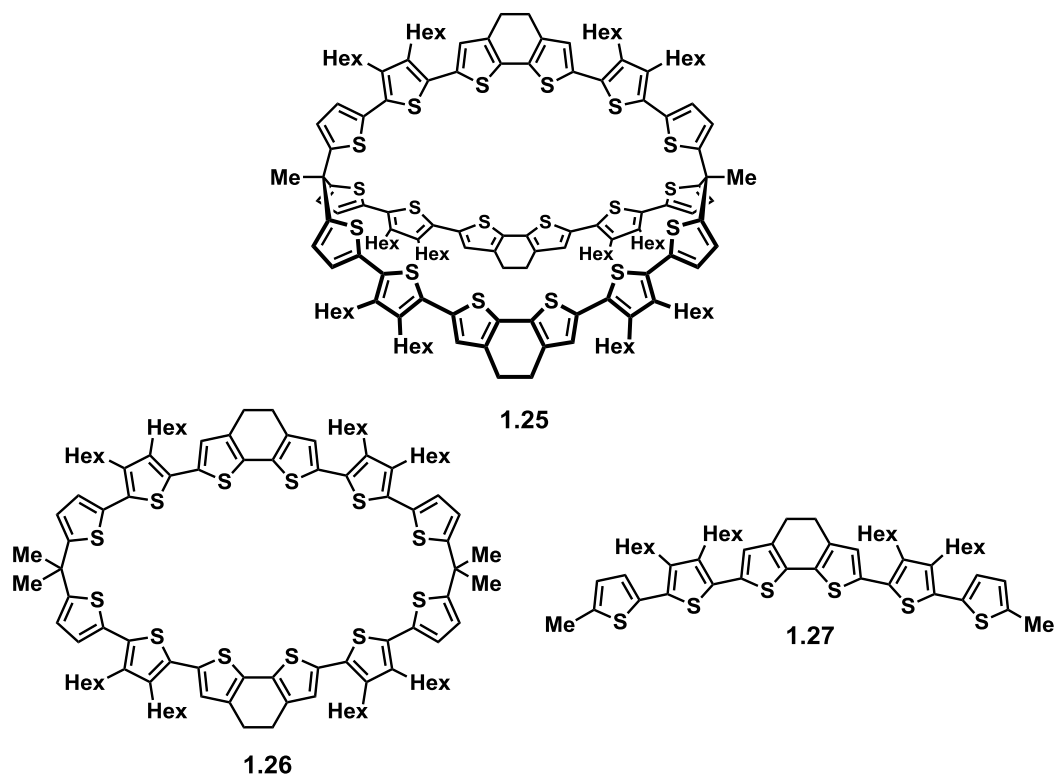


Chart 1.7.

In Chapter 3, I describe the scope and limitations of the cage synthesis methodology by applying to the synthesis of quarterthiophene and octithiophene cages **1.28** and **1.29**. Although the larger cage **1.29** failed to be identified, the smaller cage **1.28** was fully prepared and characterized by spectroscopic and crystallographic analysis.

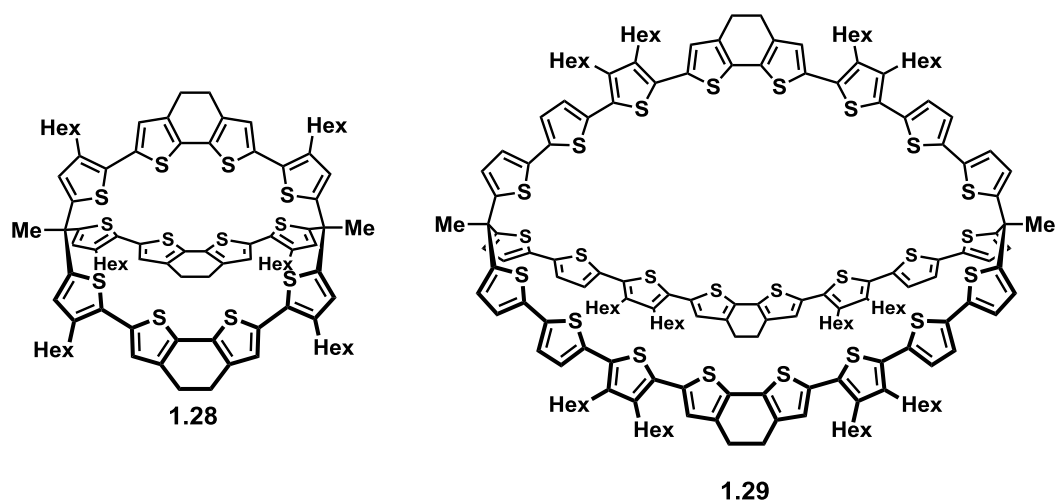


Chart 1.8.

Chapter 4 describes the optical properties of the cages **1.25** and **1.28** with comparing that of corresponding cyclic and linear analogues. The cyclic voltammetry measurements and electronic absorption spectrum suggested the significant electronic interchain interaction of cage compounds, which is more pronounced in **1.28** than **1.25**.

Chapter 5 presents the attempt of synthesis of tetrahedral-shaped oligothiophene **1.30**, which can be considered as one of the fascinating 3D oligothiophenes (Chart 1.9). I employed modified cage construction strategy that dimerization of the dimer of tris(2-thienyl)methane units for tetramerization. Although the newly designed precursor could be prepared, construction of tetrahedral molecular architecture has been unsuccessful and remains to be challenged.

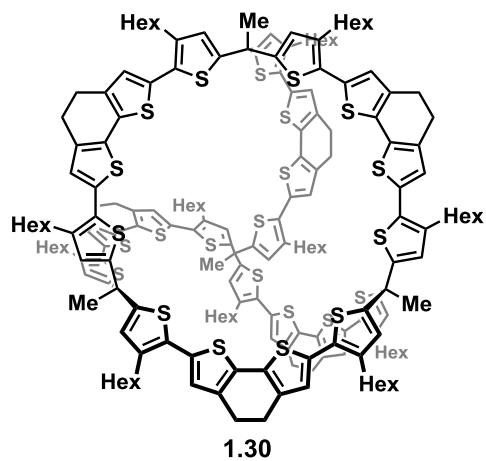


Chart 1.9.



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## Chapter 2

### Synthesis of Sexithiophene-Bridged Cage-Shaped Compound

#### 2.1. Introduction

As described in my master's thesis,<sup>[1]</sup> the synthesis of the precursor of cage-shaped compounds, or  $\beta$ -ethano-bridged cage compound, has been succeeded in moderate reaction yield (28% isolated yield). However, the thiophene–thiophene bond formation reaction has not been successful by Sholl type reaction.<sup>[2]</sup> This is the one of the example of synthetic difficulty of cage construction, or three-dimensional molecular architectures. There have been some demands of development of efficient and widely applicable synthetic methodologies. In this chapter, I describe the various synthetic attempts to form oligothiophene-bridged cage-shaped molecules from  $\beta$ -alkylene-tethered thiophenes. The resulting cage compound could be fully characterized by spectroscopic and crystallographic analysis. In addition, synthesis of cyclic and linear analogues will be also presented by utilizing the newly developed cage synthetic methodology.

#### 2.2. Results and discussions

##### 2.2.1. Structural modification of target sexithiophene bridged precursor

Before I tested various reaction condition with the already prepared precursor **2.1**, two structural modification were carried out to design key precursor **2.2** and thus target cage can be drawn as **2.3** shown in Chart 2.1. One is introduction of methyl group at the bridgehead carbon and the other is removal of three of the eighteen alkyl chains with shortening from C8 (octyl) to C6 (hexyl). The reason of the former is based on the assumption that side-reaction or decomposition of the cage could be attributed to the presence of the acidic protons on the bridgehead carbons. The synthetic method of selective functionalization on the central carbon of tri-2-thienylmethane had already developed in this laboratory<sup>[3]</sup>. The latter is due to the expectation of increased crystallinity of products, which will give critical information of molecular structure and help to understand structure-property relationships.

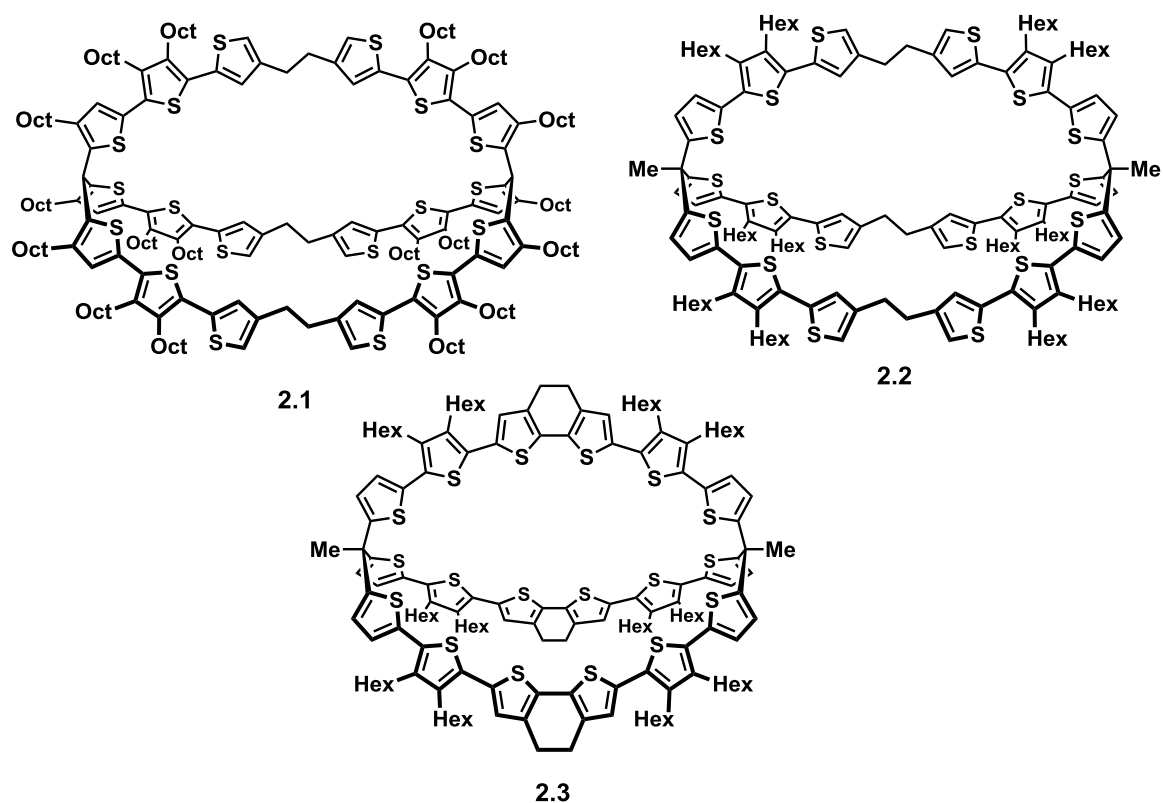
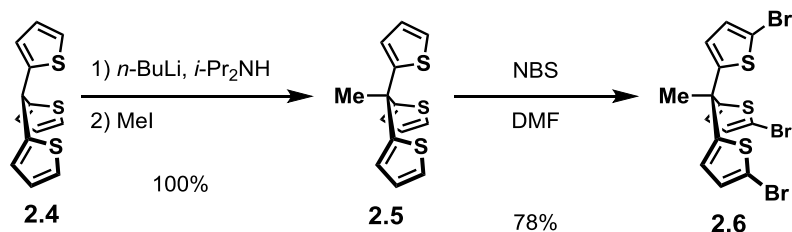


Chart 2.1

### 2.2.2. Synthesis of sexithiophene-bridged cage compound

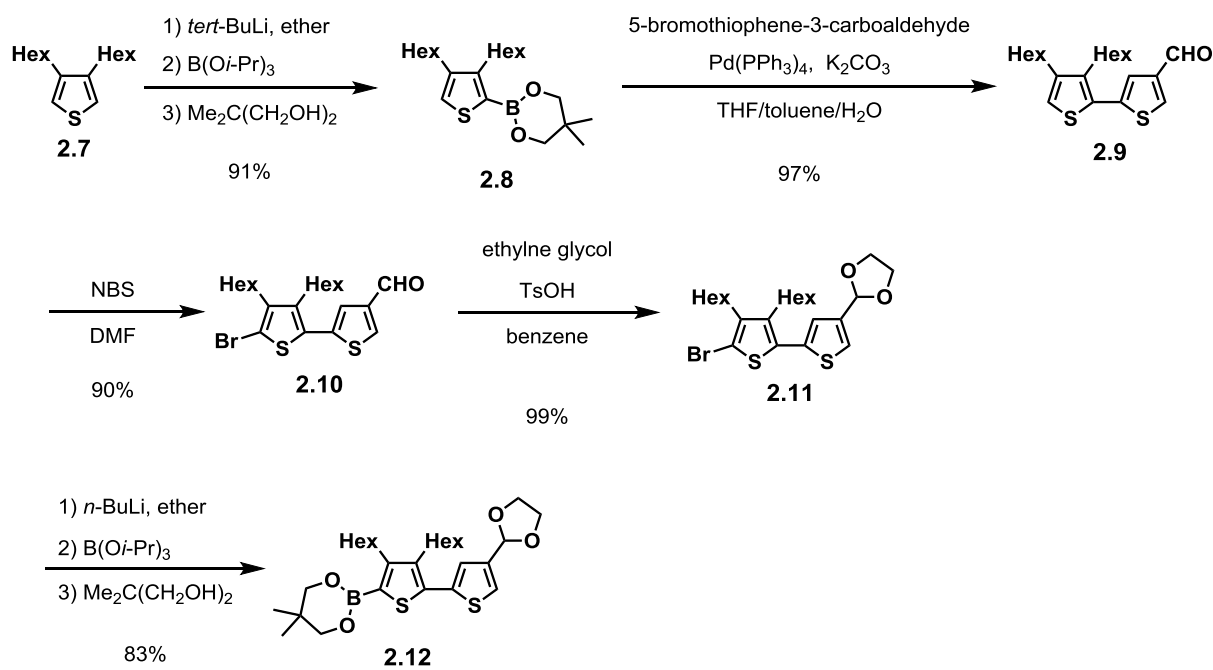
Although the key functional group and main scaffold were not changed, protecting the bridgehead carbons and changing the substitution pattern of alkyl chains should be conducted in the early synthesis stage. Thus, I started the synthesis from tris(2-thienyl)ethane **2.4** with methylation and bromination (Scheme 2.1). Lithiation of **2.4** with *n*-butyllithium and diisopropylamine at room temperature gave dark red solution, which was quenched by methyl iodide to form 1,1,1-tris(2-thienyl)ethane **2.5** in excellent yield. The reason of such the high regioselectivity in this reaction could be explained by the formation of thermodynamically stable of tris(2-thienyl)methyl anion, where negative charge is delocalized over the three thiophene rings. Following bromination with NBS also proceeded smoothly to give **2.6** in good yield.



Scheme 2.1.

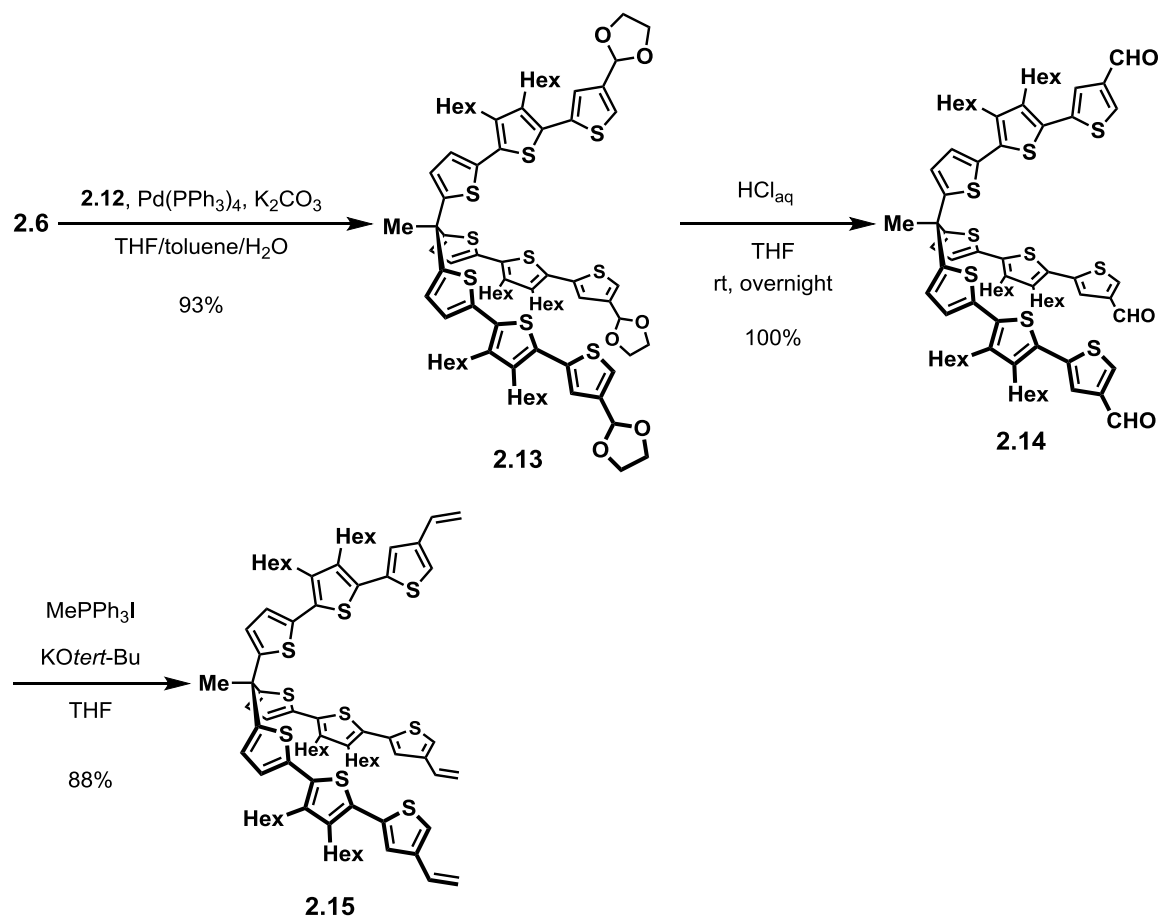
The coupling partner was then synthesized from 3,4-dihexylthiophenes **2.7**, which was lithiated with *tert*-

butyllithium, then reacted with triisopropyl borate followed by transesterification with neopentyl glycol to produce boronic ester **2.8** in one pot<sup>[4]</sup>. Since the acidity of **2.7** was relatively low, small excess of alkyl lithium was required for complete lithiation. Subsequent Suzuki-Miyaura coupling, bromination, protection of aldehyde and borylation proceeded in high yield under standard condition to afford **2.8–2.12** (Scheme 2.2).



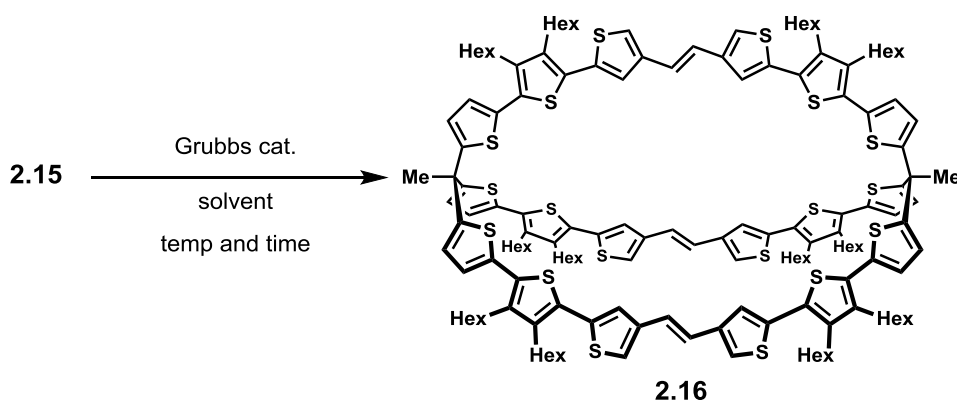
**Scheme 2.2.**

Following Suzuki-Miyaura cross-coupling reaction of tribromide **2.6** with boronic ester **2.12** gave tiracetal **2.13**. Hydrolysis and Wittig olefination with MePPh<sub>3</sub>I and KO*tert*-Bu also proceeded to give trivinyl derivative **2.15** (Scheme 2.3).



Scheme 2.3.

For the dimerization of **2.15** with Grubbs' olefin metathesis, I tested several reaction conditions to improve the product yield and availability since, in the previous example of metathesis dimerization, the reaction was not fully optimized and was reported to be needed carrying out the reaction twice for the consumption of the starting  $\beta$ -vnylated tris(terthienyl)methanes. Thus, to clarify and optimize the reaction condition, I first carried out the reaction by mixing 10 mM of **2.15** and 10 mol% Grubbs second generation catalyst (Grubbs II) in refluxed  $\text{CH}_2\text{Cl}_2$  solution (Scheme 2.4, Table 2.1). According to the TLC analysis, the reaction progressively consumed **2.15** and produced complex mixture of desired cage **2.16** with a mixture of higher oligomer and polymer. GPC separation of the resulting mixture gave pure **2.16** in 14% isolated yield (entry 1). Dilute the solution of **2.15** led to increase of the reaction yield (entry 2). However, further dilution resulted in almost the same product yield (entry 3). Solvent replacement from  $\text{CH}_2\text{Cl}_2$  to toluene did not change the product yield (entry 4). Next, I changed the catalyst from Grubbs II to Hoveyda-Grubbs II in various solvents (entries 5–8). Although  $\text{CH}_2\text{Cl}_2$  needed to elongate the reaction time for consumption of **2.15** (entry 5), benzene (entry 6) and toluene (entry 8) were enough to furnish the reaction for 24 h reflux. Unfortunately 1,2-dimethoxyethane (DME) did not give metathesized product but resulted in recovery of **2.15** (entry 7). In all cases with Hoveyda-Grubbs II, the product yields were almost the same except for the condition in entry 7. Although the best results were obtained in entries 2 and 7, I decided to employ the condition in entry 2 as an optimum condition for the following metathesis cage construction.



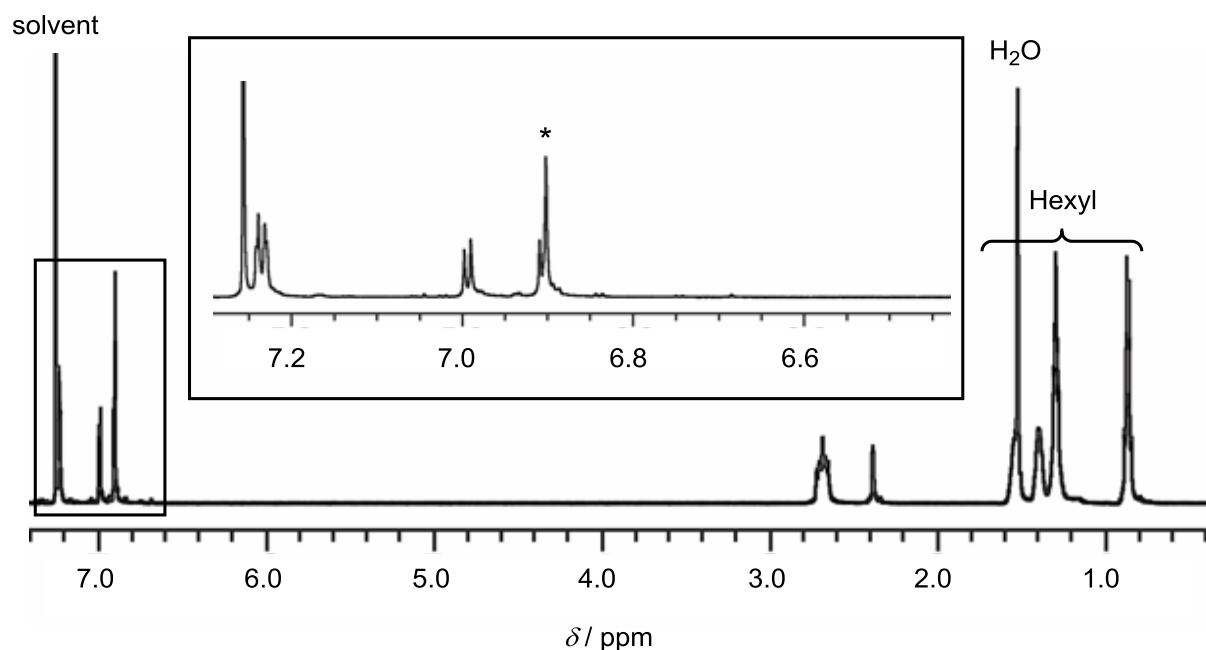
**Scheme 2.4.**

**Table 2.1.** Reaction conditions of metathesis reaction in Scheme 2.4.

entry	Grubbs cat.	solvent	concentration / mM	temp and time	yield / %
1	Grubbs II	CH <sub>2</sub> Cl <sub>2</sub>	1.0	40 °C, 24 h	14
2	Grubbs II	CH <sub>2</sub> Cl <sub>2</sub>	0.50	40 °C, 24 h	27
3	Grubbs II	CH <sub>2</sub> Cl <sub>2</sub>	0.25	40 °C, 24 h	26
4	Grubbs II	toluene	0.50	110 °C, 24 h	22
5	Hoveyda-Grubbs II	CH <sub>2</sub> Cl <sub>2</sub>	0.50	40 °C, 72 h	22
6	Hoveyda-Grubbs II	benzene	0.50	80 °C, 24 h	20
7	Hoveyda-Grubbs II	DME	0.50	80 °C, 24 h	recovery
8	Hoveyda-Grubbs II	toluene	0.50	110 °C, 24 h	27

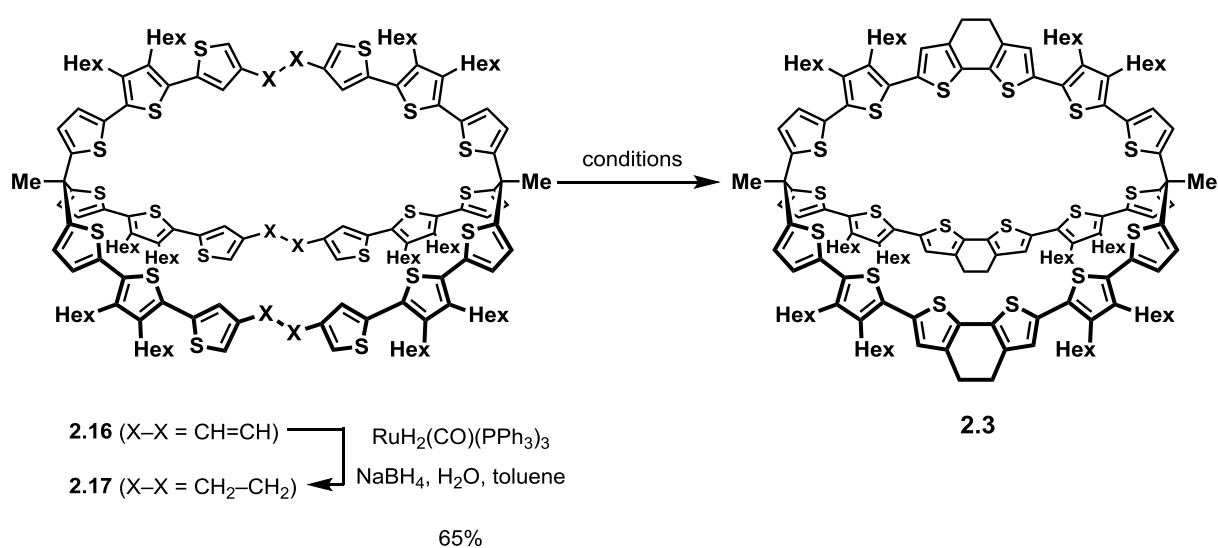
Since there are two configuration of carbon-carbon double bond, **2.16** should have two possibility to adopt (*E*) or (*Z*) conformation for the three double bonds. Interestingly, the <sup>1</sup>H-NMR spectrum of all the products give the same and quite simple ones, which suggested the three double bonds in **2.16** had the same configurations (Figure 2.1). Although a single crystal of **2.16** has not been obtained yet, the conformation was the signal of vinylic protons are observed at  $\delta$  6.90 ppm, of which value is similar to that of (*E*)-1,2-bis(2-thienyl)ethene (7.06 ppm)<sup>[5]</sup> rather than those of (*Z*)-1,2-bis(2-thienyl)ethene (6.59 ppm)<sup>[6]</sup> or (*Z*)-etheno-bridged tris(2-thienyl)methane cages (6.45–6.54 ppm).<sup>[7]</sup> Therefore the configurations of the three double bonds of compound **2.16** are indicated to be all (*E*)-form, probably because the thermodynamically favorable conformation was produced as a result of reversible bond formation/dissociation.





**Figure 2.1.**  $^1\text{H}$  NMR spectrum of **2.16** (500 MHz, 30 °C,  $\text{CDCl}_3$ ). (Inset) The expansion of the aromatic region including the signal assignable to the vinylene linkage of **2.16** ( $\delta$  6.90 ppm, marked with \*) overlapping with one of the  $\beta$ -protons of thiophenes attached to the bridge head carbon atom.

After hydrogenation with ruthenium catalyzed reduction method,<sup>[8]</sup> the  $\beta$ -ethano-linked compound **2.17** was subjected into the oxidative coupling condition (Scheme 2.5, Table 2.2). The resulting product was highly fluorescent, which strongly suggested the formation of sexithiophene chain from terthiophene fragments (entry 1). Disappointingly, however, the product could not be identified by neither  $^1\text{H}$  NMR spectroscopy nor MALDI-TOF mass spectrometry. Other oxidation condition (DDQ/TFA) also gave fluorescent, but unidentified product (entry 2).



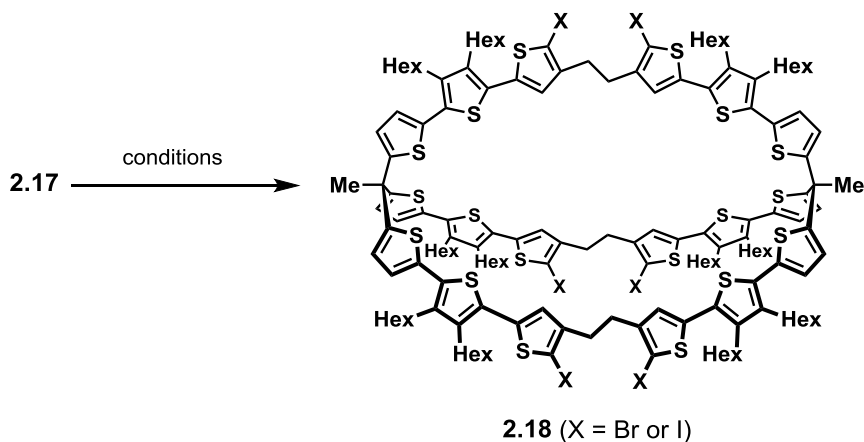
**Scheme 2.5.**

**Table 2.2** Reaction conditions of Scheme 2.5.

entry	conditions	results
1	Fe(ClO <sub>4</sub> ) <sub>3</sub> ·nH <sub>2</sub> O, CH <sub>2</sub> Cl <sub>2</sub> /MeCN, rt, 30 min	complex mixture
2	3.6 eq. DDQ, TFA, CH <sub>2</sub> Cl <sub>2</sub> , 0 °C, 5 min	complex mixture

This fact indicates that oxidative coupling reaction would cause not only desired coupling reaction, but also decomposition of the cage skeleton. Since the resulting sexithiophene has low oxidation potential than terthiophene precursor, such decomposition would occur under the condition of partially coupled sexithiophene(s) with strong oxidant. To circumvent such synthetic condition, I decided to employ hexahalogenated compound **2.18** instead of **2.17**. This compound has six halogenated carbons, which could involve reductive coupling or transition-metal mediated coupling reaction for C–C bond formation. Therefore, I expected that **2.18** could be transformable to **2.3** in the condition of avoiding formation of radical cation intermediates.

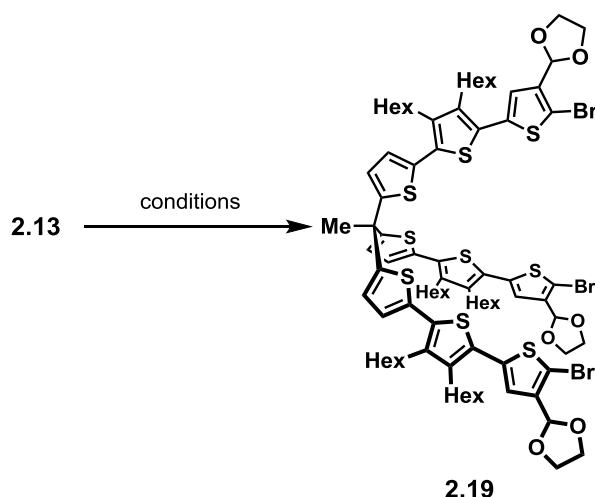
It is a frequently employed strategy that halogenation-coupling reaction sequence for synthesis of oligothiophenes, so that I next tested halogenation reactions (Scheme 2.6, Table 2.3). Although the addition of slight excess amount of NBS could successfully introduce bromine groups, the resulting product was found to possess more than six bromine atoms according to MALDI-TOF MS analysis. To suppress such the over-bromination, I conducted lithiation-halogenation procedure. However, both of bromodichloroethane (entry 2) and iodine (entry 3) could not achieve full conversion of the  $\alpha$ -positions in **2.17**. These facts highlight the synthetic difficulty of selective functionalization on six  $\alpha$ -site in **2.17**.

**Scheme 2.6.**

**Table 2.3.** Reaction conditions of bromination in Scheme 2.6.

entry	conditions	results
1	8.0 eq. NBS, CHCl <sub>3</sub> , 0 °C, 30 min	over-brominated compounds
2	1) 15 eq. <i>n</i> -BuLi, THF, -78 °C then 0 °C, 30 min 2) 30 eq. (BrCCl <sub>2</sub> ) <sub>2</sub> , 0 °C to rt, overnight	recovery of <b>2.17</b> (58%)
3	1) 15 eq. <i>n</i> -BuLi, THF, -78 °C then 0 °C, 30 min 2) 30 eq. I <sub>2</sub> , 0 °C then rt, 2 h	partially iodinated compounds (X = I or H)

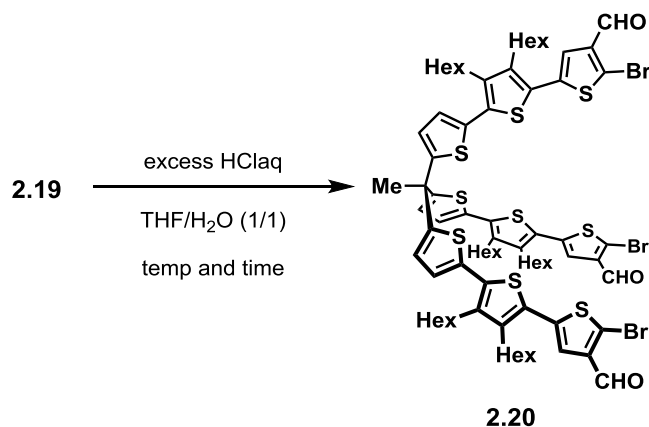
Since the direct halogenation strategy failed, I then attempted to prepare **2.18** by metathesis reaction of trihalogenated precursor. For this purpose, NBS was added in a solution of **2.13** at reflux temperature for synthesis of tribromide **2.19**. However, formation of several brominated species are suggested by TLC analysis. Further addition of NBS was not effective and the product was exceedingly brominated tris(terthienyl)methanes, suggested by MALDI-TOF MS (entry 1). On the other hand, reaction of lithiated **2.13** with dibromotetrachloroethane ((BrCCl<sub>2</sub>)<sub>2</sub>) afforded the desired **2.19** in excellent yield (entry 2). The presence of acetal group might cause the reactivity differences between **2.13** and **2.17** by stabilizing the lithiated intermediate.

**Scheme 2.7.****Table 2.4.** Reaction conditions of bromination in Scheme 2.7..

entry	conditions	results
1	3.6 eq. NBS, CHCl <sub>3</sub> , reflux, 1 h, then 3.6 eq. NBS, reflux, 1 h	Complex Mixture (Multi-brominated Compounds?)
2	1) 3.6 eq. <i>n</i> -BuLi, THF, -78 °C, then 0 °C, 30 min 2) 6.0 eq. (BrCCl <sub>2</sub> ) <sub>2</sub> , 0 °C, 1 h then rt, 30 min	<b>2.19</b> (99% yield)

Surprisingly, hydrolysis of **2.19** did not proceed and resulted in recovery under the same condition as that employed for **2.13** (Scheme 2.8, Table 2.5, entry 1) and need quite long reaction time to furnish the reaction even though the yield of **2.20** was low (entry 2). Elevating temperature resulted in production of unidentifiable compounds that could not be separated from **2.20** (entry 3). Other deprotection method of using I<sub>2</sub> in acetone<sup>[9]</sup>

(entry 5) or TFA<sup>[10]</sup> (entry 6) failed to isolate **2.20** in good yield.

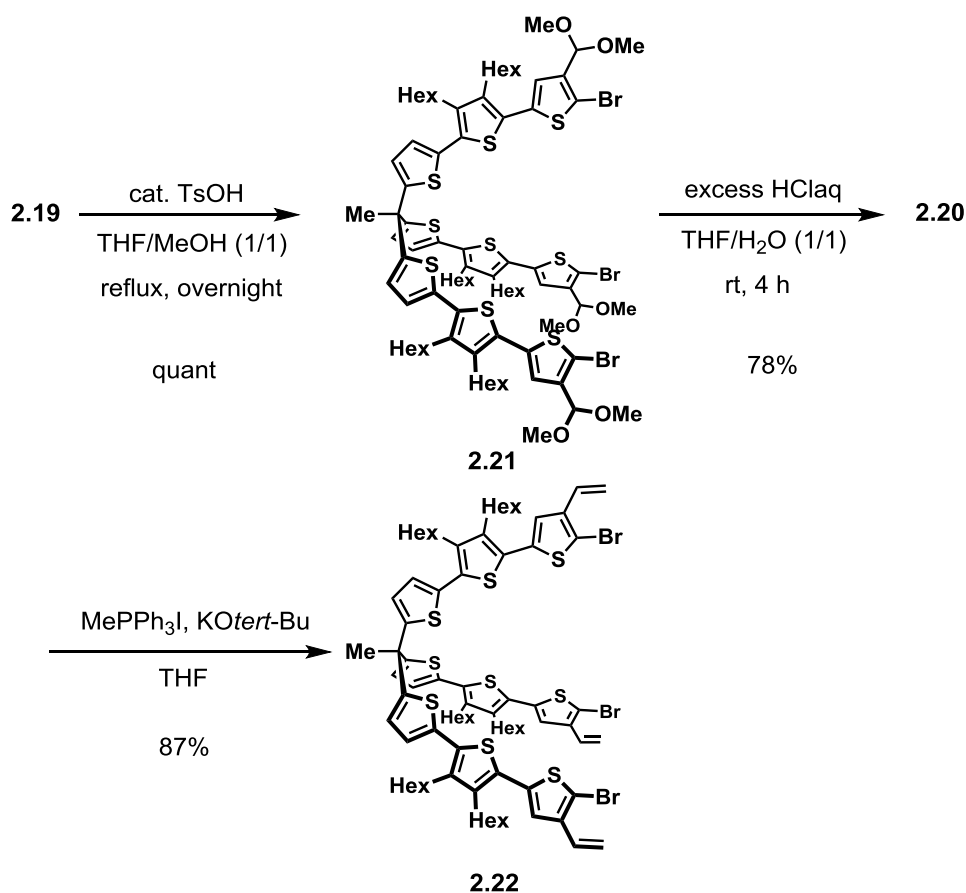


**Scheme 2.8.**

**Table 2.5.** Reaction conditions of hydrolysis of **2.19** in Scheme 2.8.

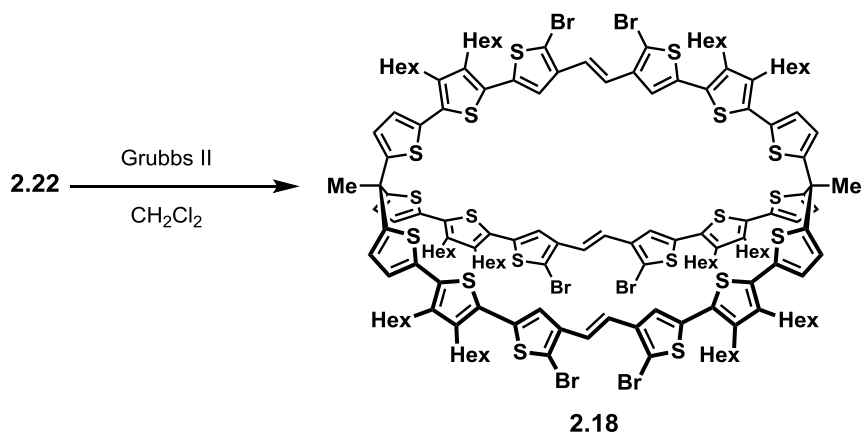
entry	reagents	solvent	temp and time	results
1	HCl <sub>aq</sub> (6M)	THF	rt, overnight	partial reduction
2	HCl <sub>aq</sub> (6M)	THF	rt, 10 days	<b>2.20</b> (30% yield)
3	HCl <sub>aq</sub> (6M)	THF	reflux overnight	<b>2.20</b> with unidentified products
4	I <sub>2</sub>	acetone	rt, 1 h	partial deprotection
5	I <sub>2</sub>	acetone	rt, overnight	complex mixture
6	TFA	CH <sub>2</sub> Cl <sub>2</sub>	rt, 3 days	decomposition

In this case, it was found that the efficient method was two step deprotection as shown in Scheme 2.9. Thus, conversion of 1,3-dioxolane into dimethyl acetal then hydrolysis of **2.21** produced the tribromide **2.20** in good yield. This reactivity difference might be rationalized by two factors. One is homogeneity at the acetal transformation step of **2.19**. Probably because the affinity of **2.19** toward water is too low, so that hydrolysis of **2.19** was sluggish in THF–H<sub>2</sub>O suspension. On the other hand, transesterification with MeOH easily occurred in homogeneous THF–MeOH solution. The other is the difference of hydrolysis reaction rate between 1,3-dioxolane and dimethyl acetal, or rapid cleavage of dimethyl acetal relative to 1,3-dioxolane.<sup>[11]</sup> Dimethyl acetal can be readily hydrolyzed and afford desired carbonyl compound.



Scheme 2.9.

The conversion of the trialdehyde **2.22** was succeeded with  $\text{MePPh}_3\text{I}/\text{KO}t\text{ert-Bu}$  system (Scheme 2.9). However, olefin metathesis of **2.22** in refluxed  $\text{CH}_2\text{Cl}_2$  solution probably led to decomposition or only polymerization, which was suggested by the fact that the reaction mixture gave no spot that moved up on TLC (Scheme 2.10 and Table 2.6, entry 1). Lowering temperature could not suppress such side-reactions, but resulted in a mixture of **2.22** and unidentifiable compounds (entry 2). These results show that the presence of bromine substituent should interfere the dimerization of **2.22** due to steric and/or electronic effects



Scheme 2.10.

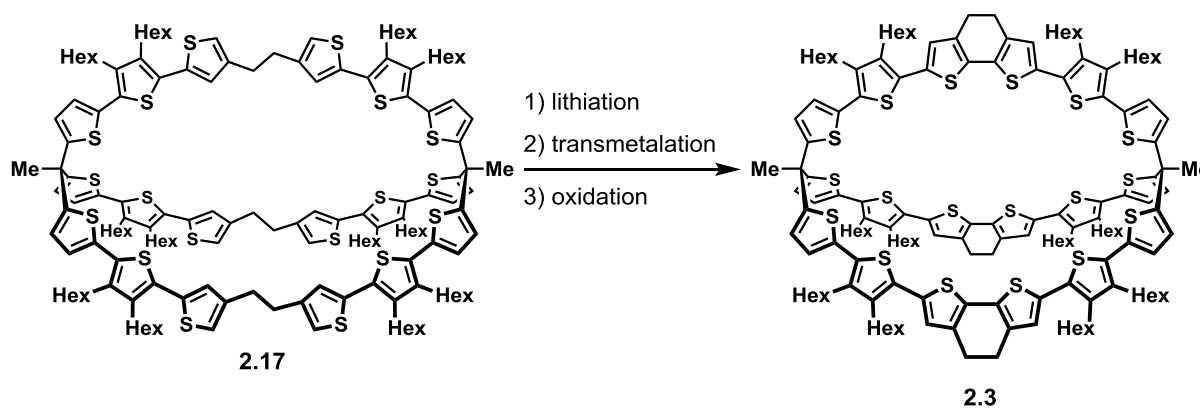
**Table 2.6.** Reaction conditions of metathesis reaction in Scheme 2.10.

entry	temp and time	results
1	reflux, 3 days	main one spot at the origin on TLC
2	rt, 3 days	recovery of <b>2.18</b> (30%) and unclear peaks on TLC

As an alternative pathway, I next examined oxidative coupling reaction of metalated thiophenes (Scheme 2.11). High reactivity of lithiated species will make it possible to use various oxidants. Based on this assumption, I tested coupling reaction with *n*-butyl lithium and copper chloride powder. However, under standard reaction condition, only the starting **2.17** was recovered (entry 1). On the other hand, use of a combination of CuCl<sub>2</sub> and LiCl in 1:2 molar ratio, formulated as Li<sub>2</sub>CuCl<sub>4</sub>, instead of CuCl<sub>2</sub> powder could lead to C–C coupling reaction (entry 2). The product was highly fluorescent, which suggested sexhithiophene chain formation. Gratifyingly, in this case, I could confirm the formation of desired cage **2.3** by high resolution mass spectrometry as a sodium adducted monocation (observed *m/z*: 2639.9890, calcd for [**2.3** + Na]<sup>+</sup>: 2639.9889, in Figure 2.2). This demonstrate the possibility of the lithiation-oxidation reaction as the final piece for cage shaped oligothiophene synthesis. However, the isotope pattern of the spectrum did not agree well with that that of calculated. This fact indicated that the product was a mixture of **2.3** and partially coupled compound. This result indicated that further modification of the reaction condition should be conducted.

Metal-bridged intermediates are frequently employed for macrocyclization reaction. Among them, I chose the method utilizing Lipshutz cuprate, which give efficiently small memebered cyclic aryl compounds.<sup>[12]</sup> However, the reference condition resulted in recovery of **2.17** (entry 3). Elongation of time of transmetalation or oxidation step also gave back **2.17** at a high rate. Replacement of trasmetalating reagent by Li<sub>2</sub>Cu(CN)Cl<sub>2</sub><sup>[13]</sup> or ZnCl<sub>2</sub>, or of oxidant by Li<sub>2</sub>CuCl<sub>4</sub> afforded **2.17** as an only identifiable component (entries 4–9).

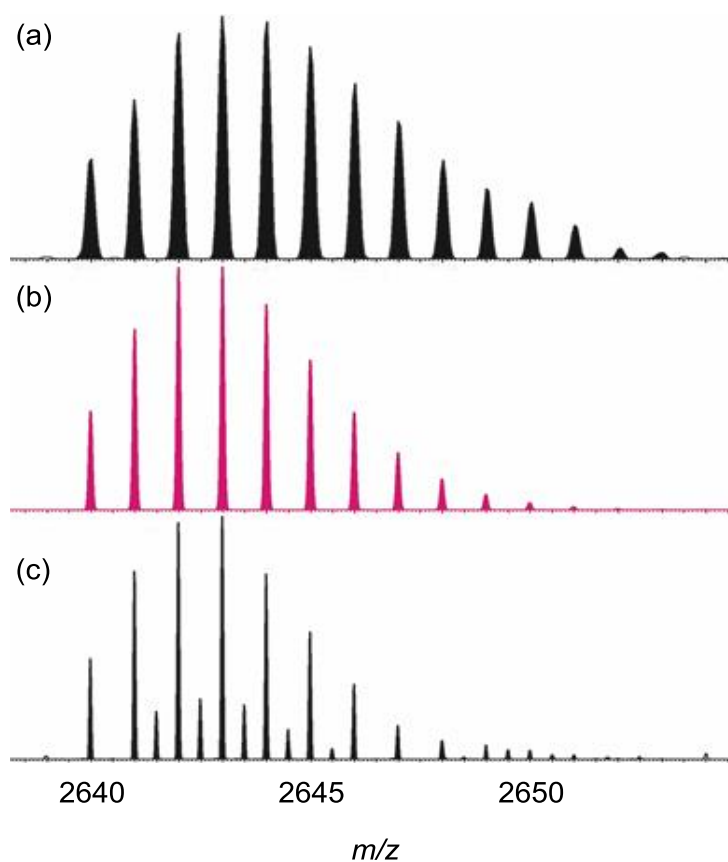
Based on these results, I decided to re-consider Li<sub>2</sub>CuCl<sub>4</sub> oxidation condition and found that slight modulation of preparation of Li<sub>2</sub>CuCl<sub>4</sub> was critical for clean bond formation (entry9). Thus, with using a THF solution of Li<sub>2</sub>CuCl<sub>4</sub> prepared by the procedure of baking a vigorously stirred mixture of CuCl<sub>2</sub> and LiCl before dissolving in anhydrous THF, the clean transformation from **2.17** into **2.3** could be confirmed by high resolution mass spectrometry. Unfortunately, however, it was also found that some by-products inseparable from desired **2.3** were formed in the condition, suggested by NMR spectroscopic measurement. Finally, the isolation of **2.3** was achieved by conducting the oxidative coupling under –78 °C (entry 10).

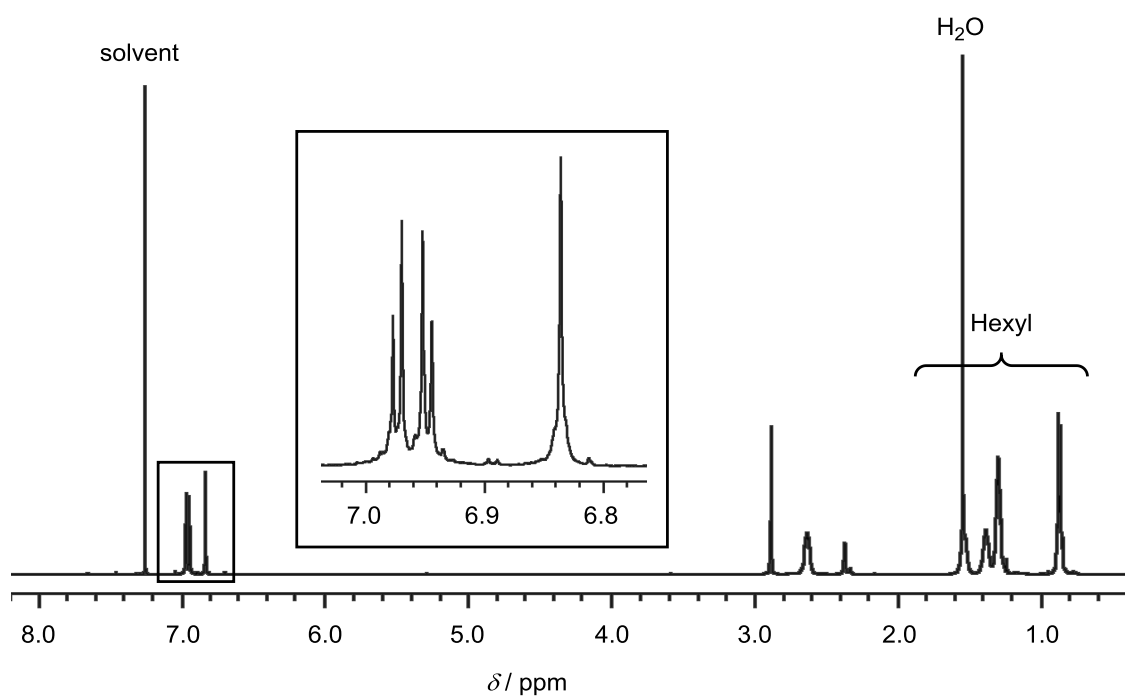
**Scheme 2.11.**

**Table 2.7.** Reaction conditions of oxidative coupling reaction in Scheme 2.11.

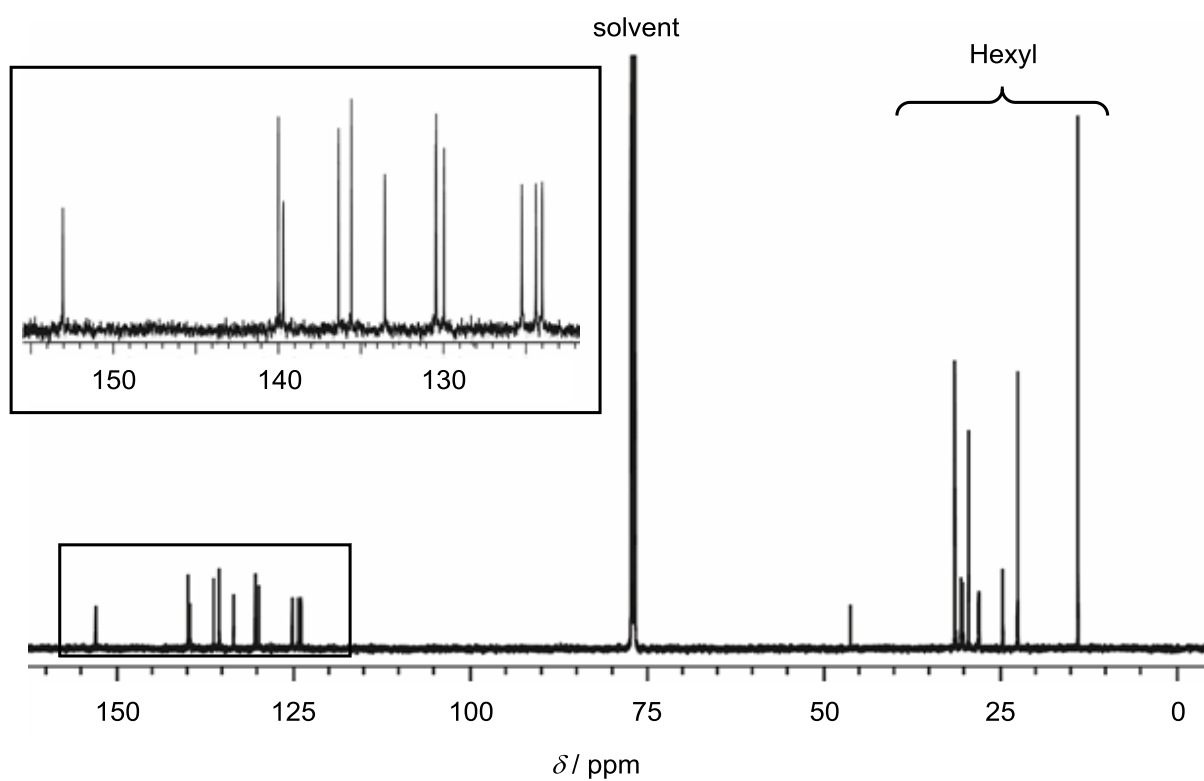
entry	reagents			results
	lithiation	transmetalation	oxidation	
1 <sup>[a]</sup>	15 eq. <i>n</i> -BuLi <sup>[b]</sup>	none	30 eq. CuCl <sub>2</sub> (powder)	recovery of <b>2.17</b> (87%)
2 <sup>[a]</sup>	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	none	30 eq. Li <sub>2</sub> CuCl <sub>4</sub> (in THF) <sup>[d],[e]</sup>	<b>2.3</b> and partial coupling
3	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	7.5 eq. CuCN <sup>[f]</sup>	30 eq. Duroquinone <sup>[d]</sup>	recovery of <b>2.17</b> (83%)
4	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	7.5 eq. CuCN <sup>[f]</sup>	30 eq. Li <sub>2</sub> CuCl <sub>4</sub> (in THF) <sup>[d],[e]</sup>	recovery of <b>2.17</b> (86%)
5	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	7.5 eq. CuCN <sup>[g]</sup>	30 eq. Duroquinone <sup>[h]</sup>	recovery of <b>2.17</b> (71%)
6	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	7.5 eq. Li <sub>2</sub> Cu(CN)Cl <sub>2</sub> <sup>[f]</sup>	30 eq. Duroquinone <sup>[h]</sup>	recovery of <b>2.17</b> (42%)
7	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	7.5 eq. ZnCl <sub>2</sub> <sup>[i]</sup>	30 eq. Duroquinone <sup>[h]</sup>	recovery of <b>2.17</b> (98%)
8	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	7.5 eq. ZnCl <sub>2</sub> <sup>[i]</sup>	30 eq. Li <sub>2</sub> CuCl <sub>4</sub> (in THF) <sup>[c],[d]</sup>	recovery of <b>2.17</b> (84%)
9 <sup>[a]</sup>	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	none	30 eq. Li <sub>2</sub> CuCl <sub>4</sub> (in THF) <sup>[d],[j]</sup>	crude <b>2.3</b>
10 <sup>[a]</sup>	15 eq. <i>n</i> -BuLi <sup>[c]</sup>	none	30 eq. Li <sub>2</sub> CuCl <sub>4</sub> (in THF) <sup>[j],[k]</sup>	<b>2.3</b> (31% yield)

[a] Skipped the step (2) in Scheme 2.11. [b] Stirred at  $-78$  °C then  $0$  °C, 30 min. [c] Stirred at  $-78$  °C, 1 h. [d] Prepared by dissolving CuCl<sub>2</sub> and LiCl (1 : 2 molar ratio) in THF without baking [d] Stirred at  $-78$  °C to rt, overnight. [f] Stirred at  $-78$  °C then rt, 1 h. [g] Stirred at  $-78$  °C then rt, 3 h. [h] Stirred at rt, 3 days. [i] Stirred at  $-78$  °C then  $0$  °C, 2 h. [j] Prepared by dissolving CuCl<sub>2</sub> and LiCl (1 : 2 molar ratio) in THF after baking. [k] Stirred at  $-78$  °C, 3 h.

**Figure 2.2.** High resolution mass spectra of the reaction product ((a) entry 1; (b) calculated; (c) entry 10)



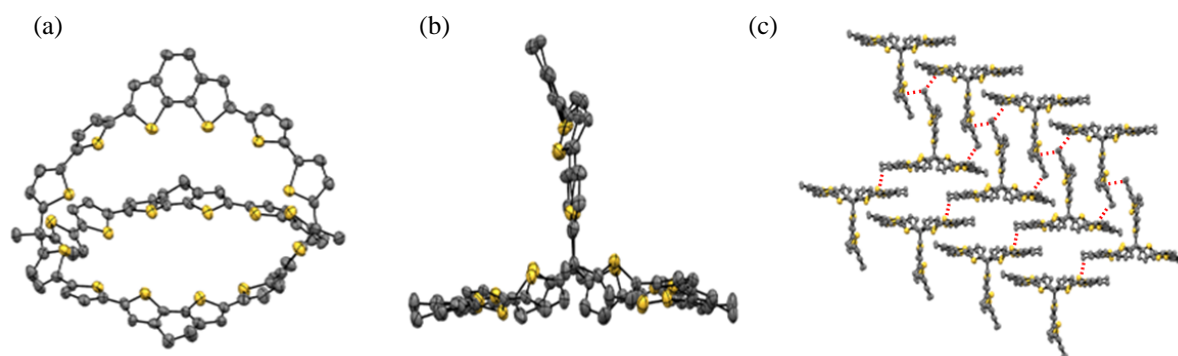
**Figure 2.3.**  $^1\text{H-NMR}$  spectrum of **2.3**. (500 MHz, 30 °C, in  $\text{CDCl}_3$ ). (Inset) Thiophene signals in the aromatic region.



**Figure 2.4.**  $^{13}\text{C-NMR}$  spectrum of **2.3**. (125 MHz, 30 °C, in  $\text{CDCl}_3$ ). (Inset) Thiophene signals in the aromatic region.



The characterization of **2.3** was carried out by high-resolution mass spectrometry,  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopy. In the mass spectrum, the observed value as well as the isotope pattern exhibited good agreement with those calculated (Figure 2.2.c). In addition,  $^1\text{H}$ -NMR spectrum exhibited two sets of doublets and one singlet in the aromatic region, which strongly support the clean formation and highly symmetric structure of **2.3** (Figure 2.3).  $^{13}\text{C}$  NMR spectrum also gave simple pattern, suggesting the symmetric structure of **2.3** in solution (Figure 2.4). Finally, the formation of **2.3** was unambiguously confirmed by X-ray crystallographic analysis (Figure 2.5).  
[14]



**Figure 2.5.** ORTEP drawings of **2.3** at the 50% probability level [(a) and (b)] and (c) packing structure of **2.3**. Intermolecular contacts smaller than the sum of van der Waals radii are represented as red dotted lines. Hydrogen atoms and hexyl chains are omitted for clarity.

Because the quality of the crystal was not so high due to the disorder of some of the hexyl chains, bond length could not be discussed in detail. Fortunately, however, the cage skeleton itself could be clearly determined. In contrast to the NMR observation in  $\text{CDCl}_3$  solution, the crystal structure of **2.3** was not three-fold symmetric one as two sexithiophene chains were arranged nearly planar (Figure 2.5.b). Interestingly, only two of the six thiophenes were attached to carbon atoms at the bridgehead direct S atoms outside of the central cavity. As a result, one of the three sexithiophenes adopts an all-*syn*-conformation, whereas the other two thiophene chains are arranged in a *syn-syn-syn-syn-anti* manner. A similar thiophene-inversion could be observed in the crystal structure of cyclic analogue (see Figure 3; vide infra). This fact suggests that the inversion of only two thiophenes observed in **2.3** is due to not only packing forces but also the molecular structure in which sexithiophenes are bridged between  $\text{sp}^3$  carbons. The torsion angles of adjacent thiophene units vary over a large range from  $5.6^\circ$  to  $58.4^\circ$ . These values differ greatly from those of linear sexithiophene derivatives as observed in the crystal structure of cyclo[10]thiophene (C10T).<sup>[15]</sup> The large difference in torsion angles of **2.3** is likely caused by the nearly coplanar conformation of the central bithiophene moieties, which demand that the other thiophene-thiophene bonds compensate for the molecular strain. S–S distances are distributed widely (3.13–3.57 Å) except for the inverted thiophenes. These values are smaller than the sum of van der Waals radii (3.6 Å).<sup>[16]</sup> Some of the hexyl chains interpenetrate into the central cavities of the adjacent molecules to form a one-dimensional molecular alignment (Figure 2.5.c). CH- $\pi$  interactions are observed between the neighbouring columns (red dotted lines in Figure 2.5c).

### 2.2.3 Synthesis of cyclic and linear analogs

In this section, I described the synthesis of model compound **2.23** and **2.24** by applying the synthetic strategy to the cyclic and linear sexithiophene **2.23** and **2.24** (Chart 2.2). Both of them are considered to be good model compounds for cage **2.3**.

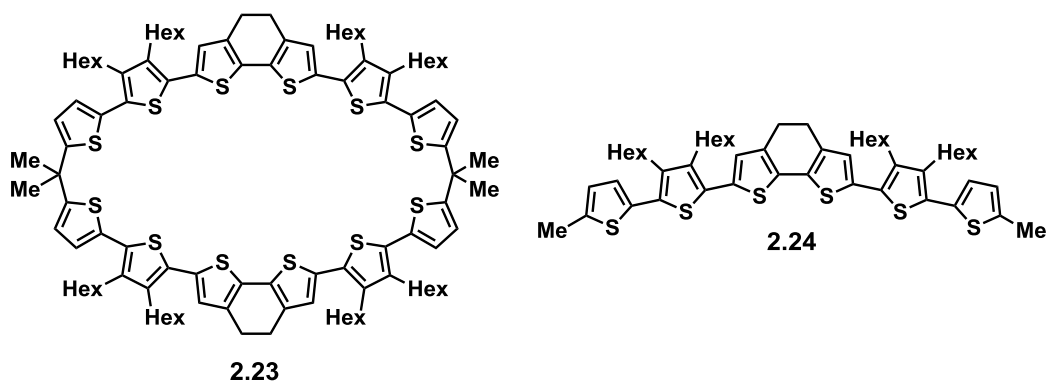
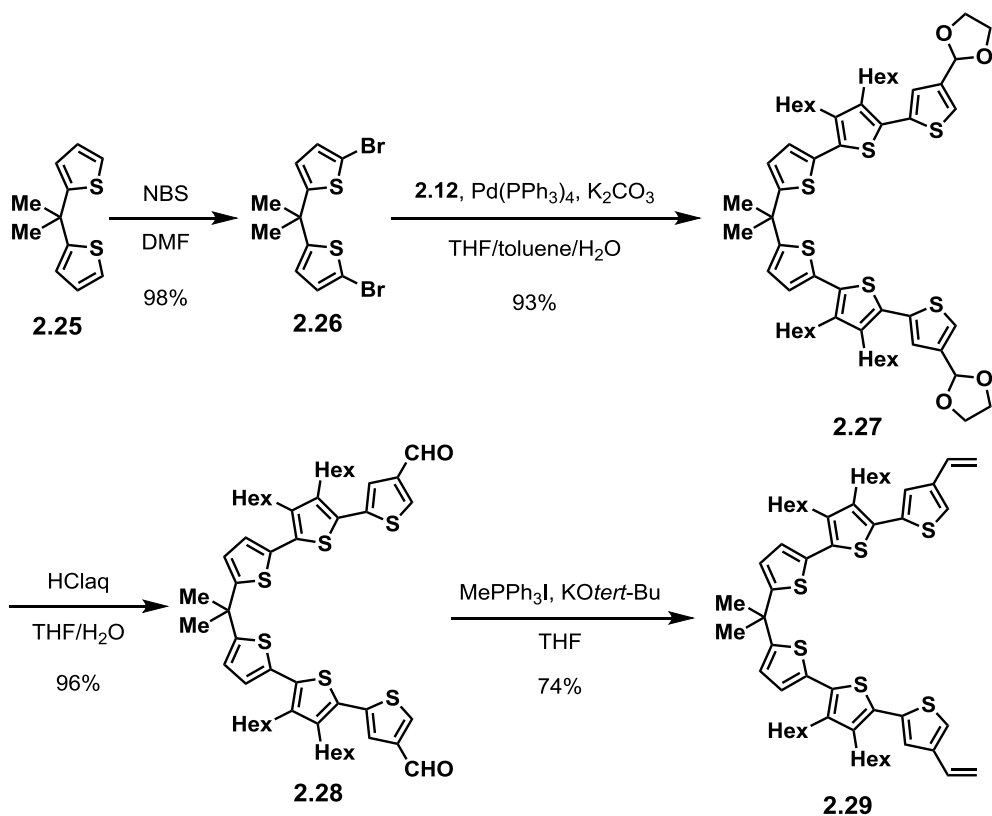


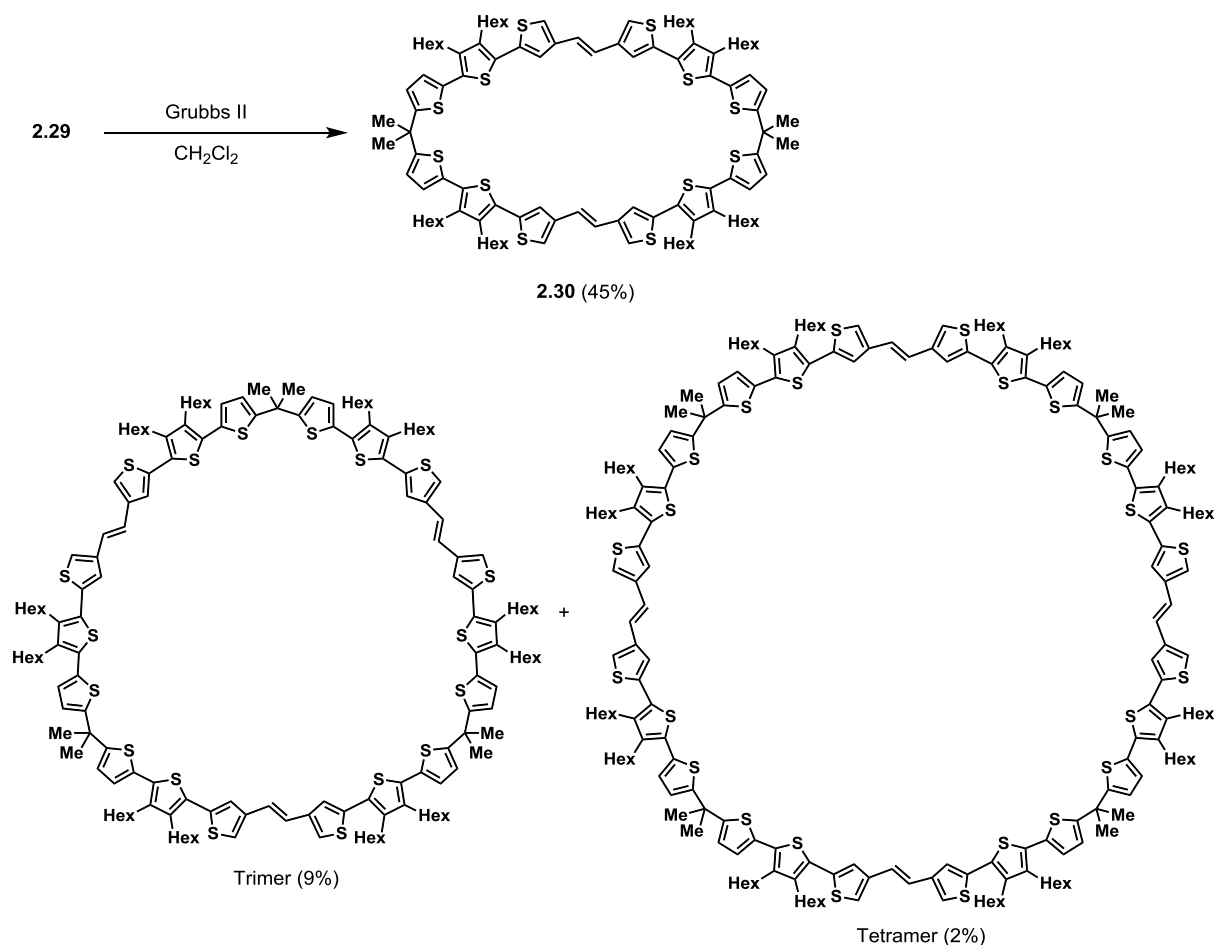
Chart 2.2.

The synthesis of compound **2.23** could be achieved only replacing trithienylmethane by dithienylmethane. Thus, 2,2-bis(2-thienyl)methane **2.25**, which was prepared by reported procedure,<sup>[7],[17]</sup> was first brominated to give **2.26** (Scheme 2.12). Suzuki-Miyaura coupling with bithiophene boronic ester **2.12** prepared in the previous section proceeded smoothly to afford the acetal protected bis(terthienyl)methane **2.26**. Hydrolysis can be carried out with an aqueous solution of HCl and THF. Wittig reaction proceeded without any modulation from the cage synthesis procedure to yield **2.29**.



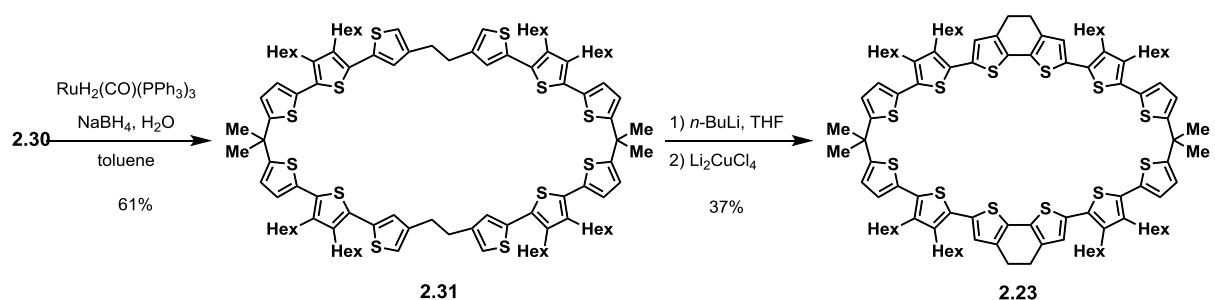
**Scheme 2.12.**

Metathesis reaction also gave desired dimeric cycle **2.30**. Interestingly, in addition to **2.30**, cyclic trimer and tetramer were also isolated in 9 and 2%, respectively. The structure of these compounds were estimated by NMR and HRMS. The production of higher oligomer is frequently observed in macrocyclization step.<sup>[18]</sup>



**Scheme 2.14.**

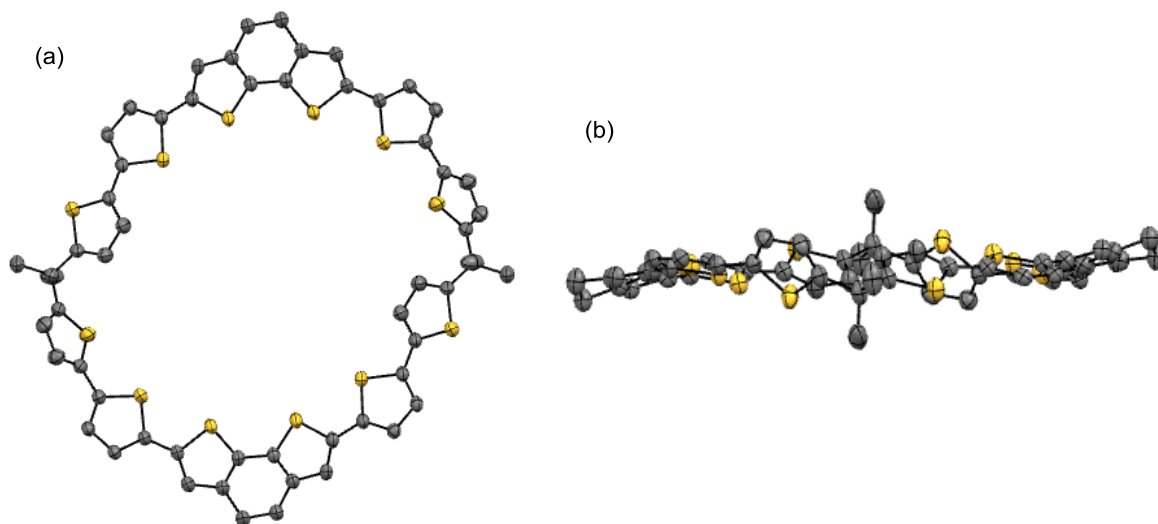
Compound **2.30** was then subjected to reduction followed by oxidative coupling reaction to give sexithiophene-based cycle **2.23** (Scheme 2.15). This compound was also characterized by high-resolution mass spectrometry,  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopy and X-ray crystallographic analysis.



**Scheme 2.15.**

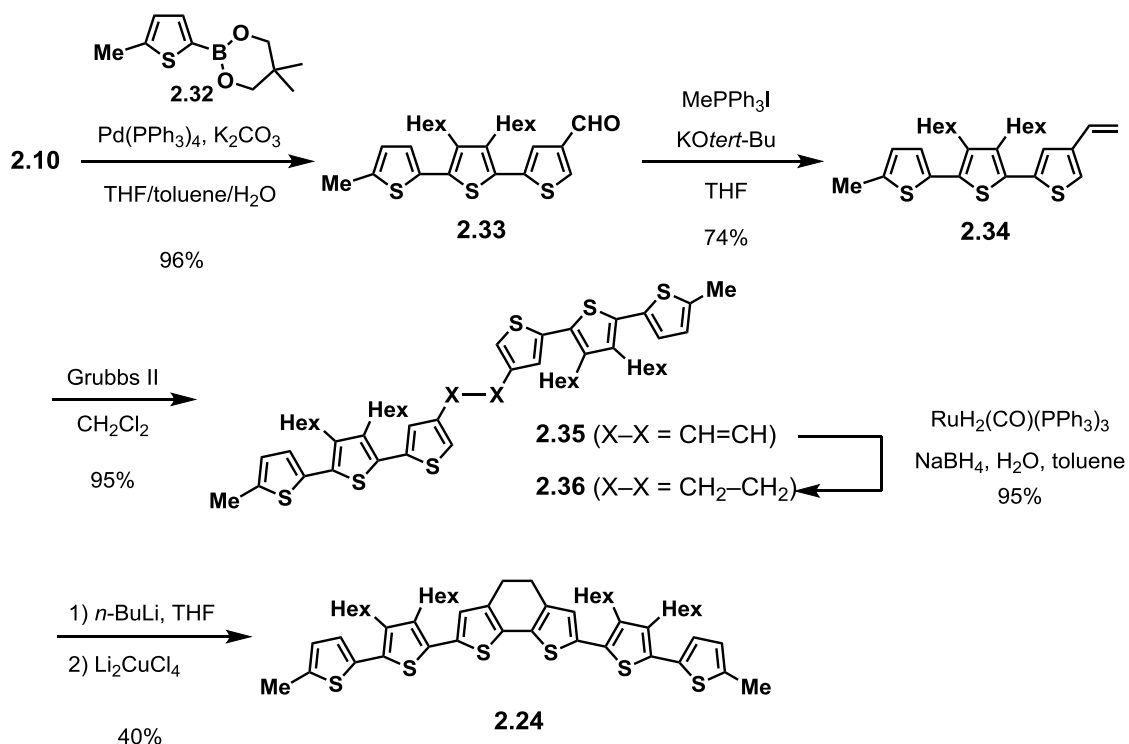
A crystal structure of **2.23**<sup>[19]</sup> was found to be the nearly planar cycle containing "inverted" thiophenes (Figure 2.7). Although the structural discussion had already presented above, it should be mentioned that all the atoms of

not only thiophene scaffold but also side hexyl chains are completely determined. The hexyl chains interpenetrated the central cavities of the neighboring rings and tightly fixed. This is why the high quality of the crystal was obtained in the case of **2.23** even though it has eight hexyl chains.



**Figure 2.7.** ORTEP drawings of **2.23** at the 50% probability level. Hydrogen atoms and hexyl chains are omitted for clarity. (a) Top view and (b) side view.

The synthesis of linear **2.24** was then carried out as shown Scheme 2.16. Terthiophene **2.33** was synthesized from **2.10** and known boronic acid ester **2.32**.<sup>[20]</sup> Wittig reaction gave vinylthiophene **2.34**, which was then subjected into metathesis reaction. It was unsurprising that the metathesis reaction underwent concentrated concentration and gave desired **2.35** in high yield. This clearly demonstrate the high efficiency of metathesis reaction with  $\beta$ -vinylethyl thiophenes.<sup>[21]</sup> The hydrogenation and Cu-mediated oxidative coupling reaction also preceeded smoothly to afford linear **2.24**. The characterization for all compounds were performed by high-resolution mass spectrometry,  $^1\text{H}$  and  $^{13}\text{C}$ -NMR spectroscopy. The high yield synthesis of the linear **2.24** highlights the high efficiency of elementary reaction employed for the cage construction strategy, which would lead to moderate yield in the cage compound synthesis.



Scheme 2.16.

### 2.3. Conclusion

The sixthiophene-bridged cage compound **2.3** was successfully prepared. Although metathesis strategy had found to be effective way to afford the  $\beta$ -ethano-bridged compound, such as **2.17**, the last C-C bond formation reaction did not proceed through the type dehydrogenative coupling reaction. Slight structural modification of the protection of bridge-head gave no effect for the bond formation. On the other hand, employment of lithiation-Cu oxidation procedure by *n*-BuLi and Li<sub>2</sub>CuCl<sub>4</sub> was found to be a good solution for the construction of cage scaffold and gave the cage **2.3**. I could apply this method to the synthesis cyclic and linear **2.23** and **2.24**. The high efficiency for the bond formation between closely-fixed thiophenes would make this methodology a promising synthetic tool for not only cage molecular synthesis but also strained oligothiophene construction.

## 2.4 Experimental Section

### 2.4.1 General

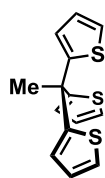
All experiments with moisture- or air-sensitive compounds were conducted in anhydrous solvents under a nitrogen atmosphere in well-dried glassware. Anhydrous dichloromethane and tetrahydrofuran (THF) were purchased from Kanto Chemical Co., Inc. and used without further purification. Other anhydrous solvents were prepared by distillation over calcium hydride. Column chromatography were performed on a silica gel (Silica gel 60N, Kanto Chemical Co., Inc.) or alumina (Aluminium oxide 90, Merck). Melting points were taken on a Yanako MP 500D apparatus and are uncorrected. Preparative gel permeation chromatography (GPC) was performed on a recycling HPLC (JAI LC-9201 equipped with JAIGEL 1H and JAIGEL 2 H columns) with using chloroform as an eluent. Infrared spectra were recorded on a JASCO FT/IR-660M spectrometer. UV-vis absorption spectra were measured on a JASCO V-570 spectrometer. Fluorescence spectra were measured on a JASCO FP-6300 spectrofluorometer.  $^1\text{H-NMR}$  and  $^{13}\text{C-NMR}$  spectra were recorded on a JEOL ECA500 spectrometer. The chemical shifts were recorded by using tetramethylsilane (0.00 ppm) as an internal reference for  $^1\text{H-NMR}$  spectra and  $\text{CDCl}_3$  (77.00 ppm) for  $^{13}\text{C-NMR}$  spectra. Mass spectra were recorded on a Shimadzu GCMS-QP2010, a Shimadzu AXIMA-CFR and a ThermoFisher Scientific LTQ Orbitrap-XL mass spectrometer for EI, MALDI-TOF and ESI-Orbitrap MS, respectively. The high-resolution mass spectra (HRMS) were analyzed by using ThermoXcalibur 2.1.0.1140 software. Data collection for X-ray crystal analysis was performed on a Rigaku/Varimax diffractometer (Mo-K $\alpha$ ,  $\lambda = 0.71075 \text{ \AA}$ ). The structure was solved with direct methods and refined with full-matrix least-squares (teXsan). Cyclic voltammetry measurement was conducted with a BAS CV-50W electrochemical analyzer in a 0.1 M *n*-Bu $_4$ NPF $_6$  dichloromethane solution at room temperature. Elemental analyses were performed at the Elemental Analysis Center in the Faculty of Science, Osaka University.

### 2.4.2. Synthetic Procedures

#### **Preparation of a THF solution of $\text{Li}_2\text{CuCl}_4$ <sup>1</sup>**

A vigorously stirred mixture of  $\text{CuCl}_2$  and  $\text{LiCl}$  (1:2 molar ratio) was baked with heat gun for 5 min *in vacuo*. After cooled to room temperature, the resulting powder was dissolved in THF to give reddish orange solution. This solution was prepared every time prior to use.

### 1,1,1-Tris(2-thienyl)ethane (2.5)

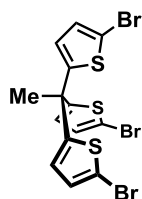


2.5

To a solution of tris(2-thienyl)methane **2.4** (5.944 g, 22.7 mmol) and *i*-Pr<sub>2</sub>NH (4.8 mL, 34.2 mmol) in THF (30 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 17.0 mL, 25.5 mmol) at  $-78$  °C. The resulting mixture was warmed up to room temperature and stirred for 1 h. After a dropwise addition of MeI (1.6 mL, 25.6 mmol) at room temperature, the resulting mixture was stirred for an additional 1 h at the same temperature. A saturated aqueous solution of NH<sub>4</sub>Cl (20 mL) was added to the reaction mixture, then the aqueous layer was extracted with diethyl ether (3 × 40 mL). The combined organic extracts were washed with water (1 × 30 mL) and brine (1 × 30 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane (1/9)) to afford the title compound **2.5** (6.275 g, 100%) as a colorless solid.

Mp: 43.4–43.9 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.21 (dd, *J* = 1.1, 5.0 Hz, 3H), 6.92 (dd, *J* = 3.6, 5.0 Hz, 3H), 6.81 (dd, *J* = 1.1, 3.6 Hz, 3H), 2.33 (s, 3H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 153.65, 126.24, 125.69, 124.43, 46.31, 33.99; IR (KBr):  $\nu$ /cm<sup>-1</sup> 3099 (m), 3069 (m), 2979 (m), 2923 (w), 2862 (w), 1800 (w), 1736 (w), 1672 (w), 1602 (w), 1523 (w), 1446 (m), 1434 (m), 1373 (m), 1350 (m), 1241 (s), 1230 (s), 1201 (w), 1178 (w), 1122 (w), 1081 (w), 1053 (m), 1011 (m), 903 (w), 853 (s), 834 (s), 781 (w), 757 (m), 745 (w), 716 (s), 701 (s), 637 (w), 616 (w); MS (EI, rel intensity): *m/z* 276 (29, [M]<sup>+</sup>), 261 (100, [M–Me]<sup>+</sup>); Elemental analysis: calcd for C<sub>14</sub>H<sub>12</sub>S<sub>3</sub>, C 60.83, H 4.38; found, C 60.83, H 4.39.

### 1,1,1-Tris(5-bromo-2-thienyl)ethane (2.6)

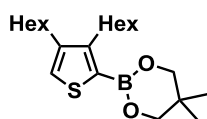


2.6

To a solution of 1,1,1-tris(2-thienyl)ethane **2.5** (6.275 g, 22.7 mmol) in DMF (30 mL) was added dropwise a solution of NBS (13.313 g, 74.8 mmol) in DMF (30 mL) at 0 °C. After completion of the addition, the reaction mixture was warmed up to room temperature and stirred for 2 h. Water (25 mL) was added to the reaction mixture, then the aqueous layer was extracted with diethyl ether (5 × 50 mL). The combined organic extracts were washed with water (3 × 30 mL) and brine (1 × 30 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, *n*-hexane) to afford the title compound **2.6** (9.029 g, 78%) as a colorless powder.

Mp: 72.3–73.1 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.89 (d, *J* = 3.9 Hz, 3H), 6.58 (d, *J* = 3.9 Hz, 3H), 2.17 (s, 3H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 153.01, 129.33, 126.27, 111.95, 47.09, 32.93; IR (KBr):  $\nu$ /cm<sup>-1</sup> 3089 (w), 2967 (m), 2925 (w), 1747 (w), 1534 (m), 1436 (m), 1373 (m), 1319 (m), 1215 (s), 1176 (w), 1062 (m), 1022 (s), 1011 (s), 958 (s), 805 (s), 793 (s), 772 (m), 750 (s), 735 (w), 724 (w), 650 (m); MS (EI, rel intensity): *m/z* 510/512/514/516 (8/28/29/11, [M]<sup>+</sup>), 495/497/499/501 (31/94/100/41, [M–Me]<sup>+</sup>); Elemental analysis: calcd for C<sub>14</sub>H<sub>9</sub>Br<sub>3</sub>S<sub>3</sub>, C 32.77, H 1.77; found, C 32.75, H 1.74.

### 2-(3,4-Dihexylthiophen-2-yl)-5,5-dimethyl-1,3,2-dioxaborinane (2.8)



2.8

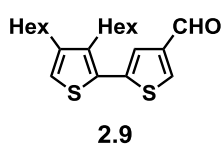
To a solution of 3,4-dihexylthiophene **2.7** (5.074 g, 20.1 mmol) in diethyl ether (50 mL) was added dropwise a solution of *tert*-BuLi (1.5 M in *n*-pentane, 20 mL, 30 mmol) at  $-78$  °C. After stirring for 1 h at 0 °C, B(O*i*-Pr)<sub>3</sub> (9.2 mL, 39.9 mmol) was added in one portion at  $-78$  °C. The resulting mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (6.272 g, 60.2 mmol) was added, then the reaction mixture was stirred for



an additional 1 h. After addition of water (50 mL), the aqueous layer was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were washed with water (1 × 30 mL) and brine (1 × 30 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/8) to afford the title compound **2.8** (6.623 g, 91%) as a pale yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.10 (s, 1H), 3.74 (s, 4H), 2.78 (t, *J* = 7.7 Hz, 2H), 2.51 (t, *J* = 7.6 Hz, 2H), 1.61 (quin, *J* = 7.6 Hz, 2H), 1.49–1.43 (m, 2H), 1.39–1.26 (m, 12H), 1.02 (s, 6H), 0.90–0.88 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 151.95, 144.00, 125.73, 72.26, 31.92, 31.75, 31.63, 30.08, 29.43, 29.31, 28.67, 28.33, 22.62, 22.58, 21.91, 14.09, 14.07; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>21</sub>H<sub>37</sub>BO<sub>2</sub>SNa, 387.2500; found, 387.2504 ([M+Na]<sup>+</sup>).

### 3',4'-Dihexyl-2,2'-bithiophene-4-carbaldehyde (**2.9**)

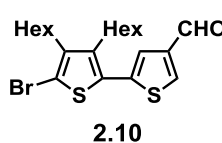


To a solution of 5-bromo-3-thiophenecarbaldehyde (3.100 g, 16.2 mmol), K<sub>2</sub>CO<sub>3</sub> (4.494 g, 32.5 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (914 mg, 0.791 mmol) in toluene/water (3/1, 20 mL) was added a solution of boronic acid ester **2.8** (6.623 g 18.2 mmol) in THF (15 mL). The reaction mixture was heated to reflux and stirred for 2 days. After cooling to room temperature,

water (20 mL) was added to the reaction mixture. The aqueous layer was extracted with diethyl ether (3 × 30 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/25) to afford the title compound **2.9** (5.678 g, 97%) as a pale yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 9.88 (s, 1H), 8.05 (d, *J* = 1.4 Hz, 1H), 7.49 (d, *J* = 1.4 Hz, 1H), 6.91 (s, 1H), 2.67 (t, *J* = 8.1 Hz, 2H), 2.53 (t, *J* = 7.9 Hz, 2H), 1.65 (quin, *J* = 7.7 Hz, 2H), 1.53–1.47 (m, 2H), 1.44–1.22 (m, 12H), 0.92–0.86 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 184.83, 143.64, 143.03, 140.15, 139.29, 136.04, 129.26, 123.12, 120.16, 31.71, 31.47, 30.40, 29.68, 29.42, 29.26, 29.18, 27.59, 22.60, 22.56, 14.05, 14.01; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>21</sub>H<sub>30</sub>OS<sub>2</sub>Na, 385.1630; found, 385.1635 ([M+Na]<sup>+</sup>).

### 5'-Bromo-3',4'-dihexyl-(2,2'-bithiophene)-4-carbaldehyde (**2.10**)

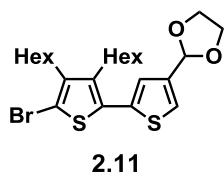


To a solution of 4'-formyl-3,4-dihexyl-2,2'-bithiophene **2.9** (5.678 g, 15.7 mmol) in DMF (15 mL) was added a solution of NBS (2.952 g, 16.6 mmol) in DMF (15 mL) at 0 °C. After completion of the addition, the reaction mixture was warmed up to room temperature and stirred for 2 h. After addition of water (20 mL), the aqueous layer was extracted with diethyl

ether (5 × 50 mL). The combined organic extracts were washed with water (3 × 50 mL) and brine (1 × 50 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/25) to afford the title compound **2.10** (6.231 g, 90%) as a yellow oil.

<sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>): δ 9.87 (s, 1H), 8.06 (d, *J* = 1.3 Hz, 1H), 7.45 (d, *J* = 1.3 Hz, 1H), 2.67–2.64 (m, 2H), 2.55–2.52 (m, 2H), 1.55–1.46 (m, 4H), 1.43–1.24 (m, 12H), 0.92–0.86 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 184.65, 143.02, 142.70, 140.21, 137.89, 136.30, 129.29, 123.64, 109.82, 31.53, 31.40, 30.66, 29.53, 29.34, 29.33, 28.68, 28.31, 22.57, 22.53, 14.04, 13.99; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>21</sub>H<sub>29</sub>BrOS<sub>2</sub>Na, 463.0735; found, 463.0742 ([M+Na]<sup>+</sup>).

### 2-Bromo-4'-(1,3-dioxolan-2-yl)-3,4-dihexyl-2,2'-bithiophene (2.11)



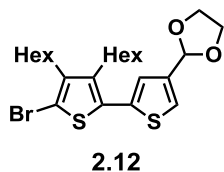
2.11

A solution of 5'-bromo-3',4'-dihexyl-(2,2'-bithiophene)-4-carbaldehyde **2.10** (6.225 g, 14.1 mmol), ethylene glycol (1.6 mL, 28.7 mmol) and TsOH·H<sub>2</sub>O (19 mg, 0.100 mmol) in benzene (30 mL) was heated to reflux in Dean-Stark apparatus and stirred overnight. After cooling to room temperature, a saturated aqueous solution of NaHCO<sub>3</sub> (10 mL) was added.

The aqueous layer was extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (3 × 10 mL) and brine (1 × 10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration, the filtrate was concentrated and dried *in vacuo* to afford the title compound **2.11** (6.741 g, 99%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.37 (dd, *J* = 0.6, 1.4 Hz, 1H), 7.09 (d, *J* = 1.4 Hz, 1H), 5.86 (s, 1H), 4.12–4.00 (m, 4H), 2.66–2.63 (m, 2H), 2.53–2.50 (m, 2H), 1.55–1.46 (m, 4H), 1.42–1.25 (m, 12H), 0.92–0.87 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 142.40, 140.26, 139.16, 136.46, 130.69, 124.77, 123.63, 100.68, 100.29, 65.10, 31.53, 31.40, 30.70, 29.54, 29.36, 29.34, 28.67, 28.31, 22.56, 22.55, 14.03, 13.99; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>23</sub>H<sub>33</sub>BrO<sub>2</sub>S<sub>2</sub>Na, 507.0998; found, 507.1006 ([M+Na]<sup>+</sup>).

### 2-(4'-(1,3-Dioxolan-2-yl)-3,4-dihexyl-(2,2'-bithiophen-5-yl)-5,5-dimethyl-1,3,2-dioxaborinane (2.12)



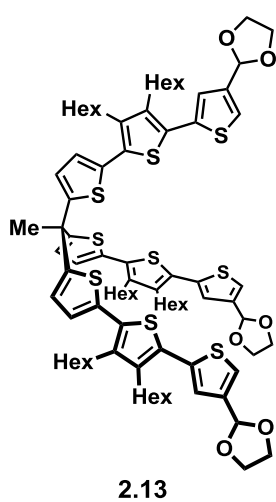
2.12

To a solution of 2-bromo-4'-(1,3-dioxolan-2-yl)-3,4-dihexyl-2,2'-bithiophene **2.11** (6.730 g, 13.9 mmol) in diethyl ether (25 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 9.5 mL, 14.3 mmol) at –78 °C. After stirring for 30 minutes at –78 °C, B(*Oi*-Pr)<sub>3</sub> (6.5 mL, 28.2 mmol) was added in one portion. The resulting mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (4.375 g, 42.0 mmol) was added,

then the reaction mixture was stirred for an additional 1 h. After addition of water (20 mL), the aqueous layer was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were washed with water (1 × 20 mL) and brine (1 × 20 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/8) to afford the title compound **2.12** (6.157 g, 86%) as a yellowish orange oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.35–7.34 (m, 1H), 7.17 (d, *J* = 1.4 Hz, 1H), 5.88 (s, 1H), 4.11–3.99 (m, 4H), 3.74 (s, 4H), 2.77–2.74 (m, 2H), 2.68–2.64 (m, 2H), 1.53–1.47 (m, 4H), 1.39–1.26 (m, 12H), 1.02 (s, 6H), 0.91–0.87 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 153.31, 140.65, 140.23, 138.14, 135.87, 124.29, 123.22, 100.46, 72.31, 65.11, 32.28, 31.95, 31.59, 31.50, 30.75, 29.56, 29.54, 28.94, 27.68, 22.61, 22.58, 21.90, 14.09, 14.04; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>28</sub>H<sub>43</sub>BO<sub>4</sub>S<sub>2</sub>Na, 541.2588; found 541.2596 ([M+Na]<sup>+</sup>).

### 1,1,1-Tris(4''-(1,3-dioxolan-2-yl)-3',4'-dihexyl-2,2':5',2''-terthiophen-2-yl)ethane (2.13)

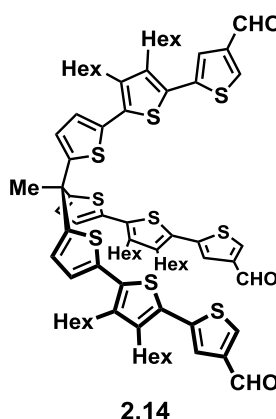


2.13

A mixture of 1,1,1-tris(5-bromo-2-thienyl)ethane **2.6** (1.217 g, 2.37 mmol), boronic acid ester **2.12** (5.482 g, 10.6 mmol),  $K_2CO_3$  (2.015 g, 14.6 mmol) and  $Pd(PPh_3)_4$  (282 mg, 0.244 mmol) in THF/toluene/water (3/3/1, 35 mL) was heated to reflux and stirred for 2 days. After cooling to room temperature, water (20 mL) was added to the reaction mixture. The aqueous layer was extracted with diethyl ether ( $3 \times 30$  mL). The combined organic extracts were washed with water ( $1 \times 20$  mL) and brine ( $1 \times 20$  mL), then dried over anhydrous  $Na_2SO_4$ . After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/3) to afford the title compound **2.13** (3.281 g, 93%) as a yellow orange oil.  $^1H$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  7.36–7.35 (m, 3H), 7.14 (d,  $J = 1.3$  Hz, 3H), 6.95 (d,  $J = 3.7$  Hz, 3H), 6.83 (d,  $J = 3.7$  Hz, 3H), 5.87 (s, 3H), 4.12–4.00 (m, 12H), 2.68–2.64 (m, 12H), 2.35 (s, 3H), 1.60–1.50 (m, 12H), 1.42–1.26 (m, 36H), 0.90–0.83 (m, 18H);

$^{13}C$ -NMR (125 MHz,  $CDCl_3$ ):  $\delta$  152.52, 140.31, 140.25, 139.98, 137.24, 135.66, 130.11, 129.48, 126.17, 124.83, 124.34, 123.25, 100.42, 65.13, 46.83, 33.37, 31.48, 30.72, 30.61, 29.53, 29.51, 28.17, 28.09, 22.61, 22.58, 14.05, 14.04; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{83}H_{108}O_6S_9Na$ , 1511.5524; found, 1511.5531 ( $[M+Na]^+$ ).

### 1,1,1-Tris(4''-formyl-3',4'-dihexyl-2,2':5',2''-terthiophen-2-yl)ethane (2.14)



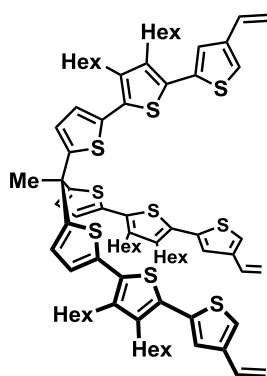
2.14

To a solution of triacetal **S8** (3.281 g, 2.20 mmol) in THF (20 mL) was added a 6 M aqueous solution of HCl (20 mL) at room temperature and the resulting mixture was stirred overnight. The aqueous layer was extracted with diethyl ether ( $3 \times 30$  mL). The combined organic extracts were washed with water ( $5 \times 20$  mL) and brine ( $1 \times 20$  mL), then dried over anhydrous  $Na_2SO_4$ . After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/4) to afford the title compound **2.14** (2.981 g, 100%) as a yellow orange oil.

$^1H$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  9.88 (s, 3H), 8.05 (d,  $J = 1.3$  Hz, 3H), 7.50 (d,  $J = 1.3$  Hz, 3H), 6.98 (d,  $J = 3.9$  Hz, 3H), 6.86 (d,  $J = 3.9$  Hz, 3H), 2.69–2.66 (m, 12H), 2.37 (s, 3H), 1.56–1.50 (m, 12H), 1.40–1.24 (m, 36H), 0.89–0.83 (m, 18H);  $^{13}C$ -NMR (125

MHz,  $CDCl_3$ ):  $\delta$  184.63, 152.72, 143.00, 141.23, 140.09, 140.06, 138.49, 135.98, 135.22, 131.00, 127.99, 126.14, 125.12, 122.99, 46.75, 33.19, 31.38, 31.36, 30.58, 30.52, 29.41, 29.38, 28.07, 27.96, 22.49, 22.48, 13.98, 13.95; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{77}H_{96}O_3S_9Na$ , 1379.4738; found, 1379.4743 ( $[M+Na]^+$ ).

### 1,1,1-Tris(3',4'-dihexyl-4''-vinyl-2,2':5',2''-terthiophen-2-yl)ethane (**2.15**)

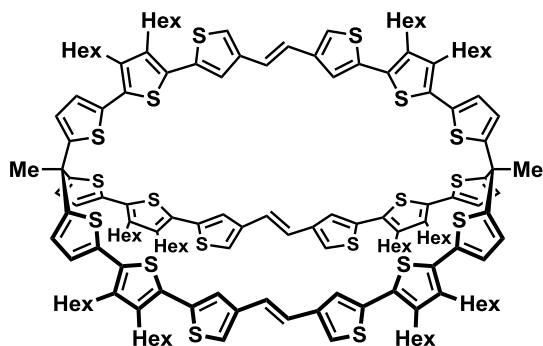


**2.15**

A mixture of trialdehyde **2.14** (3.382 g, 2.49 mmol), KO*tert*-Bu (4.204 g, 37.5 mmol) and MePPh<sub>3</sub>I (15.058 g, 37.3 mmol) was suspended in THF (40 mL) and stirred overnight at room temperature. After addition of a saturated aqueous solution of NH<sub>4</sub>Cl (10 mL), the aqueous layer was extracted with diethyl ether (3 × 40 mL). The combined organic extracts were washed with water (1 × 20 mL) and brine (1 × 20 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/9) to afford the title compound **2.15** (2.965 g, 88%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.23 (d, *J* = 1.3 Hz, 3H), 7.13 (d, *J* = 1.3 Hz, 3H), 6.96 (d, *J* = 3.7 Hz, 3H), 6.84 (d, *J* = 3.7 Hz, 3H), 6.65 (dd, *J* = 10.9, 17.5 Hz, 3H), 5.57 (dd, *J* = 0.9, 17.5 Hz, 3H), 5.21 (dd, *J* = 0.9, 10.9 Hz, 3H), 2.69–2.65 (m, 12H), 2.36 (s, 3H), 1.56–1.50 (m, 12H), 1.43–1.22 (m, 36H), 0.90–0.84 (m, 18H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 152.53, 140.54, 140.30, 140.01, 136.75, 135.66, 130.92, 130.04, 129.60, 126.15, 124.83, 123.31, 122.22, 113.81, 46.83, 33.32, 31.49, 31.47, 30.73, 30.62, 29.52, 28.16, 28.09, 22.60, 22.58, 14.06, 14.04; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>80</sub>H<sub>102</sub>S<sub>9</sub>Na, 1373.5360; found, 1373.5370 ([M+Na]<sup>+</sup>).

### β-Etheno-linked hexakis(terthiophenyl) cage (**2.16**)

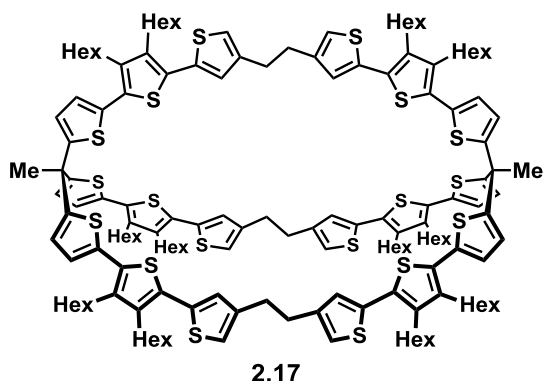


**2.16**

A solution of tris(terthiophenyl)methane **2.15** (81 mg, 0.0599 mmol) and Grubbs 2nd generation catalyst (6 mg, 0.00707 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (120 mL) was heated to reflux and stirred for 24 h. After cooling to room temperature, ethyl vinyl ether (0.5 mL) was added to the reaction mixture. The resulting solution was concentrated, then filtered through silica gel short plug (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/1). The filtrate was concentrated and the crude product was purified by GPC to afford the title compound **2.16** (21 mg, 27%) as a yellowish orange powder.

Mp: 186.9–187.5 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.24 (d, *J* = 1.3 Hz, 6H), 7.23 (d, *J* = 1.3 Hz, 6H), 6.99 (d, *J* = 3.9 Hz, 6H), 6.91 (d, *J* = 3.9 Hz, 6H), 6.90 (s, 6H), 2.72–2.65 (m, 24H), 2.39 (s, 6H), 1.58–1.51 (m, 24H), 1.43–1.25 (m, 72H), 0.90–0.85 (m, 36H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 152.81, 140.09, 139.93, 139.64, 136.45, 135.71, 129.78, 129.74, 125.95, 125.25, 124.92, 122.88, 120.35, 46.69, 32.55, 31.49, 31.46, 30.74, 30.62, 29.56, 29.49, 28.19, 28.12, 22.61, 22.58, 14.06, 14.05; IR (KBr): *ν*/cm<sup>-1</sup> 2952 (s), 2925 (s), 2854 (s), 1464 (m), 1376 (w), 1223 (w), 1185 (w), 952 (m), 870 (w), 831 (w), 801 (w), 728 (w), 637 (w); UV-vis (CH<sub>2</sub>Cl<sub>2</sub>): λ<sub>max</sub>/nm (log ε) 354 (sh), 323 (5.13), 274 (5.05), 227 (4.92); HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>154</sub>H<sub>192</sub>S<sub>18</sub>Na, 2639.9889; found, 2639.9825 ([M+Na]<sup>+</sup>); Elemental analysis: calcd for C<sub>154</sub>H<sub>192</sub>S<sub>18</sub>, C 70.59, H 7.39; found, C 70.26, H 7.30.

### $\beta$ -Ethano-linked hexakis(terthienyl) cage (**2.17**)

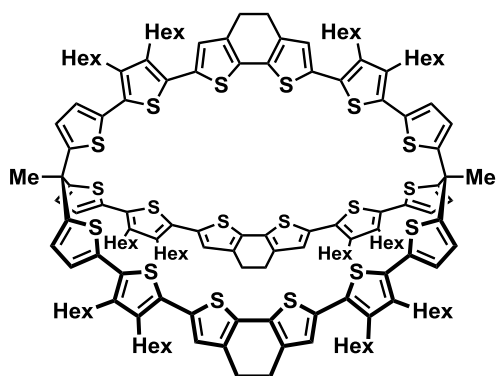


**2.17**

To a suspension of  $\beta$ -etheno-linked cage **2.16** (598 mg, 0.228 mmol),  $\text{NaBH}_4$  (1.295 g, 34.2 mmol) and  $\text{RuH}_2(\text{CO})(\text{PPh}_3)_3$  (248 mg, 0.270 mmol) in toluene (30 mL) was added water (3.1 mL, 166 mmol) at room temperature under hydrogen atmosphere. The reaction mixture was heated to 100 °C and stirred for 24 h. After cooling to room temperature, a 1 M aqueous solution of HCl (30 mL) was slowly added to the reaction mixture. The aqueous layer was extracted with diethyl ether (3  $\times$  30 mL). The combined organic extracts

were washed with water (1  $\times$  10 mL) and brine (1  $\times$  10 mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel,  $\text{CH}_2\text{Cl}_2/n$ -hexane = 1/6) to afford the title compound **2.17** (388 mg, 65%) as a yellow oil.  
 $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.89–6.88 (m, 12H), 6.75 (d,  $J$  = 1.4 Hz, 6H), 6.73 (d,  $J$  = 3.7 Hz, 6H), 2.91 (s, 12H), 2.65–2.62 (m, 24H), 2.34 (s, 6H), 1.54–1.47 (m, 24H), 1.39–1.25 (m, 72H), 0.88–0.82 (m, 36H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  152.24, 141.84, 139.70, 139.60, 135.93, 135.73, 130.15, 129.67, 127.50, 126.19, 124.77, 120.54, 46.80, 33.23, 31.61, 31.50, 31.47, 30.63, 30.60, 29.54, 29.51, 28.16, 28.13, 22.62, 22.57, 14.08, 14.06; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{154}\text{H}_{198}\text{S}_{18}\text{Na}$ , 2646.0358; found, 2646.0291 ( $[\text{M}+\text{Na}]^+$ ).

### $\beta$ -Ethano-linked tris(sexithienyl) cage (**2.3**)

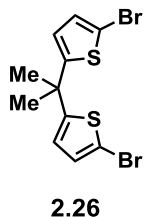


**2.3**

To a solution of  $\beta$ -ethano-linked cage **2.17** (329 mg, 0.125 mmol) in THF (30 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 1.3 mL, 1.95 mmol) at  $-78$  °C. After stirring for 1 h at  $-78$  °C, a THF solution of  $\text{Li}_2\text{CuCl}_4$ , which was freshly prepared from  $\text{CuCl}_2$  (519 mg, 3.86 mmol),  $\text{LiCl}$  (337 mg, 7.95 mmol) and THF (30 mL), was added dropwise. The reaction mixture was stirred for further 3 h at  $-78$  °C. After addition of methanol (30 mL), the resulting mixture was filtered through alumina short plug ( $\text{CH}_2\text{Cl}_2/n$ -hexane = 1/1) and then concentrated *in vacuo*. The crude product was purified by GPC followed by column chromatography (silica gel,  $\text{CH}_2\text{Cl}_2/n$ -hexane = 1/7) to afford the title compound **2.3** (101 mg, 31%) as an orange powder.

Mp: 216.0–216.3 °C;  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.97 (d,  $J$  = 3.8 Hz, 6H), 6.95 (d,  $J$  = 3.8 Hz, 6H), 6.84 (s, 6H), 2.89 (s, 12H), 2.66–2.62 (m, 24H), 2.37 (s, 6H), 1.58–1.51 (m, 24H), 1.42–1.24 (m, 72H), 0.89–0.85 (m, 36H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  153.05, 140.00, 139.70, 136.35, 135.57, 133.55, 130.47, 130.43, 129.96, 125.24, 124.39, 124.01, 46.27, 31.49, 31.48, 31.32, 30.62, 30.33, 29.54, 29.53, 28.11, 28.07, 24.70, 22.60, 22.59, 14.05; IR (KBr):  $\nu/\text{cm}^{-1}$  3071 (w), 2952 (s), 2925 (s), 2854 (s), 1519 (w), 1464 (m), 1376 (w), 1302 (w), 1244 (w), 1187 (w), 1157 (w), 1058 (w), 841 (w), 800 (m), 724 (w), 645 (w); UV-vis ( $\text{CH}_2\text{Cl}_2$ ):  $\lambda_{\text{max}}/\text{nm}$  (log  $\epsilon$ ) 418 (5.02), 377 (4.96), 270 (4.79), 228 (4.80); HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{154}\text{H}_{192}\text{S}_{18}\text{Na}$ , 2639.9889; found, 2639.9787 ( $[\text{M}+\text{Na}]^+$ ); Elemental analysis: calcd for  $\text{C}_{154}\text{H}_{192}\text{S}_{18}$ , C 70.59, H 7.39; found, C 70.28, H 7.32.

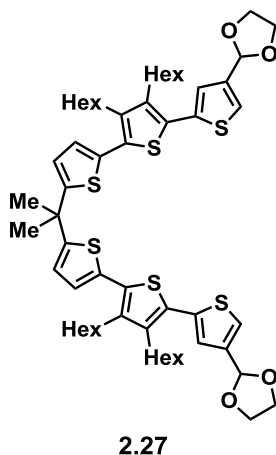
### 2,2-Bis(5-bromo-2-thienyl)propane (2.26)



To a solution of 2,2-bis(2-thienyl)propane **2.25** (4.857 g, 23.3 mmol) in DMF (25 mL) was added dropwise a solution of NBS (8.737 g, 49.1 mmol) in DMF (25 mL) at 0 °C. After completion of the addition, the reaction mixture was warmed up to room temperature and stirred for 2 h. Water (25 mL) was added to the reaction mixture, then the aqueous layer was extracted with diethyl ether (5 × 50 mL). The combined organic extracts were washed with water (3 × 30 mL) and brine (1 × 30 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, *n*-hexane) to afford the title compound **2.26** (8.401 g, 98%) as a colorless oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.85 (d, *J* = 3.8 Hz, 2H), 6.61 (d, *J* = 3.8 Hz, 2H), 1.76 (s, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 155.98, 129.20, 123.49, 110.46, 40.92, 32.33; MS (EI, rel intensity): *m/z* 364/366/368 (15/29/16, [M]<sup>+</sup>), 349/351/353 (51/100/54, [M-Me]<sup>+</sup>); Elemental analysis: calcd for C<sub>11</sub>H<sub>10</sub>Br<sub>2</sub>S<sub>2</sub>, C 36.09, H 2.75; found, C 36.32, H 2.76.

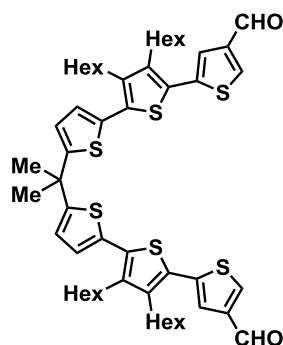
### 2,2-Bis(4''-(1,3-dioxolan-2-yl)-3',4'-dihexyl-2,2':5',2''-terthiophen-2-yl)propane (2.27)



A solution of dibromide **2.25** (975 mg, 2.66 mmol), boronic acid ester **S5** (4.138 g, 7.98 mmol), K<sub>2</sub>CO<sub>3</sub> (1.495 g, 10.8 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (200 mg, 0.173 mmol) in THF/toluene/water (3/3/1, 35mL) was heated to reflux and stirred for 2 days. After cooling to room temperature, water (20 mL) was added to the reaction mixture. The aqueous layer was extracted with diethyl ether (3 × 40 mL). The combined organic extracts were washed with water (1 × 20 mL) and brine (1 × 20 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/6) to afford the title compound **2.27** (2.526 g, 93%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>) δ 7.35 (m, 2H), 7.14 (d, *J* = 1.3 Hz, 2H), 6.92 (d, *J* = 3.7 Hz, 2H), 6.83 (d, *J* = 3.7 Hz, 2H), 5.88 (s, 2H), 4.12–4.00 (m, 8H), 2.67–2.64 (m, 8H), 1.88 (s, 6H), 1.56–1.50 (m, 8H), 1.43–1.26 (m, 24H), 0.90–0.86 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 154.86, 140.29, 140.24, 139.74, 137.30, 134.50, 130.36, 129.29, 125.01, 124.30, 123.55, 123.20, 100.43, 65.13, 40.60, 32.79, 31.48, 31.46, 30.72, 30.64, 29.55, 29.50, 28.12, 28.11, 22.62, 22.58, 14.06, 14.05; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>57</sub>H<sub>76</sub>O<sub>4</sub>S<sub>6</sub>Na, 1039.3960; found, 1039.3967 ([M+Na]<sup>+</sup>).

### 2,2-Bis(4''-formyl-3',4'-dihexyl-2,2':5',2''-terthiophen-2-yl)propane (2.28)

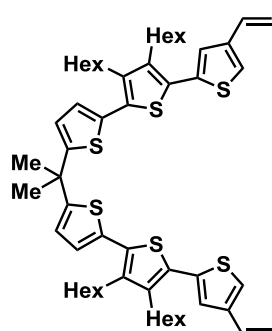


**2.28**

To a solution of bisacetal **2.28** (731 mg, 0.718 mmol) in THF (10 mL) was added a 6 M aqueous solution of HCl (10 mL) at room temperature and the resulting mixture was stirred overnight. The aqueous layer was extracted with diethyl ether (3 × 30 mL). The combined organic extracts were washed with water (1 × 20 mL) and brine (1 × 20 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/7) to afford the title compound **2.28** (638 mg, 96%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 9.88 (s, 2H), 8.05 (d, *J* = 1.4 Hz, 2H), 7.50 (d, *J* = 1.4 Hz, 2H), 6.95 (d, *J* = 3.7 Hz, 2H), 6.85 (d, *J* = 3.7 Hz, 2H), 2.69–2.65 (m, 8H), 1.89 (s, 6H), 1.57–1.50 (m, 8H), 1.42–1.26 (m, 24H), 0.90–0.86 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 184.79, 155.22, 143.08, 141.32, 139.93, 138.71, 135.98, 134.10, 131.40, 127.83, 125.37, 123.61, 123.07, 40.64, 32.74, 31.45, 31.44, 30.68, 30.63, 29.48, 28.10, 28.07, 22.57, 14.05, 14.02; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>53</sub>H<sub>68</sub>O<sub>2</sub>S<sub>6</sub>Na, 951.3436; found, 951.3441 ([M+Na]<sup>+</sup>).

### 2,2-Bis(3',4'-dihexyl-4''-vinyl-2,2':5',2''-terthiophen-2-yl)propane (2.29)

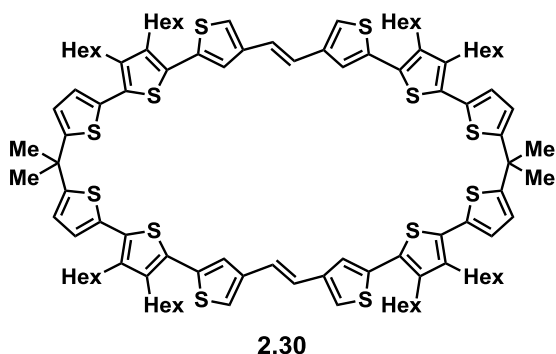


**2.29**

A mixture of dialdehyde **2.28** (637 mg, 0.685 mmol), KO<sup>*tert*</sup>-Bu (781 mg, 6.96 mmol) and MePPh<sub>3</sub>I (2.775 g, 6.87 mmol) was suspended in THF (15 mL) and stirred overnight at room temperature. After addition of a saturated aqueous solution of NH<sub>4</sub>Cl (15 mL), the aqueous layer was extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/20) to afford the title compound **2.29** (470 mg, 74%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.23 (d, *J* = 1.3 Hz, 2H), 7.12 (d, *J* = 1.3 Hz, 2H), 6.93 (d, *J* = 3.7 Hz, 2H), 6.83 (d, *J* = 3.7 Hz, 2H), 6.65 (dd, *J* = 10.9, 17.6 Hz, 2H), 5.57 (dd, *J* = 1.0, 17.6 Hz, 2H), 5.21 (dd, *J* = 1.0, 10.9 Hz, 2H), 2.69–2.65 (m, 8H), 1.88 (s, 6H), 1.57–1.52 (m, 8H), 1.43–1.26 (m, 24H), 0.90–0.86 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 154.89, 140.55, 140.31, 139.81, 136.84, 134.49, 130.96, 130.31, 129.39, 125.02, 123.55, 123.29, 122.19, 113.81, 40.60, 32.77, 31.51, 31.46, 30.75, 30.65, 29.55, 29.51, 28.12, 22.61, 22.59, 14.06, 14.04; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>55</sub>H<sub>72</sub>S<sub>6</sub>Na, 947.3850; found, 947.3862 ([M+Na]<sup>+</sup>).

### $\beta$ -Etheno-linked tetrakis(terthienyl) cycle (**2.30**)

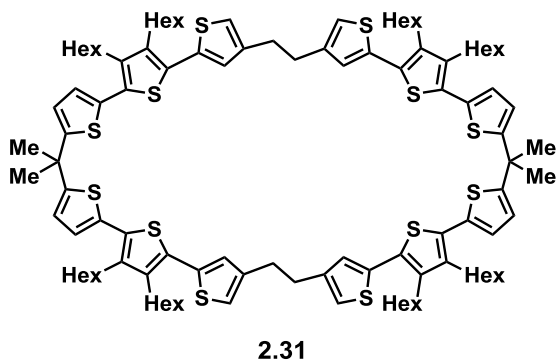


A solution of bis(terthienyl)methane **2.29** (106 mg, 0.115 mmol) and Grubbs 2nd generation catalyst (6 mg, 0.00742 mmol) in  $\text{CH}_2\text{Cl}_2$  (230 mL) was heated to reflux and stirred for 24 h. After cooling to room temperature, ethyl vinyl ether (0.5 mL) was added to the reaction mixture. The reaction mixture was concentrated, then filtered through silica gel short plug ( $\text{CH}_2\text{Cl}_2/n\text{-hexane} = 1/1$ ). The filtrate was concentrated and the crude product was purified by GPC to afford the title compound **2.30** (46 mg, 45%) as a

yellowish orange powder.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  7.24 (d,  $J = 1.4$  Hz, 4H), 7.21 (d,  $J = 1.4$  Hz, 4H), 6.93 (d,  $J = 3.7$  Hz, 4H), 6.89 (s, 4H), 6.87 (d,  $J = 3.7$  Hz, 4H), 2.71–2.65 (m, 16H), 1.89 (s, 12H), 1.59–1.53 (m, 16H), 1.42–1.29 (m, 48H), 0.90–0.87 (m, 24H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  155.10, 140.23, 139.89, 139.72, 136.71, 134.70, 130.28, 129.51, 124.82, 124.56, 123.33, 123.07, 121.01, 40.51, 32.46, 31.51, 31.47, 30.78, 30.66, 29.58, 29.52, 28.16, 28.10, 22.63, 22.60, 14.07; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{106}\text{H}_{136}\text{S}_{12}$ , 1792.7285; found, 1792.7302 ( $[\text{M}]^+$ ).

### $\beta$ -Ethano-linked tetrakis(terthienyl) cycle (**2.31**)



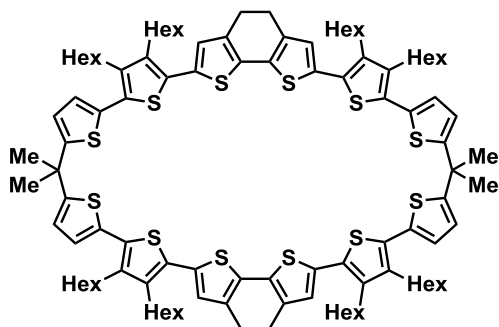
To a suspension of  $\beta$ -etheno-linked cycle **2.30** (312 mg, 0.174 mmol),  $\text{NaBH}_4$  (666 mg, 17.6 mmol) and  $\text{RuH}_2(\text{CO})(\text{PPh}_3)_3$  (127 mg, 0.138 mmol) in toluene (15 mL) was added water (1.6 mL, 88.8 mmol) at room temperature under hydrogen atmosphere. The reaction mixture was heated to 100 °C and stirred for 24 h. After cooling to room temperature, a 1 M aqueous solution of HCl (15 mL) was slowly added to the reaction mixture. The aqueous layer was extracted with diethyl ether ( $3 \times 20$  mL).

The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel,  $\text{CH}_2\text{Cl}_2/n\text{-hexane} = 1/6$ ) to afford the title compound **2.31** (190 mg, 61%) as a pale yellow powder.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.90–6.89 (m, 8H), 6.88 (d,  $J = 1.4$  Hz, 4H), 6.82 (d,  $J = 3.7$  Hz, 4H), 2.93 (s, 8H), 2.66–2.62 (m, 16H), 1.87 (s, 12H), 1.56–1.48 (m, 16H), 1.41–1.26 (m, 48H), 0.88–0.86 (m, 24H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  154.84, 142.02, 139.75, 139.68, 136.16, 134.73, 129.92, 129.89, 127.14, 124.80, 123.34, 120.34, 40.51, 32.56, 31.52, 31.47, 31.35, 30.68, 30.63, 29.56, 29.52, 28.14, 28.12, 22.63, 22.60, 14.08; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{106}\text{H}_{140}\text{S}_{12}$ , 1796.7598; found, 1796.7621 ( $[\text{M}]^+$ ).



### $\beta$ -Ethano-linked bis(sexithienyl) cycle (2.23)



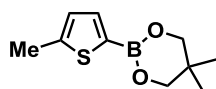
2.23

To a solution of  $\beta$ -ethano-linked cycle **2.31** (57 mg, 0.0317 mmol) in THF (6 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 0.21 mL, 0.315 mmol) at  $-78$  °C. After stirring for 1 h at  $-78$  °C, a THF solution of  $\text{Li}_2\text{CuCl}_4$ , which was freshly prepared from  $\text{CuCl}_2$  (88 mg, 0.655 mmol), LiCl (57 mg, 1.34 mmol) and THF (6 mL), was added dropwise. The reaction mixture was stirred for further 3 h at  $-78$  °C. After addition of methanol (6 mL), the resulting mixture was filtered through alumina short plug ( $\text{CH}_2\text{Cl}_2/n$ -hexane = 1/1) and then

concentrated *in vacuo*. The crude product was purified by GPC followed by column chromatography (silica gel,  $\text{CH}_2\text{Cl}_2/n$ -hexane = 1/7) to afford the title compound **2.23** (21 mg, 37%) as an orange powder.

Mp: 202.0–202.6 °C;  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.91 (d,  $J = 3.7$  Hz, 4H), 6.89 (d,  $J = 3.7$  Hz, 4H), 6.84 (s, 4H), 2.90 (s, 8H), 2.67–2.63 (m, 16H), 1.88 (s, 12H), 1.58–1.50 (m, 16H), 1.43–1.26 (m, 48H), 0.90–0.88 (m, 24H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  155.29, 140.01, 139.82, 135.51, 135.00, 133.19, 130.68, 130.42, 129.87, 125.12, 124.45, 123.01, 40.44, 32.21, 31.45, 30.63, 30.54, 29.54, 28.12, 28.08, 24.68, 22.61, 14.06; IR (KBr):  $\nu/\text{cm}^{-1}$  3067 (w), 2952 (s), 2926 (s), 2855 (s), 1519 (w), 1465 (m), 1378 (w), 1362 (w), 1300 (w), 1252 (w), 1219 (w), 1188 (w), 1158 (w), 1069 (w), 840 (w), 795 (m), 724 (w), 625 (w); UV-vis ( $\text{CH}_2\text{Cl}_2$ ):  $\lambda_{\text{max}}/\text{nm}$  (log  $\epsilon$ ) 418 (4.84), 367 (4.72), 271 (4.58), 231 (4.62); HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{106}\text{H}_{136}\text{S}_{12}$ , 1792.7285; found, 1792.7304 ( $[\text{M}]^+$ ); Elemental analysis: calcd for  $\text{C}_{106}\text{H}_{136}\text{S}_{12}$ , C 70.93, H 7.64; found, C 70.63, H 7.59.

### 5,5'-Dimethyl-2-(5-methylthiophen-2-yl)-1,3,2-dioxaborinane (2.32)



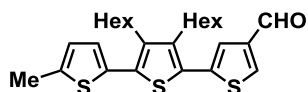
2.32

To a solution of 2-methylthiophene (5.0 mL, 52.0 mmol) in diethyl ether (80 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 38 mL, 57.0 mmol) at  $-78$  °C. After stirring for 1 h at 0 °C,  $\text{B}(\text{O}i\text{-Pr})_3$  (18 mL, 78.0 mmol) was added in one portion at  $-78$  °C.

The resulting mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (10.784 g, 104 mmol) was added, then the reaction mixture was stirred for an additional 1 h. After addition of a saturated aqueous solution of  $\text{NH}_4\text{Cl}$  (50 mL), the aqueous layer was extracted with diethyl ether ( $3 \times 50$  mL). The combined organic extracts were washed with water ( $1 \times 50$  mL) and brine ( $1 \times 50$  mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent *in vacuo*, reprecipitation from MeOH afforded the title compound **2.32** (7.292 g, 67%) as a colorless crystal.

Mp: 63.7–64.5 °C;  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  7.37 (d,  $J = 3.4$  Hz, 1H), 6.81–6.80 (m, 1H), 3.73 (s, 4H), 2.52 (d,  $J = 0.9$  Hz, 3H), 1.01 (s, 6H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  143.32, 136.02, 126.80, 140.15, 72.34, 32.02, 21.89, 15.36.

### 3',4'-Dihexyl-5''-methyl-4-formyl-2,2':5',2''-terthiophene (2.33)



2.33

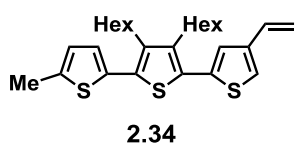
solution of 5'-bromo-3',4'-dihexyl-(2,2'-bithiophene)-4-carbaldehyde **2.32** (2.832 g, 6.41 mmol), 5,5-dimethyl-2-(5-methylthiophen-2-yl)-1,3,2-dioxaborinane (2.031 g, 9.67 mmol),  $\text{K}_2\text{CO}_3$  (1.786 g, 12.9 mmol) and  $\text{Pd}(\text{PPh}_3)_4$  (376 mg, 0.325 mmol) in THF/toluene/water (3/3/1, 28 mL) was heated to reflux and stirred for

2 days. After cooling to room temperature, water (20 mL) was added to the reaction mixture. The aqueous layer

was extracted with diethyl ether (3 × 30 mL). The combined organic extracts were washed with water (1 × 20 mL) and brine (1 × 20 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 1/25) to afford the title compound **2.33** (2.810 g, 96%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 9.88 (s, 1H), 8.05 (d, *J* = 1.4 Hz, 1H), 7.50 (d, *J* = 1.4 Hz, 1H), 6.92 (d, *J* = 3.4 Hz, 1H), 6.72–6.71 (m, 1H), 2.69–2.65 (m, 4H), 2.51 (d, *J* = 1.0 Hz, 3H), 1.58–1.54 (m, 4H), 1.44–1.24 (m, 12H), 0.91–0.87 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 184.81, 143.07, 141.29, 140.39, 139.64, 138.75, 135.96, 133.36, 131.66, 127.61, 126.14, 125.61, 123.06, 31.49, 31.45, 30.72, 30.69, 29.55, 29.51, 28.09, 22.60, 22.58, 15.29, 14.04, 14.02; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>26</sub>H<sub>34</sub>OS<sub>3</sub>, 481.1664; found, 481.1667 ([M+Na]<sup>+</sup>).

### 3',4'-Dihexyl-5''-methyl-4-vinyl-2,2':5',2''-terthiophene (**2.34**)

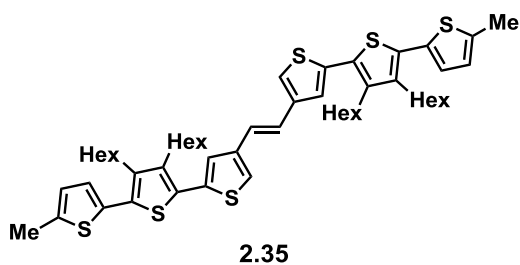


A mixture of aldehyde **2.33** (939 mg, 2.05 mmol), KO<sup>*tert*</sup>-Bu (1.161 g, 10.3 mmol) and MePPh<sub>3</sub>I (2.775 g, 6.87 mmol) was suspended in THF (15 mL) and stirred overnight at room temperature. After addition of a saturated aqueous solution of NH<sub>4</sub>Cl (15 mL), the aqueous layer was extracted with diethyl ether (3 × 20 mL). The

combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/20) to afford the title compound **2.34** (470 mg, 74%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.23 (d, *J* = 1.1 Hz, 1H), 7.13 (d, *J* = 1.1 Hz, 1H), 6.91 (d, *J* = 3.6 Hz, 1H), 6.71–6.70 (m, 1H), 6.66 (dd, *J* = 10.9, 17.6 Hz, 1H), 5.58 (dd, *J* = 1.0, 17.6 Hz, 1H), 5.21 (dd, *J* = 1.0, 10.9 Hz, 1H), 2.69–2.64 (m, 4H), 2.50 (d, *J* = 0.9 Hz, 3H), 1.59–1.52 (m, 4H), 1.42–1.29 (m, 12H), 0.91–0.88 (m, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 140.55, 140.36, 139.99, 139.54, 136.85, 133.80, 130.98, 130.55, 129.17, 125.83, 125.53, 123.31, 122.18, 113.82, 31.51, 30.76, 30.74, 29.58, 28.14, 28.11, 22.62, 15.29, 14.05; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>27</sub>H<sub>36</sub>S<sub>3</sub>Na, 479.1871; found, 479.1879 ([M+Na]<sup>+</sup>).

### 1,2-Bis(3',4'-dihexyl-5''-methyl-(2,2':5',2''-terthiophen)-4-yl)ethene (**2.35**)



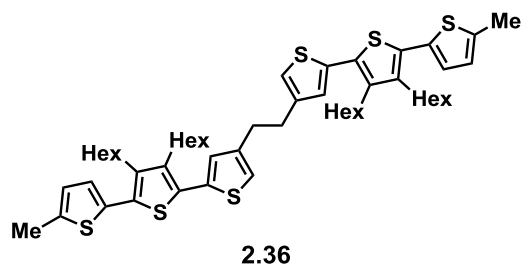
A solution of 3',4'-dihexyl-5''-methyl-4-vinyl-2,2':5',2''-terthiophene **2.34** (499 mg, 0.501 mmol) and Grubbs 2nd generation catalyst (10 mg, 0.0118 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (10 mL) was heated to reflux and stirred for 24 h. After cooling to room temperature, ethyl vinyl ether (0.5 mL) was added. The reaction mixture was then concentrated *in vacuo*. The crude product was purified by column chromatography (silica gel,

CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/20) to afford the title compound **2.35** (457 mg, 95%) as a pale yellow powder.

Mp: 88.0–88.6 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.30 (d, *J* = 1.4 Hz, 2H), 7.18 (d, *J* = 1.4 Hz, 2H), 6.92 (d, *J* = 3.4 Hz, 2H), 6.91 (s, 2H), 6.72–6.71 (m, 2H), 2.72–2.66 (m, 8H), 2.51 (d, *J* = 0.9 Hz, 6H), 1.61–1.53 (m, 8H), 1.44–1.31 (m, 24H), 0.91–0.89 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 140.37, 140.07, 140.03, 139.58, 137.06, 133.81, 130.60, 129.16, 125.84, 125.55, 123.28, 123.09, 121.95, 31.52, 30.77, 30.76, 29.60, 29.59, 28.18, 28.14, 22.65, 22.63, 15.31, 14.09, 14.07; UV-vis (CH<sub>2</sub>Cl<sub>2</sub>): λ<sub>max</sub>/nm (log ε) 361 (sh), 323 (4.69), 274 (4.61), 227 (4.49); HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>52</sub>H<sub>68</sub>S<sub>6</sub>Na, 907.3537; found, 907.3550 ([M+Na]<sup>+</sup>); Elemental analysis:

calcd for C<sub>52</sub>H<sub>68</sub>S<sub>6</sub>, C 70.53, H 7.74; found, C 70.53, H 7.67.

### 1,2-Bis(3',4'-dihexyl-5''-methyl-(2,2':5',2''-terthiophen)-4-yl)ethane (2.36)

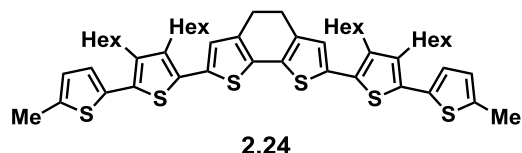


A suspension of 1,2-bis(3',4'-dihexyl-5''-methyl-(2,2':5',2''-terthiophen)-4-yl)ethane **2.35** (216 mg, 0.244 mmol), NaBH<sub>4</sub> (467 mg, 12.3 mmol) and RuH<sub>2</sub>(CO)(PPh<sub>3</sub>)<sub>3</sub> (89 mg, 0.0970 mmol) in toluene (10 mL) was added water (1.0 mL, 55.5 mmol) at room temperature under hydrogen atmosphere. The reaction mixture was heated to 100 °C and stirred for 24 h. After cooling to room temperature, a 1 M aqueous solution of

HCl (10 mL) was slowly added to the reaction mixture. The aqueous layer was extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/15) to afford the title compound **2.36** (207 mg, 95%) as a pale yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.96 (d, *J* = 1.4 Hz, 2H), 6.90 (d, *J* = 3.6 Hz, 2H), 6.89 (d, *J* = 1.4 Hz, 2H), 6.70–6.69 (m, 2H), 2.94 (s, 4H), 2.68–2.64 (m, 8H), 2.50 (d, *J* = 1.0 Hz, 6H), 1.58–1.51 (m, 8H), 1.41–1.26 (m, 24H), 0.91–0.87 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 142.09, 139.86, 139.85, 139.52, 136.30, 133.93, 130.17, 129.63, 126.88, 125.72, 125.50, 120.39, 31.51, 31.35, 30.74, 30.70, 29.58, 28.15, 28.13, 22.62, 15.29, 14.07, 14.05; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>52</sub>H<sub>70</sub>S<sub>6</sub>Na, 909.3694; found, 909.3705 ([M+Na]<sup>+</sup>).

### β-Ethano-linked sexithiophene (2.24)



To a solution of 1,2-bis(3',4'-dihexyl-5''-methyl-(2,2':5',2''-terthiophen)-4-yl)ethane **2.36** (86 mg, 0.0969 mmol) in THF (15 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 1.3 mL, 1.95 mmol) at –78 °C. After stirring for 1 h at –78 °C, a THF solution of Li<sub>2</sub>CuCl<sub>4</sub>, which was freshly

prepared from CuCl<sub>2</sub> (134 mg, 0.997 mmol), LiCl (84 mg, 1.98 mmol) and THF (15 mL), was added dropwise. The reaction mixture was stirred for further 3 h at –78 °C. After addition of methanol (30 mL), the resulting mixture was filtered through alumina short plug (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/1) and then concentrated *in vacuo*. The crude product was purified by GPC followed by column chromatography (silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/7) to give orange oil. Recrystallization from *n*-hexane/*i*-PrOH afforded the title compound **2.24** (34 mg, 40%) as an orange powder.

Mp: 79.8–80.6 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.93 (s, 2H), 6.91 (d, *J* = 3.5 Hz, 2H), 6.71–6.70 (m, 2H), 2.91 (s, 4H), 2.73–2.65 (m, 8H), 2.51 (d, *J* = 0.9 Hz, 6H), 1.62–1.53 (m, 8H), 1.46–1.25 (m, 24H), 0.92–0.89 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 139.92, 139.76, 139.73, 135.30, 133.91, 132.69, 130.59, 130.10, 129.71, 125.93, 125.72, 125.55, 31.52, 31.48, 30.73, 30.58, 29.59, 29.57, 28.26, 28.15, 24.56, 22.63, 22.61, 15.31, 14.08, 14.06; IR (KBr): ν/cm<sup>-1</sup> 3066 (w), 2950 (s), 2923 (s), 2854 (s), 2359 (w), 1523 (w), 1462 (m), 1376 (w), 1301 (w), 1220 (w), 1188 (w), 1161 (w), 1050 (w), 835 (w), 789 (m), 724 (w), 641 (w); UV-vis (CH<sub>2</sub>Cl<sub>2</sub>): λ<sub>max</sub>/nm (log ε) 437 (4.65), 312 (4.13), 263 (4.31), 229 (4.34); HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>52</sub>H<sub>68</sub>S<sub>6</sub>, 884.3640; found, 884.3650 ([M]<sup>+</sup>); Elemental analysis: calcd for C<sub>52</sub>H<sub>68</sub>S<sub>6</sub>, C 70.53; H 7.74; found, C 70.17, H 7.47.

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48, 6632–6635.

[19] Crystal data of **2.23**: Triclinic,  $P-1$ ,  $a = 14.1021(9) \text{ \AA}$ ,  $b = 14.4560(9) \text{ \AA}$ ,  $c = 15.5321(16) \text{ \AA}$ ,  $\alpha = 100.8821(15)^\circ$ ,  $\beta = 113.4271(16)^\circ$ ,  $\gamma = 110.000(3)^\circ$ ,  $V = 2529.1(3) \text{ \AA}^3$ ,  $Z = 1$ ,  $D_{\text{calc}} = 1.178 \text{ g/cm}^3$ ,  $R1 (I > 2\sigma(I)) = 0.0698$ ,  $wR2 (\text{all data}) = 0.1938$ ,  $\text{Refl./Param.} = 8891/538$ ,  $\text{GOF} = 1.133$ ,  $T = 200 \text{ K}$ . CCDC 1011130.

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## Chapter 3

### Synthesis of Quaterthiophene and Octithiophene-Bridged Cage Compounds

#### 3.1. Introduction

In the previous chapter, I presented the synthesis of sexithiophene-bridged cage compound by a synthetic sequence of 1) metathesis reaction of two tris(2-thienyl)methanes possessing  $\beta$ -vinyl groups at the terminal thiophenes, 2) hydrogenation of the resulting etheno linkers then 3) C–C bond formation between the neighboring thiophenes. Fortunately, this strategy could also apply to the syntheses of cyclic and linear analogues. To demonstrate the utility of this strategy, I next attempted to synthesize other oligothiophene-based cages by changing the number of bridged thiophene units more and less. Thus, I newly designed the quaterthiophene and octithiophene-bridged cage compounds **3.1** and **3.2** (Chart 3.1). These cages will give information of the limitation of the cage synthesis strategy depending on the thiophene chain length, which will evaluate the synthetic methodology as a tool for oligothiophene-based 3D architecture syntheses. In addition, those cages will give helpful information of the optical and electronic properties based on the cage structures.

In this chapter, I discuss the synthesis of quaterthiophene cage **3.1** and octithiophene cage **3.2**. Gratifyingly, smaller cage **3.1** could be obtained and characterized by spectroscopic and X-ray crystallographic analysis. Interestingly, the X-ray structure of **3.2** was found to be nearly three-fold with all-*syn*-arranged thiophene array in contrast to that of **3.1**. Although the formation of larger cage **3.2** could be confirmed by high resolution mass spectrometry, it has failed to isolate compound **3.2** in pure form, suggested by NMR spectroscopy. In addition the synthesis of linear analogue **3.3** and **3.4** are also presented (Chart 3.1).

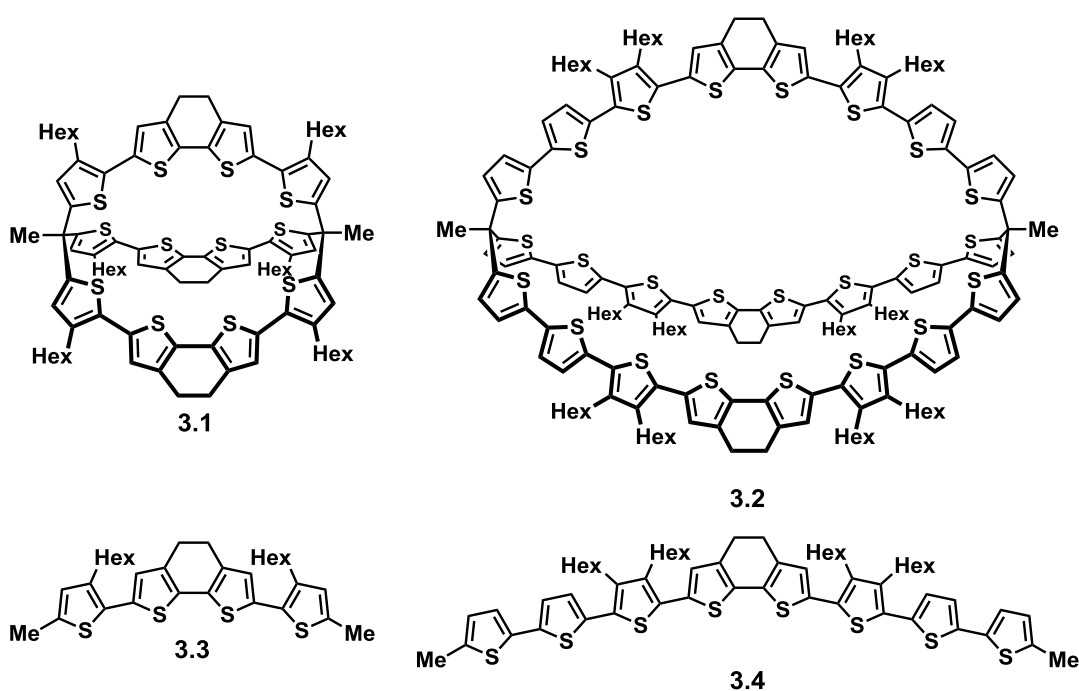
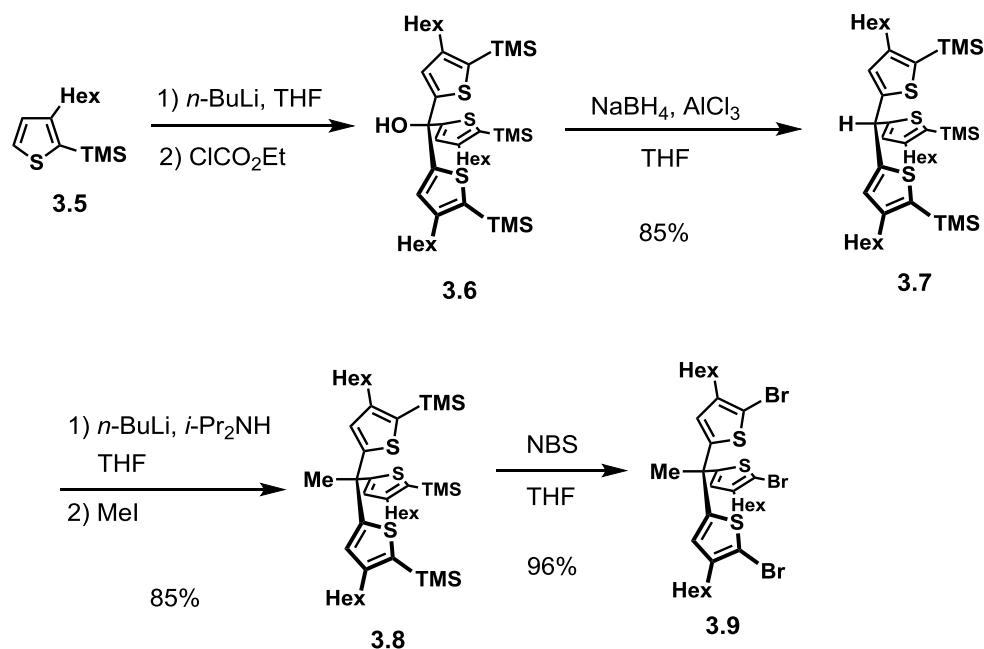


Chart 3.1.

## 3.2. Results and discussions

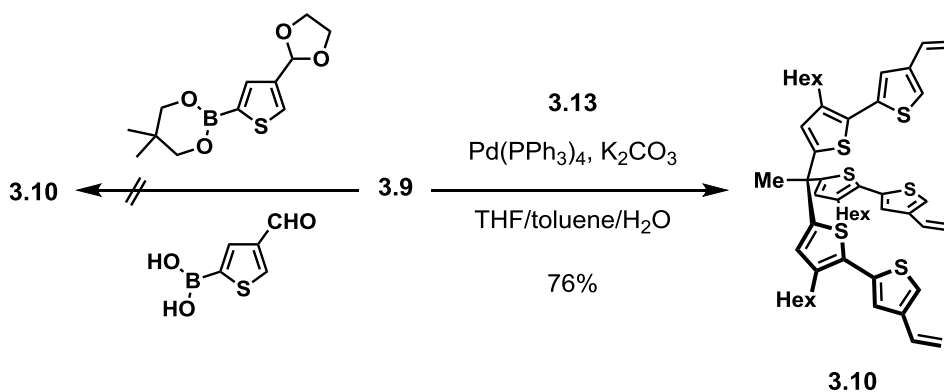
### 3.2.1 Synthesis of quaterthiophene-bridged cage **3.1**

Quaterthiophene cage **3.1** has hexyl chains on the one of two  $\beta$ -positions of the thiophene ring attached to bridge head carbons, or 4-position of the tris(2-thienyl)methane core. The position of the alkyl chain introduction was decided due to the synthetic difficulty of substitution on the central carbon of tris(3-alkyl-2-thienyl)ethanes, which would result from steric congestion.<sup>[1]</sup> Thus, 1,1,-tris(3-hexyl-2-thienyl)methane unit was needed to be newly synthesized from the known 4-hexylthiophene (Scheme 3.1). Lithiation of 2-trimethylsilyl-3-hexylthiophene **3.5**<sup>[2]</sup> was reacted with ethyl chloroformate to procedure alcohol **3.6**, which was covered into **3.7** by recution with a mixture of NaBH<sub>4</sub> and AlCl<sub>3</sub>.<sup>[3]</sup> Subsequent methylation and bromination proceeded in good yield to afford the **3.8** and **3.9**, respectively.

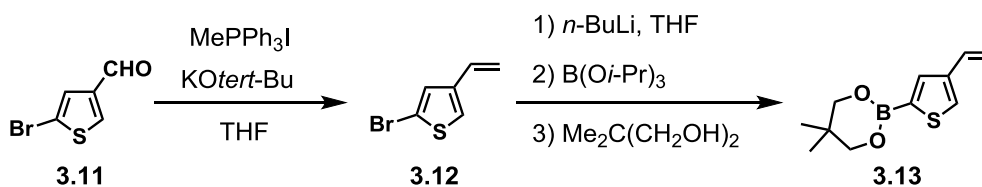


Scheme 3.1.

An attempt of introduction of 3-formyl-2-thienylboronic acid or 3-(1,3-dioxolan-2-yl)-2-thienylboronic acid ester did not afford the tris(bithienyl)methane **3.10** (Scheme 3.1). Compound **3.9** and deboronated thiophenes were recovered. In this reaction, employment of boronic ester of  $\beta$ -vinylated thiophene **3.13**, which was prepared from **3.11** (Scheme 3.3) and was found to be key coupling partner of **3.9** to give **3.10**.

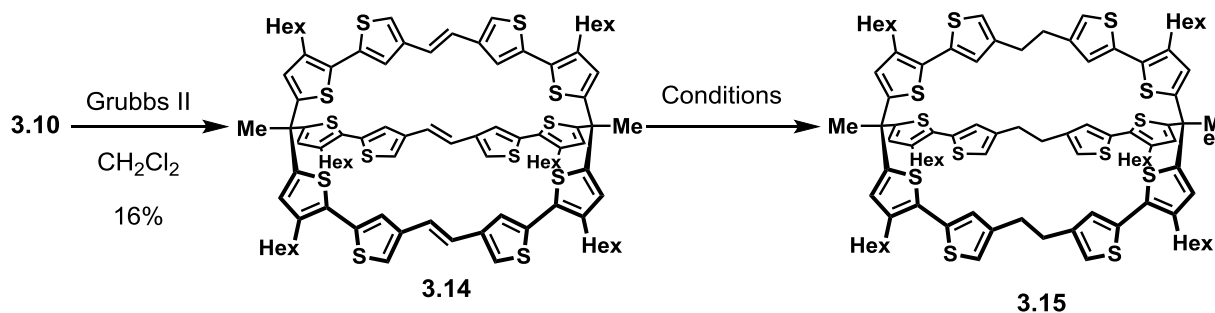


**Scheme 3.2.**



**Scheme 3.3.**

Metathesis cage formation could afford **3.14**. <sup>1</sup>H NMR spectrum of the product suggested all-(*E*)-olefin bridged cage skeleton. However, ruthenium catalyzed reduction could not cause hydrogenation under the same condition as described in the previous chapter. Increase of reagent equivalents (entry 2) or higher hydrogen pressure (entry 3) resulted in recovery or partial reduction. The condition in entry 3 sometimes led to the complete reduction, suggested by <sup>1</sup>H-NMR spectroscopy, however, I could not have found the reproducible reaction procedure under this condition yet. Reproducible reduction could be achieved by using a mixture of tosylhydrazone and sodium hydrogen sulfate. These combination produces diimide *in situ*, which would react immediately with **3.14** to give **3.15**. It should be pointed out that portionwise addition of TsNHNH<sub>2</sub>/NaHCO<sub>3</sub> was key to complete conversion otherwise the reduction will stop at partial conversion stage.<sup>[4]</sup> Thus addition of these reagent can successfully convert the double bonds completely to isolate **3.15** in 77% in spite of the necessity of portionwise addition of reagents (entry 4). Although the reason of failure of Ru-catalyzed hydrogenation is unclear, the replacement by cheaper reagent will make this methodology more cost-effective and allow us to prepare large amount of cage compounds.



**Scheme 3.4.**

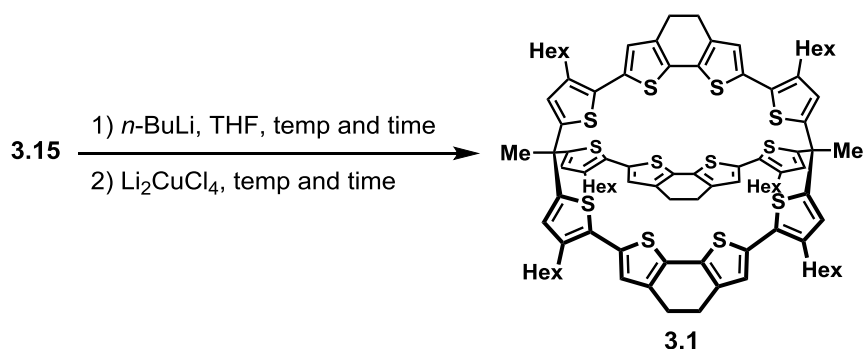


**Table 3.1.** Reaction conditions of hydrogenation in Scheme 3.4.

entry	conditions	reaction pressure	results
1	1.2 eq. RuH <sub>2</sub> (CO)(PPh <sub>3</sub> ) <sub>3</sub> , NaBH <sub>4</sub> , H <sub>2</sub> O, toluene	1 atm (H <sub>2</sub> )	partial reduction
2	3.0 eq. RuH <sub>2</sub> (CO)(PPh <sub>3</sub> ) <sub>3</sub> , NaBH <sub>4</sub> , H <sub>2</sub> O, toluene	1 atm (H <sub>2</sub> )	partial reduction
3	3.0 eq. RuH <sub>2</sub> (CO)(PPh <sub>3</sub> ) <sub>3</sub> , NaBH <sub>4</sub> , H <sub>2</sub> O, toluene	4 atm (H <sub>2</sub> )	partial reduction
4	30 eq. TsNHNH <sub>2</sub> , <sup>[1]</sup> 30 eq. NaHCO <sub>3</sub> , <sup>[1]</sup> MeOC <sub>2</sub> H <sub>4</sub> OH, toluene	1 atm (N <sub>2</sub> )	<b>3.15</b> (77%)

[1] 15 eq. of reagents were added after 12 h since the first addition of 15 eq of the same reagents.

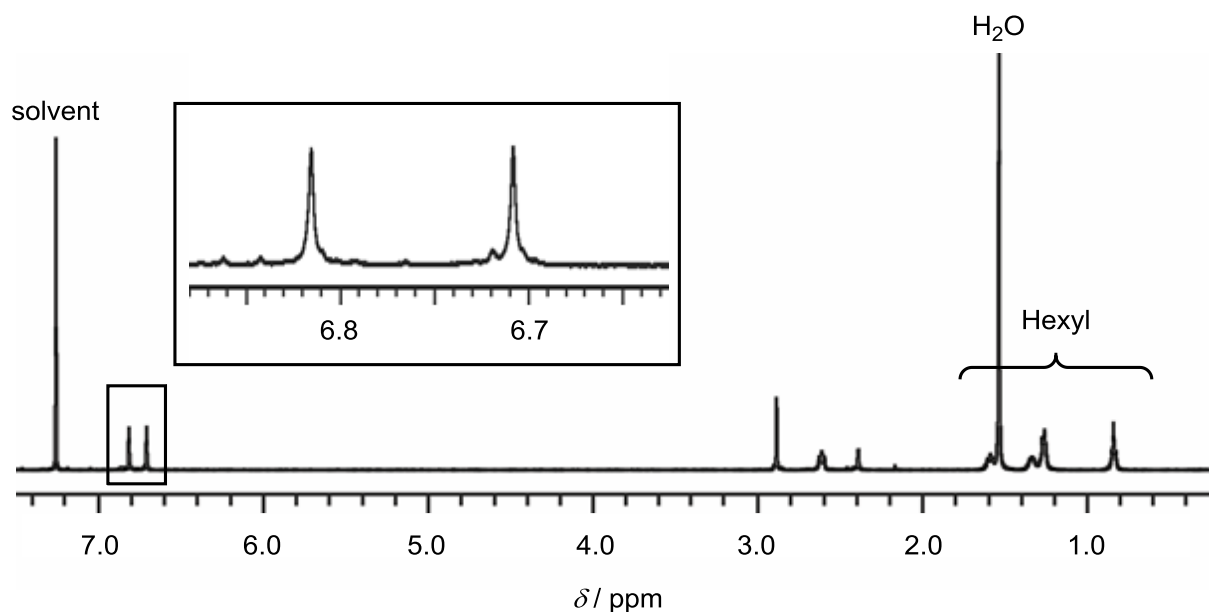
The C–C bond formation reaction was then conducted under the established condition (Scheme 3.5 and Table 3.2 entry 1). Unfortunately, this condition employed for sexithiophene-bridged cage synthesis could not convert **3.15** into **3.1**, or lead to partial bond formation, which was suggested by high resolution mass spectrometry. In this case, reaction temperature was found to be important. Thus, lithiation temperature was elevated from  $-78\text{ }^{\circ}\text{C}$  to  $0\text{ }^{\circ}\text{C}$  resulted in complete bond formation with moderate isolate yield of **3.1** (entry 2). The reason of successful conversion under higher temperature might be rationalized by closely located anion site in the small cage **3.15**, which raised the energy of lithiated intermediate. On the other hand, elevation temperature at oxidation step led to poor production of **3.1** and no other isolable product was obtained. The resulting quaterthiophenes would be decomposed under such high temperature condition in the presence of copper salt.

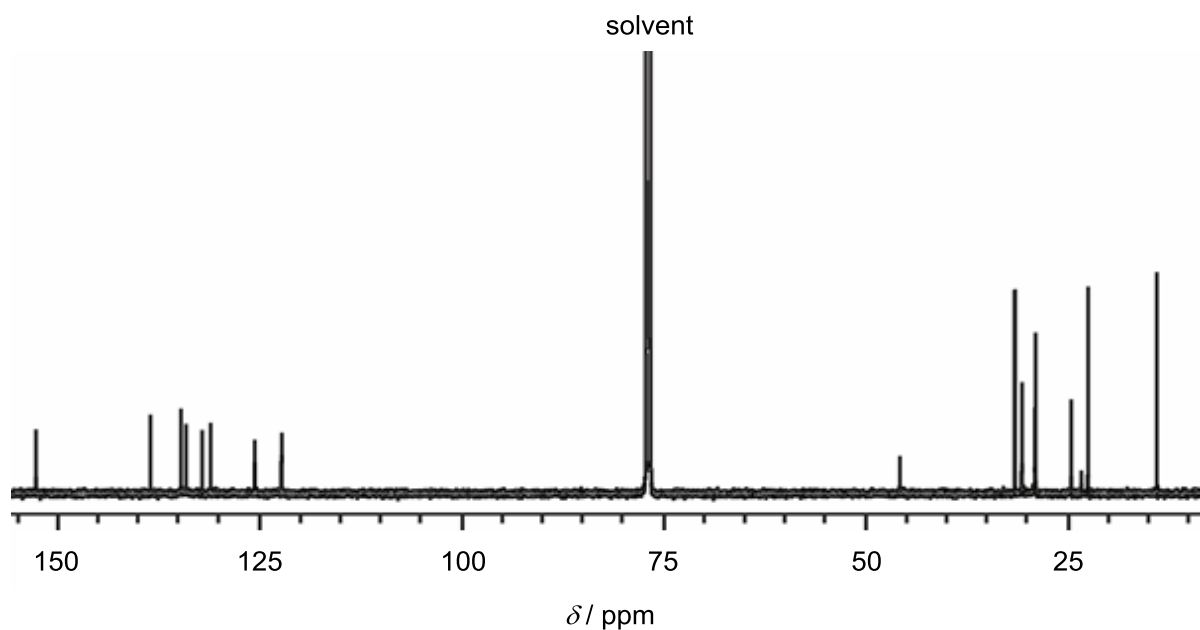
**Scheme 3.5.**

**Table 3.2.** Reaction conditions of quaterthiophene construction in Scheme 3.5.

entry	temp and time		results
	lithiation	oxidation	
1	-78 °C, 1 h	-78 °C, 3 h	<b>3.15</b> and partially coupled cage(s)
2	-78 °C then 0 °C, 1 h	-78 °C, 3 h	<b>3.1</b> (27%)
3	-78 °C then 0 °C, 1 h	0 °C, 3 h	<b>3.1</b> (4%)

The formation of **3.1** was confirmed by  $^1\text{H}$ ,  $^{13}\text{C}$  NMR spectroscopy, high resolution mass spectrometry and X-ray crystallographic analysis. The thiophene peaks of **3.1** in  $^1\text{H}$  NMR spectrum appeared as two singlets at aromatic region.  $^{13}\text{C}$ -NMR also showed only 12 signals for thiophene rings in aromatic region. These facts support three-fold symmetric structure of **3.1** in solution similar to sexithiophene-bridged cage. The observed  $m/z$  value (1620.5094) agreed well with calculated one (1620.5112). These facts strongly suggested the formation of compound **3.1**, which was further supported by X-ray crystallographic analysis in the next section.

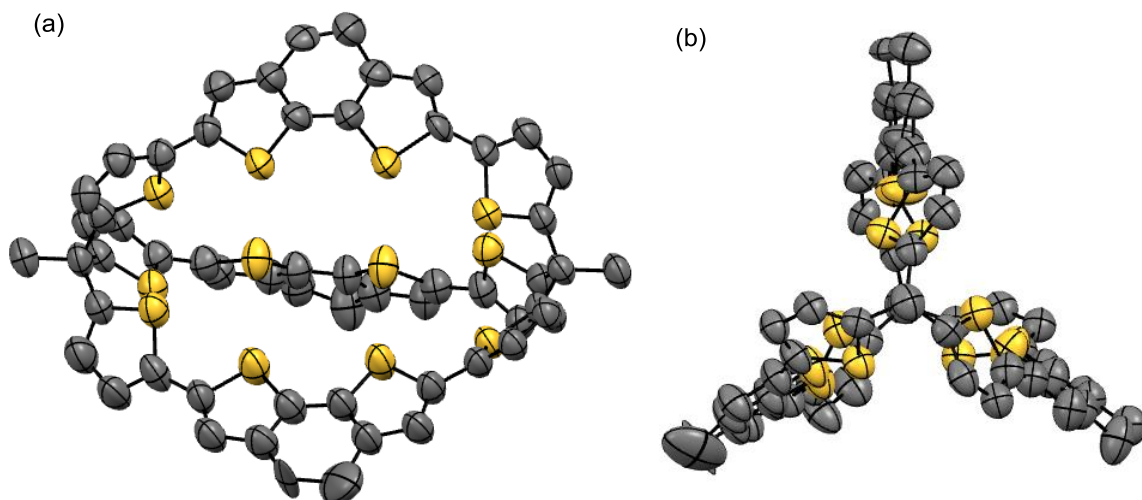
**Figure 3.1**  $^1\text{H}$ -NMR spectrum of **3.1** (500 MHz, 30 °C, in  $\text{CDCl}_3$ ). (Inset) Thiophene signals in the aromatic region.



**Figure 3.2.** <sup>13</sup>C-NMR spectrum of **3.1** (125 MHz, 30 °C, in CDCl<sub>3</sub>). (Inset) Thiophene signals in the aromatic region.

### 3.2.2. Crystal structure of **3.1**

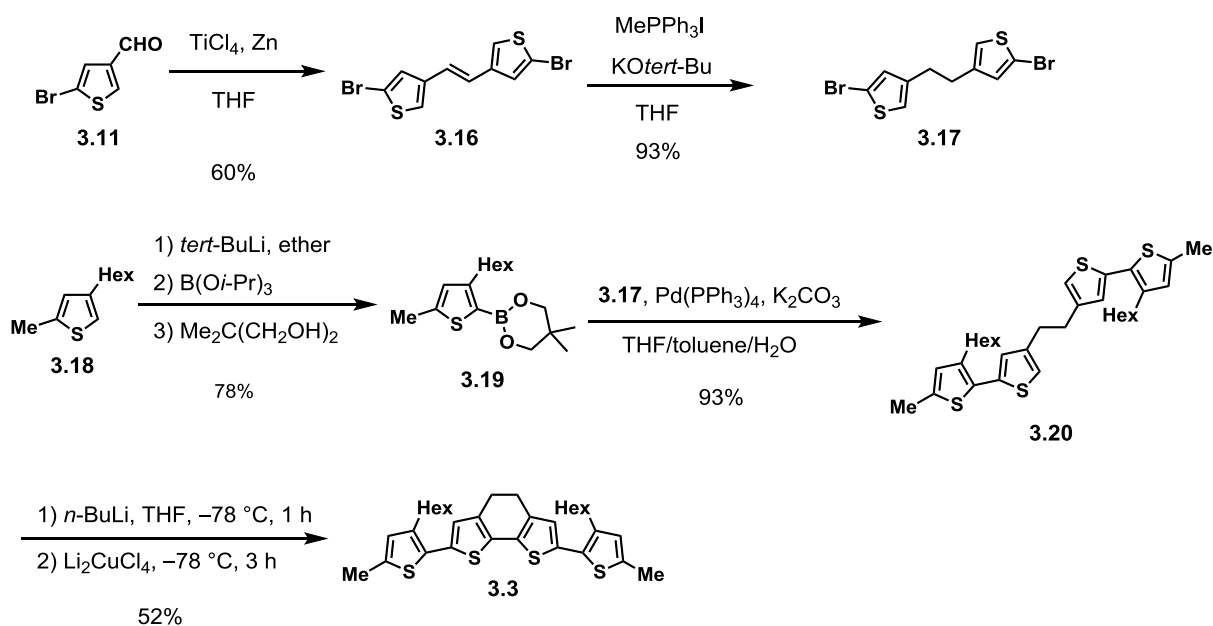
A single crystal suitable for X-ray analysis could be obtained from a mixed solvent of toluene and acetonitrile.<sup>[5]</sup> Although the quality of the crystal is not so high that some of the hexyl chains as well as β-ethano linker at the quaterthiophene chain could not be determined, the cage architecture formed by three quaterthiophenes could be observed. On the contrary to the crystal of sexithiophene cage, the bridged thiophene arranged nearly three-fold symmetric. This structural feature can be seen in the crystal structure of previously synthesized tris(2-thienyl)methane-based cage compounds.<sup>[6]</sup> The resulting all *cisoid* form would reflect the high molecular strain in **3.1**. The presence of alkyne bridges would contribute to such a thiophene arrangement by fixation of central bithiophene moiety as *syn*-manner. Similar tendency of thiophene arrangement was observed the series of thiophene containing small macrocycles.<sup>[7],[8],[9]</sup> Being different from sexithiophene cage, S-S contacts are observed in all the thiophenes attached to the bridgehead carbon. The large dihedral angle between nearly planar central bithiophenes and adjacent thiophene ring (27.1–42.9°) should reflect molecular strain in **3.1** as similar to sexithiophene cage. The smaller value of **3.1** is probably because the higher skeleton rigidity of **3.1** prevents from structural deformation by the effect of crystal packing. Neither solvent molecule nor alkyl chain was observed in the central void probably due to the small cavity size of **3.1**.



**Figure 3.3.** ORTEP drawings of **3.1** at the 50% probability level [(a) and (b)]. Hexyl chains are omitted for clarity.

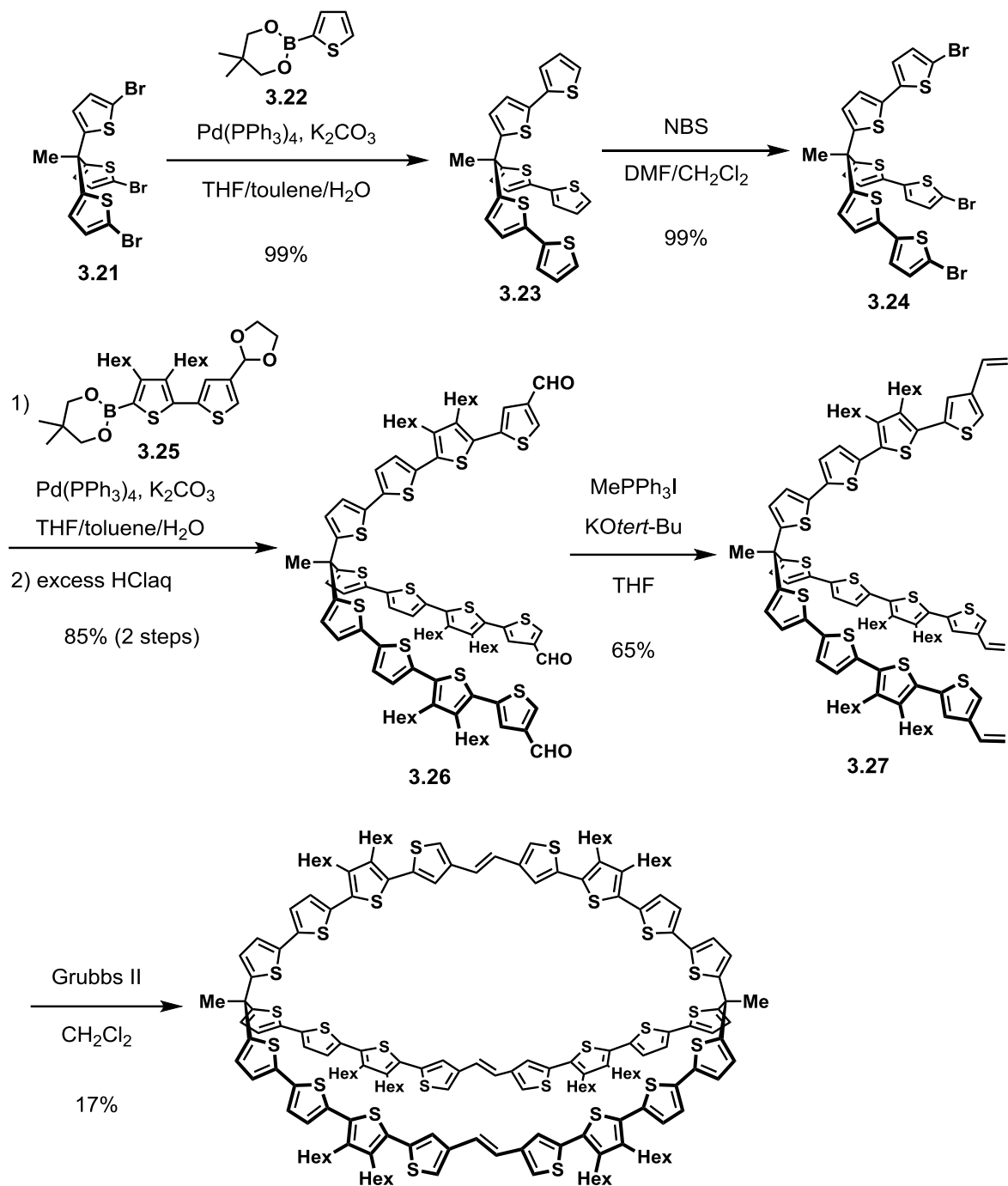
### 3.2.3. Synthesis of linear quaterthiophene

In the same manner, linear quaterthiophene **3.3** was also synthesized. Since I found the cheap and efficient reduction method of TsNHNH<sub>2</sub> and NaHCO<sub>3</sub> system, the synthesis was started from McMurry coupling of 5-bromo-3-thiophenecarbaldehyde (Scheme 3.6). The reduction of resulting **3.16** proceeded smoothly under the diimide condition to afford **3.17**. It should be mentioned that the bromine groups at  $\alpha$ -position was intact under this reduction condition. Thus, resulting dibromide **3.17** was subjected into Suzuki-Miyaura cross-coupling reaction with boronic ester **3.19**<sup>[10]</sup> generate **3.20**. The C–C bond formation undergo smoothly to produce **3.3** without elevating temperature unlike the corresponding cage **3.1**.



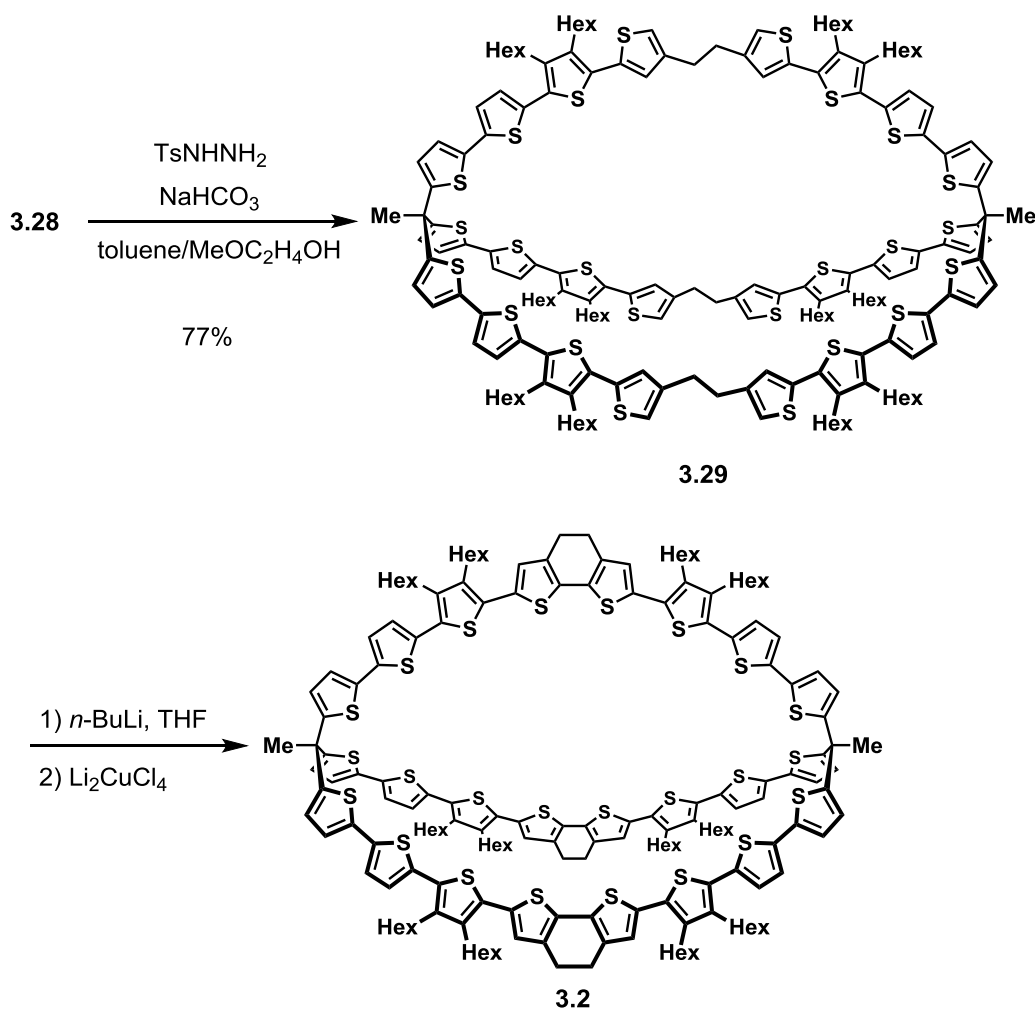
**Scheme 3.6.**

3.4. Synthetic attempt toward octithiophene-bridged cage **3.2** and synthesis of linear **3.4**



**3.28**  
Scheme 3.7.

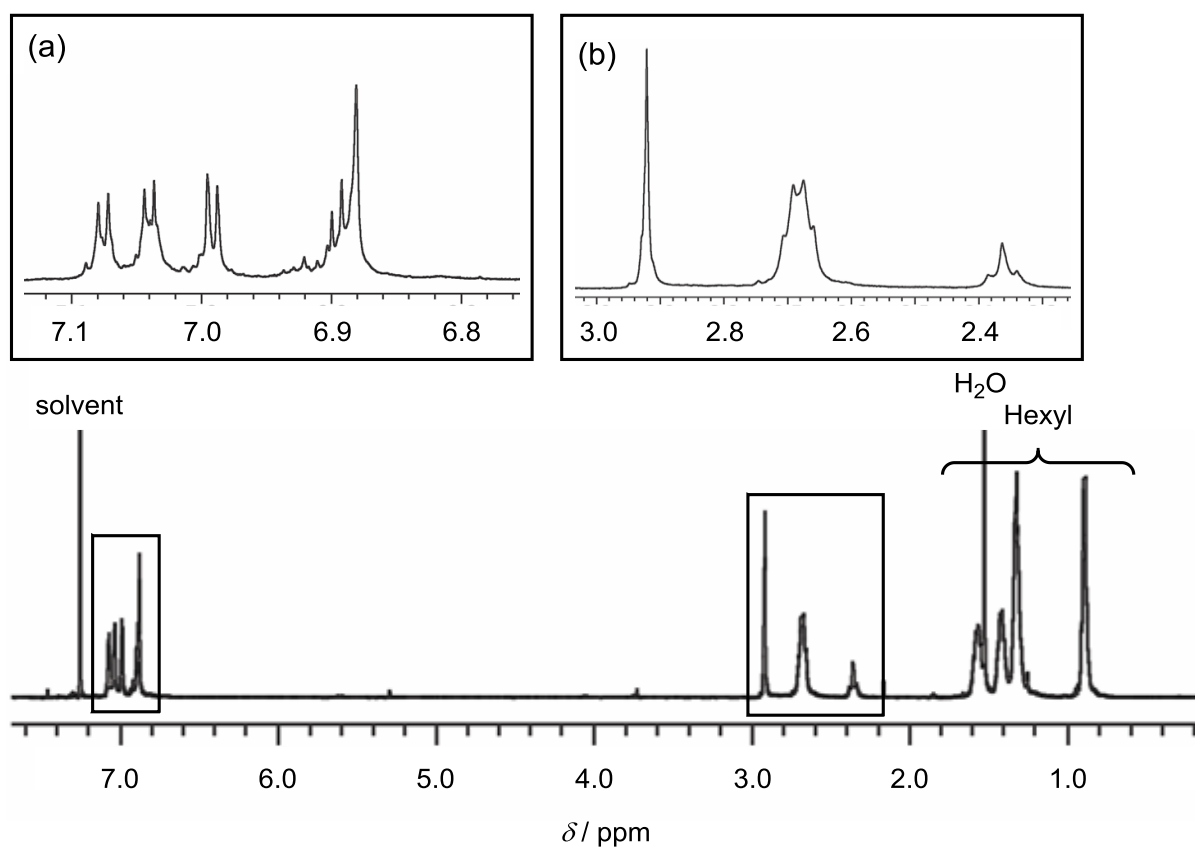
The synthesis of octithiophene cage **3.2** was started from **3.21** by elongation one thiophene unit for each chain by Suzuki-Miyaura coupling reaction with 2-thienylboronic acid ester **3.22** to produce tris(bithienyl)methane **3.23** (Scheme 3.7). Following bromination was conducted the same procedure described in the previous section except for using  $\text{CH}_2\text{Cl}_2$  as a co-solvent due to the bad solubility of **3.23** to DMF. Subsequent Suzuki-Miyaura coupling reaction with boronic ester **3.25** prepared in the previous section proceeded smoothly. Wittig reaction could be successfully applied to compound **3.26** to afford desired trivinyl compound **3.27**. It should be mentioned that the product yield of the metathesis reaction of **3.28** dropped 17%. This is probably due to increase of the thiophene chain flexibility, which caused not only alleviation of molecular strain in cage form, but also allowance of conformational freedom by thiophene rotation, which led to generation of oligomers and/or polymers. Therefore, fabrication of larger oligothiophene-based cages will be suffered from production of larger amount of oligomers and be required to employ additional strategy for efficient cage structure construction.



Scheme 3.8.

Hydrogenation of **3.28** and subsequent thiophene–thiophene bond formation reaction were carried out in the established condition (Scheme 3.8). The solution of the product was highly fluorescent and high resolution mass spectra supported the formation of three C–C bond formation, or disappearance of six hydrogen atoms (observed

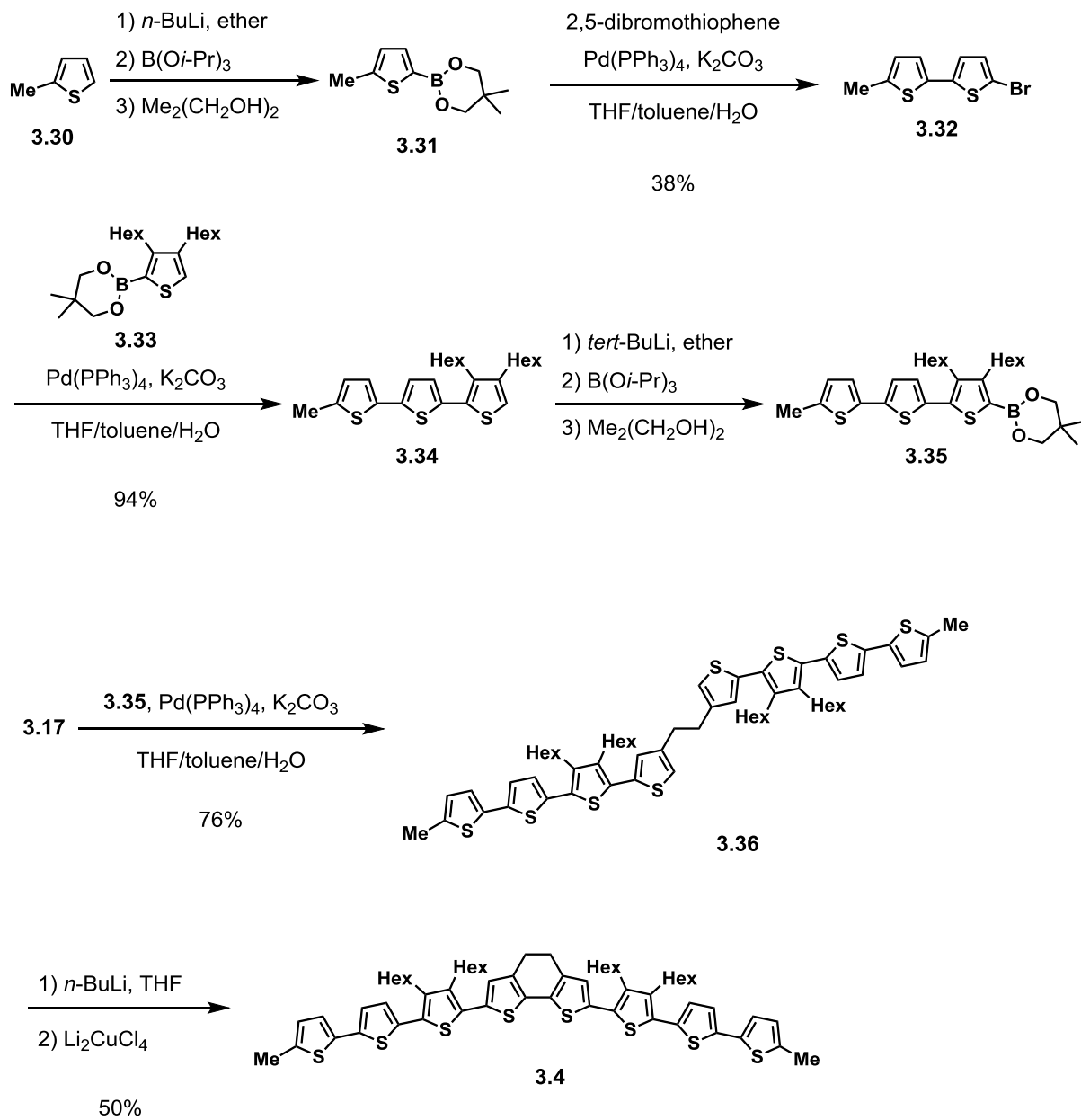
$m/z$ : 3131.9156; calcd for  $[3.2+Na]^+$ : 3131.9152). However,  $^1H$ -NMR spectrum could not give enough information of the structure of the product. The signals in the aromatic region seemed to appear 4 sets of doublets and one singlet, but the observed signals were unusually broadened if coming from thiophene protons. In addition, the bridge head methyl group was observed as triplet-like signal, not a sharp singlet. Observation of such broaden or split peaks seemed to be curious because the thiophene chains in **3.2** should be "flexible" and should adopt three-fold structure in solution as observed in the spectra of the other three-thiophene-bridged cages. The  $^{13}C$ -NMR spectrum of the product showed so bad S/N ratio that the peaks could not be picked up even though using the sample that gave clear  $^1H$ -NMR spectrum. In this case, a combination of GPC and silica-gel column chromatography was not effective to isolate **3.2** as a pure form. Unfortunately, a single crystal of the product could not be obtained yet under various solvent conditions. Therefore, at this point, the isolation of **3.2** has not been achieved and are still remains to be solved.



**Figure 3.4.**  $^1H$  NMR spectrum of the product. (Inset a) Aromatic region. (Inset b) Aliphatic region.

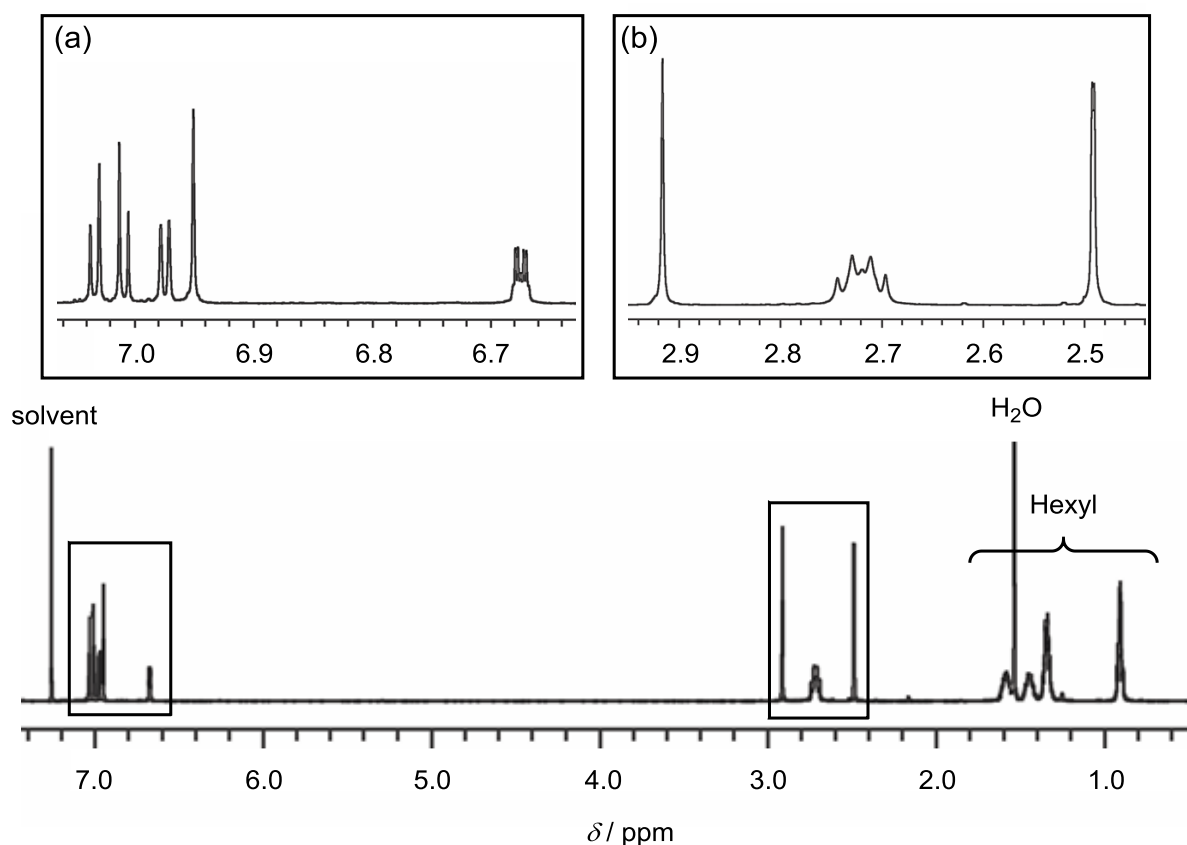
### 3.2.5. Synthesis of linear octithiophene

It should be noted that the linear octithiophene **3.4** could be synthesized by the same synthetic method and be characterized by NMR spectroscopy and mass spectrometry technique (Scheme 3.9). This suggests that the failure for the identification of **3.2** should not be brought about just octithiophene but about cage molecular architecture itself.



Scheme 3.9.





**Figure 3.5.**  $^1\text{H}$  NMR spectrum of the product. (Inset a) Aromatic region. (Inset b) Aliphatic region.

### 3.5 Conclusion

The synthetic protocol described in the previous chapter was applied to the synthesis of smaller and larger cages **3.1** and **3.2**. Quaterthiophene cage **3.1** was successfully synthesized and characterized by NMR spectroscopy, high resolution mass spectrometry and X-ray crystallographic analysis. The X-ray structure of **3.1** was nearly three-folded one, which would reflect the higher molecular strain compared to sexithiophene cage. Although the full characterization of octithiophene-bridged cage yet, high resolution mass spectrometry proved the formation of **3.2**. These results demonstrate the versatility of the synthetic method for oligothiophene-containing cage molecule synthesis. It should be pointed out that this methodology requires only  $\beta$ -vinyl groups to construct strained oligothiophenes. This means that the strategy should not be limited to the synthesis of cage compounds, but could be employed for the creation of novel strained oligothiophene-based materials that would not be obtained by conventional methods. The newly developed oligothiophenes will provide deep understanding of structure-property relationships of such the unusual  $\pi$ -systems. Therefore, this newly developed synthetic strategy can be considered as one of the promising synthetic tools and be expected to be utilized for the creation of various molecular architectures containing strained oligothiophenes.

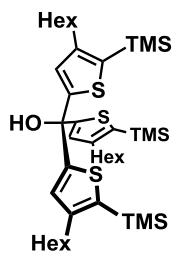
### 3.4. Experimental Section

#### 3.4.1 General

All experiments with moisture- or air-sensitive compounds were conducted in anhydrous solvents under a nitrogen atmosphere in well-dried glassware. Anhydrous dichloromethane and tetrahydrofuran (THF) were purchased from Kanto Chemical Co., Inc. and used without further purification. Other anhydrous solvents were prepared by distillation over calcium hydride. Column chromatography were performed on a silica gel (Silica gel 60N, Kanto Chemical Co., Inc.) or alumina (Aluminium oxide 90, Merck). Melting points were taken on a Yanako MP 500D apparatus and are uncorrected. Preparative gel permeation chromatography (GPC) was performed on a recycling HPLC (JAI LC-9201 equipped with JAIGEL 1H and JAIGEL 2 H columns) with using chloroform as an eluent. Infrared spectra were recorded on a JASCO FT/IR-660M spectrometer. UV-vis absorption spectra were measured on a JASCO V-570 spectrometer. Fluorescence spectra were measured on a JASCO FP-6300 spectrofluorometer.  $^1\text{H-NMR}$  and  $^{13}\text{C-NMR}$  spectra were recorded on a JEOL ECA500 spectrometer. The chemical shifts were recorded by using tetramethylsilane (0.00 ppm) as an internal reference for  $^1\text{H-NMR}$  spectra and  $\text{CDCl}_3$  (77.00 ppm) for  $^{13}\text{C-NMR}$  spectra. Mass spectra were recorded on a Shimadzu GCMS-QP2010, a Shimadzu AXIMA-CFR and a ThermoFisher Scientific LTQ Orbitrap-XL mass spectrometer for EI, MALDI-TOF and ESI-Orbitrap MS, respectively. The high-resolution mass spectra (HRMS) were analyzed by using ThermoXcalibur 2.1.0.1140 software. Data collection for X-ray crystal analysis was performed on a Rigaku/Varimax diffractometer (Mo-K $\alpha$ ,  $\lambda = 0.71075 \text{ \AA}$ ). The structure was solved with direct methods and refined with full-matrix least-squares (teXsan). Cyclic voltammetry measurement was conducted with a BAS CV-50W electrochemical analyzer in a 0.1 M *n*-Bu $_4$ NPF $_6$  dichloromethane solution at room temperature. Elemental analyses were performed at the Elemental Analysis Center in the Faculty of Science, Osaka University.

#### 3.4.2. Synthetic procedures

##### Tris(4-hexyl-5-trimethylsilyl-2-thienyl)carbinol (**3.6**)<sup>[11]</sup>



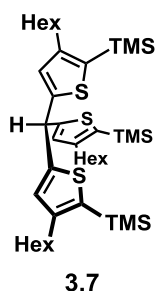
**3.6**

To a solution of 3-hexyl-2-trimethylsilylthiophene **3.5** (12.523 g, 52.1 mmol) in THF (70 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 34.5 mL, 51.8 mmol) at  $-78 \text{ }^\circ\text{C}$ . After stirring for 30 min at  $0 \text{ }^\circ\text{C}$ , a solution of ethyl chloroformate (1.5 mL, 15.6 mmol) was added dropwise at  $-78 \text{ }^\circ\text{C}$ . The resulting mixture was warmed up to room temperature and stirred for 1 h. After addition of a saturated aqueous solution of  $\text{NH}_4\text{Cl}$  (30 mL), the aqueous layer was extracted with diethyl ether ( $3 \times 50 \text{ mL}$ ). The combined organic extracts were washed with water ( $1 \times 30 \text{ mL}$ ) and brine ( $1 \times 30 \text{ mL}$ ), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and

removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel,  $\text{CH}_2\text{Cl}_2/n$ -hexane = 1/6) to afford the title compound **3.6** (9.580 g, 82%) as a pale yellow oil.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.90 (s, 3H), 3.09 (s, 1H), 2.58 (t,  $J = 7.7 \text{ Hz}$ , 6H), 1.54 (quin,  $J = 7.7 \text{ Hz}$ , 6H), 1.35–1.24 (m, 18H), 0.87 (t,  $J = 6.7 \text{ Hz}$ , 9H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  154.77, 149.89, 132.75, 129.42, 76.49, 31.77, 31.66, 31.53, 29.21, 22.62, 14.06, 0.42; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{40}\text{H}_{70}\text{OS}_3\text{Si}_3\text{Na}$ , 769.3789; found, 769.3798 ( $[\text{M}+\text{Na}]^+$ ).

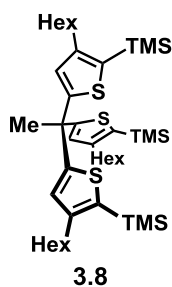
### Tris(4-hexyl-5-trimethylsilyl-2-thienyl)methane (3.7)



To a suspension of  $\text{NaBH}_4$  (2.427 g, 64.2 mmol) in THF (35 mL) was added  $\text{AlCl}_3$  (4.265 g, 32.0 mmol) in one portion at 0 °C. After stirring for 5 min at 0 °C, a solution of tris(4-hexyl-5-trimethylsilyl-2-thienyl)carbinol **3.6** (9.580 g, 12.8 mmol) in THF (35 mL) was added dropwise at 0 °C. The reaction mixture was warmed up to room temperature and stirred for 30 min. After addition of water (30 mL) at 0 °C (**CATION!!** Highly exothermic reaction), the aqueous layer was extracted with diethyl ether ( $3 \times 50$  mL). The combined organic extracts were washed with water ( $1 \times 30$  mL) and brine ( $1 \times 30$  mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent, the crude product was purified by column chromatography (silica gel, *n*-hexane) to afford the title compound **3.7** (5.834 g, 62%) as a pale yellow oil.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.85 (d,  $J = 0.6$  Hz, 3H), 5.91 (d,  $J = 0.6$  Hz, 1H), 2.57 (t,  $J = 7.7$  Hz, 6H), 1.57-1.51 (m, 6H), 1.35-1.25 (m, 18H), 0.88 (t,  $J = 6.9$  Hz, 9H), 0.29 (s, 27H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  151.03, 150.08, 131.58, 129.25, 43.00, 31.79, 31.61, 31.55, 29.28, 22.63, 14.07, 0.50; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{40}\text{H}_{70}\text{S}_3\text{Si}_3\text{Na}$ , 753.3840; found, 753.3850 ( $[\text{M}+\text{Na}]^+$ ).

### 1,1,1-Tris(4-hexyl-5-trimethylsilyl-2-thienyl)ethane (3.8)

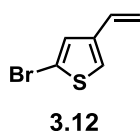


To a solution of tris(4-hexyl-5-trimethylsilyl-2-thienyl)methane **3.7** (5.834 g, 7.98 mmol) and *i*- $\text{Pr}_2\text{NH}$  (1.7 mL, 12.1 mmol) in THF (15 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 6.0 mL, 9.00 mmol) at -78 °C. The resulting mixture was warmed up to room temperature and stirred for 1 h. MeI (1.0 mL, 16.1 mmol) was added dropwise and the reaction mixture was stirred for further 1 h. After addition of a saturated aqueous solution of  $\text{NH}_4\text{Cl}$  (10 mL), the aqueous layer was extracted with diethyl ether ( $3 \times 20$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL), then dried over anhydrous

$\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, *n*-hexane) to afford the title compound **3.8** (5.200 g, 87%) as a pale yellow oil.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.72 (s, 3H), 2.56 (t,  $J = 7.6$  Hz, 6H), 2.22 (s, 3H), 1.56-1.50 (m, 6H), 1.34-1.24 (m, 18H), 0.87 (t,  $J = 6.7$  Hz, 9H), 0.29 (s, 27H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ):  $\delta$  157.39, 149.63, 130.98, 129.33, 46.79, 33.85, 31.79, 31.60, 31.55, 29.20, 22.62, 14.07, 0.52; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{41}\text{H}_{72}\text{S}_3\text{Si}_3\text{Na}$ , 767.3996; found, 767.4006 ( $[\text{M}+\text{Na}]^+$ ).

### 2-Bromo-4-vinylthiophene (3.12)<sup>[12]</sup>

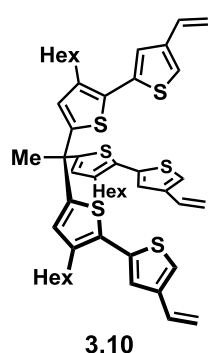


A mixture of 5-bromothiophene-3-carbaldehyde **3.11** (9.479 g, 49.6 mmol),  $\text{MePPh}_3\text{I}$  (14.133 g, 99.3 mmol) and  $\text{KO}^{\text{tert}}\text{-Bu}$  (11.209 g, 99.9 mmol) was suspended in THF (80 mL) and stirred overnight at room temperature. After an addition of a saturated aqueous solution of  $\text{NH}_4\text{Cl}$  (40 mL), the aqueous layer was extracted with diethyl ether ( $3 \times 40$  mL). The combined organic extracts

were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent, the crude product was filtered through short plug ( $\text{Al}_2\text{O}_3$ , *n*-hexane). The filtrate was concentrated and purified by distillation under reduced pressure to afford the title compound **3.12** (5.792 g, 62%) as a colorless oil.

Bp: 86–88 °C (16 mmHg); <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.19 (d, *J* = 1.6 Hz, 1H), 7.04 (d, *J* = 1.6 Hz, 1H), 6.58 (dd, *J* = 10.9, 17.5 Hz, 1H), 5.51 (dd, *J* = 0.9, 17.5 Hz, 1H), 5.19 (dd, *J* = 0.9, 10.9 Hz, 1H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 141.00, 130.29, 127.50, 114.37, 113.01; MS (EI, rel intensity): *m/z* 188/190 (58/60, [M]<sup>+</sup>), 109 (100, [M–Me]<sup>+</sup>).

### 1,1,1-Tris(3-hexyl-4'-vinyl-2,2'-bithiophen-5-yl)ethane (3.10)

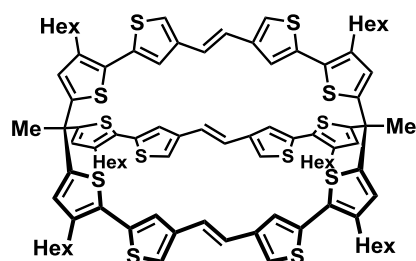


**3.10**

To a solution of 1,1,1-tris(5-bromo-4-hexyl-2-thienyl)ethane **3.9** (1.325 g, 2.51 mmol), K<sub>2</sub>CO<sub>3</sub> (2.118 g, 15.3 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (272 mg, 0.235 mmol) in toluene/water (3/1, 12 mL) was added a solution of 4-vinyl-2-thiethylboronic acid ester **3.13** (2.815 g, 12.7 mmol) in THF (9 mL). The reaction mixture was heated to reflux and stirred for 2 days. After cooling to room temperature, water (10 mL) was added and the resulting mixture was extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL) then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/20) to afford the title compound (1.628 g, 76%) as a yellow oil.

<sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>) δ 7.20 (d, *J* = 1.3 Hz, 3H), 7.10 (d, *J* = 1.3 Hz, 3H), 6.73 (s, 3H), 6.64 (dd, *J* = 10.9, 17.6 Hz, 3H), 5.56 (d, *J* = 17.6 Hz, 3H), 5.19 (d, *J* = 10.9 Hz, 3H), 2.70 (t, *J* = 7.6 Hz, 6H), 2.26 (s, 3H), 1.60 (quin, *J* = 7.6 Hz, 6H), 1.37–1.24 (m, 18H), 0.86 (t, *J* = 6.9 Hz, 9H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 150.61, 140.51, 139.10, 136.66, 130.91, 129.63, 128.69, 123.30, 122.12, 113.79, 46.44, 33.15, 31.63, 30.51, 29.32, 29.08, 22.62, 14.04; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>50</sub>H<sub>60</sub>S<sub>6</sub>Na, 875.2911; found, 875.2920 ([M+Na]<sup>+</sup>).

### β-Etheno-linked hexakis(bithienyl) cage (3.14)

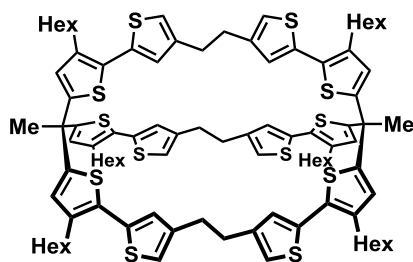


**3.14**

A solution of tris(bithienyl)methane **3.10** (431 mg, 0.504 mmol) and Grubbs 2nd generation catalyst (127 mg, 0.149 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (1000 mL) was heated to reflux and stirred for 24 h. After cooling to room temperature, ethyl vinyl ether (0.5 mL) was added to the reaction mixture. The resulting solution was concentrated, then filtered through silica gel short plug (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/1). The filtrate was concentrated and the crude product was purified by GPC to afford the title compound **3.11** (66 mg, 16%) as a colorless solid.

mp: 284.4 °C (decomp); <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.32 (d, *J* = 1.4 Hz, 6H), 7.22 (d, *J* = 1.4 Hz, 6H), 6.95 (s, 6H), 6.88 (s, 6H), 2.71 (t, *J* = 7.7 Hz, 12H), 2.41 (s, 6H), 1.60 (quin, *J* = 7.3 Hz, 12H), 1.37–1.23 (m, 36H), 0.83 (t, *J* = 7.0 Hz, 18H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 151.59, 139.56, 139.38, 136.09, 129.61, 126.75, 126.05, 122.62, 120.24, 44.89, 31.59, 30.78, 29.46, 29.20, 26.92, 22.60, 14.00; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>94</sub>H<sub>108</sub>S<sub>12</sub>Na, 1643.4992; found, 1643.5014 ([M+Na]<sup>+</sup>).

### $\beta$ -Etheno-linked hexakis(bithienyl) cage (3.15)



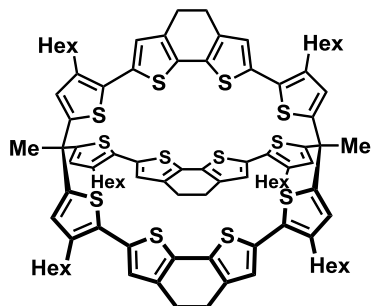
3.15

A solution of  $\beta$ -Etheno-linked hexakis(bithienyl) cage **3.14** (35 mg, 0.0216 mmol), *p*-toluenesulfonyl hydrazide (0.066 g, 0.354 mmol) and NaHCO<sub>3</sub> (31 mg, 0.166 mmol) in toluene/2-methoxyethanol (3/1, 12 ml) was heated up to 100 °C and stirred for 12 h. Additional *p*-toluenesulfonyl hydrazide (65 mg, 0.349 mmol) and NaHCO<sub>3</sub> (30 mg, 30 mmol) were then added and stirring was continued for further 12 h. After cooling to room temperature, water (10 mL) was added to the reaction mixture, and then extracted with diethyl ether (3 × 20 mL). The combined

organic extracts were washed with water (3 × 10 mL) and brine (1 × 10 mL), and then dried over sodium sulfate. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (*n*-hexane) to afford the title compound **3.15** (27 mg, 77%) as a colorless solid.

mp: 204.3–205.1 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>):  $\delta$  7.02 (d, *J* = 1.4 Hz, 6H), 6.91 (d, *J* = 1.4 Hz, 6H), 6.84 (s, 6H), 2.89 (s, 6H), 2.71 (t, *J* = 7.6 Hz, 12H), 2.34 (s, 6H), 1.60 (quin, *J* = 7.2 Hz, 12H), 1.38–1.23 (m, 36H), 0.85 (t, *J* = 6.8 Hz, 18H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>):  $\delta$  151.17, 142.02, 138.64, 136.05, 130.21, 127.58, 127.05, 120.03, 45.24, 31.73, 31.66, 30.60, 29.53, 29.22, 26.95, 22.63, 14.06; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>94</sub>H<sub>108</sub>S<sub>12</sub>Na, 1649.5461; found, 1649.5475 ([M+Na]<sup>+</sup>).

### $\beta$ -Ethano-linked tris(quarterthiophene)-bridged cage (3.1)



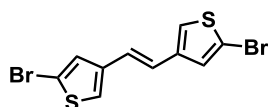
3.1

To a solution of  $\beta$ -ethano-linked hexakis(bithiophene)-bridged cage **3.15** (36 mg, 0.0221 mmol) in THF (5 mL) was added dropwise a solution of *n*-BuLi (1.5 M in hexane, 0.22 mL, 0.330 mmol) at –78 °C and the resulting mixture was stirred at 0 °C for 1 h. After cooling the reaction mixture to –78 °C, a THF solution of CuCl<sub>2</sub>·2LiCl, which was freshly prepared from CuCl<sub>2</sub> (92 mg, 0.684 mmol), LiCl (58 mg, 1.37 mmol) and THF (5 mL), was added dropwise and stirring was continued for 3 h at –78 °C. After addition of methanol (10 mL), the reaction mixture was filtered through alumina short plug (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/1) and then concentrated *in vacuo*. The crude

product was purified by column chromatography (silica-gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/9) to afford the title compound **3.1** (15 mg, 42%) as a yellow powder.

<sup>1</sup>H NMR (500 MHz, CDCl<sub>3</sub>)  $\delta$  6.82 (s, 6H), 6.71 (s, 6H), 2.89 (s, 12H), 2.61 (t, *J* = 7.6 Hz, 12H), 2.39 (s, 6H), 1.62–1.55 (m, 12H), 1.37–1.26 (m, 12H), 1.37–1.26 (m, 36H), 0.86–0.83 (m, 18H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>):  $\delta$  152.75, 138.64, 134.82, 134.16, 132.19, 131.18, 125.66, 122.36, 45.92, 31.67, 30.76, 29.18, 29.14, 24.67, 23.43, 22.58, 14.04; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>94</sub>H<sub>108</sub>S<sub>12</sub>, 1620.5094; found, 1620.5112 ([M]<sup>+</sup>).

### 1,2-Bis(2-bromo-4-thienyl)ethene (3.16)



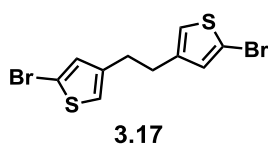
3.16

To a solution of titanium tetrachloride (0.50 mL, 4.56 mmol) in THF (10 mL) was added zinc powder (597 mg, 9.13 mmol) in one portion at 0 °C. A solution of 2-bromo-4-formylthiophene **3.11** (574 mg, 3.00 mmol) in THF (5 mL) was then added dropwise at 0 °C and the reaction mixture was stirred for 2 h at this temperature. After the addition of pyridine (0.30 mL, 3.72 mmol), the reaction mixture was refluxed for overnight. After cooling to room

temperature, water (10 mL) was added then the resulting mixture was filtered through Celite pad. The cake was washed with diethyl ether (3 × 10 mL). 1 M aqueous solution of hydrochloric acid (10 mL) was added to the filtrate, then the resulting mixture was extracted with diethyl ether (3 × 20 mL). The organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL), then dried over sodium sulfate. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (*n*-hexane) to afford the title compound **3.16** (316 mg, 60 %) as a colorless powder.

Mp: 120.2–120.5 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.23 (d, *J* = 1.6 Hz, 2H), 7.08 (d, *J* = 1.6 Hz, 2H), 6.74 (s, 2H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): 150.15, 127.41, 123.57, 122.77, 113.37; MS (EI, rel intensity): 348/350/352 (50/100/57, [M]<sup>+</sup>); Elemental analysis: calcd for C<sub>10</sub>H<sub>6</sub>Br<sub>2</sub>S<sub>2</sub>, C 34.31, H 1.73; found, C 34.55, H 1.69.

### 1,2-Bis(2-bromo-4-thienyl)ethane (3.17)

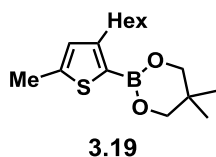


A solution of 1,2-bis(2-bromo-4-thienyl)ethane **3.16** (414 mg, 1.18 mmol), *p*-toluenesulfonyl hydrazide (1.117 g, 6.00 mmol) and NaHCO<sub>3</sub> (498 mg, 5.93 mmol) in toluene/2-methoxyethanol (3/1, 20 ml) was heated up to 100 °C and stirred for 12 h.

Additional *p*-toluenesulfonyl hydrazide (1.169 g, 6.28 mmol) and NaHCO<sub>3</sub> (500 mg, 5.95 mmol) were then added and stirring was continued for further 12 h. After cooling to room temperature, water (10 mL) was added to the reaction mixture, and then extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (3 × 10 mL) and brine (1 × 10 mL), and then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (*n*-hexane) to afford the title compound **3.17** (389 mg, 93%) as a colorless solid.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.86 (d, *J* = 1.7 Hz, 2H), 6.80 (d, *J* = 1.7 Hz, 2H), 2.84 (s, 2H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): 142.13, 130.73, 122.08, 112.02, 31.14; MS (EI, rel intensity): 350/352/354 (54/100/57, [M]<sup>+</sup>).

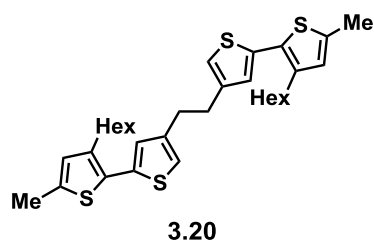
### 2-(3-Hexyl-5-methylthiophen-2-yl)-5,5-dimethyl-1,3,2-dioxaborinane (3.19)



To a solution of 4-hexyl-2-methylthiophene **3.18** (284 mg, 1.56 mmol) in diethyl ether (5 mL) was added dropwise a solution of *tert*-BuLi (1.5 M in pentane, 1.5 mL, 2.25 mmol) at –78 °C. After stirring for 1 h at 0 °C, B(*Oi*-Pr)<sub>3</sub> (0.70 mL, 3.05 mmol) was added in one portion at –78 °C. The resulting mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (457 mg, 4.39 mmol) was added, then the reaction mixture was stirred for additional 1 h. After addition of water (10 mL), the aqueous layer was extracted with diethyl ether (3 × 15 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica-gel, ethyl acetate/*n*-hexane = 1/8) to afford the title compound **3.19** (356 mg, 78%) as a pale yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.65 (d, *J* = 0.9 Hz, 1H), 3.72 (s, 4H), 2.77 (t, *J* = 7.6 Hz, 2H), 2.45 (d, *J* = 0.9 Hz, 3H), 1.56–1.50 (m, 2H), 1.34–1.24 (m, 6H), 1.00 (s, 6H), 0.88 (t, *J* = 6.7 Hz, 3H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): 153.66, 144.59, 129.38, 72.19, 31.88, 31.68, 31.65, 30.12, 29.06, 22.57, 21.87, 15.36, 14.09; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>16</sub>H<sub>27</sub>BO<sub>2</sub>SN<sub>a</sub>, 317.1717; found, 317.1722 ([M+Na]<sup>+</sup>).

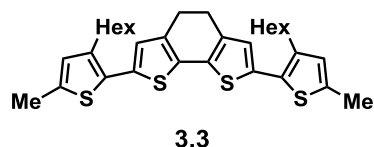
### 1,2-Bis(3'-hexyl-5'-methyl-2,2'-bithiophen-4-yl)ethane (3.20)



To a solution of 1,2-bis(2-bromo-4-thienyl)ethane **3.17** (143 mg, 0.409 mmol),  $K_2CO_3$  (229 mg, 1.66 mmol) and  $Pd(PPh_3)_4$  (29 mg, 0.0250 mmol) in toluene/water (3/1, 8 mL) was added a solution of 3-hexyl-5-methyl-2-thienylboronic acid neopentyl glycol ester **3.19** (352 mg, 1.20 mmol) in THF (6 mL). The reaction mixture was heated to reflux and stirred for 2 days. After cooling to room temperature, water (10 mL) was added and the resulting mixture was extracted with diethyl ether ( $3 \times 20$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL) then dried over anhydrous  $Na_2SO_4$ . After removal of the solvent *in vacuo*, the crude product was purified by silica-gel column chromatography (*n*-hexane) to afford the title compound **3.20** (211 mg, 93%) as pale yellow oil.

$^1H$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  6.87 (d,  $J = 1.4$  Hz, 2H), 6.86 (d,  $J = 1.4$  Hz, 2H), 6.58 (d,  $J = 1.0$  Hz, 2H), 2.93 (s, 4H), 2.65 (t,  $J = 7.7$  Hz, 4H), 2.43 (d,  $J = 1.0$  Hz, 6H), 1.59 (quin,  $J = 7.7$  Hz, 4H), 1.37-1.24 (m, 12H), 0.87 (t,  $J = 6.9$  Hz, 6H);  $^{13}C$ -NMR (125 MHz,  $CDCl_3$ ): 142.08, 139.39, 137.80, 136.55, 128.35, 128.26, 126.48, 119.88, 31.67, 31.32, 30.63, 29.22, 22.60, 15.19, 14.07; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{32}H_{42}S_4Na$ , 577.2062; found, 577.2066 ( $[M+Na]^+$ ).

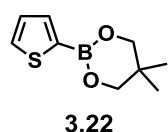
### $\beta$ -Ethano-linked quarterthiophene (3.3)



To a solution of 1,2-bis(3'-hexyl-5'-methyl-2,2'-bithiophen-4-yl)ethane **3.20** (187 mg, 0.337 mmol) in THF (25 mL) was added dropwise a solution of *n*-BuLi (1.5 M in hexane, 1.1 mL, 1.65 mmol) at  $-78$  °C. After stirring for 1 h, a THF solution of  $CuCl_2 \cdot 2LiCl$ , which was freshly prepared from  $CuCl_2$  (469 mg, 3.49 mmol),  $LiCl$  (248 mg, 5.85 mmol) and THF (25 mL), was added dropwise and stirring was continued for 3 h at  $-78$  °C. After addition of methanol (10 mL), the reaction mixture was filtered through alumina short plug ( $CH_2Cl_2/n$ -hexane = 1/1) and then concentrated *in vacuo*. The crude product was purified by GPC followed by silica-gel column chromatography ( $CH_2Cl_2/n$ -hexane = 1/20) gave yellow oil. Recrystallization from  $CH_2Cl_2$  and methanol at  $-20$  °C afforded the title compound **3.3** (97 mg, 52%) as a yellow powder.

mp:  $52.0$ – $52.4$  °C;  $^1H$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  6.84 (s, 2H), 6.59 (d,  $J = 1.1$  Hz, 2H), 2.88 (s, 4H), 2.69 (t,  $J = 7.7$  Hz, 4H), 2.44 (d,  $J = 1.1$  Hz, 6H), 1.62 (quin,  $J = 7.9$  Hz, 4H), 1.41-1.28 (m, 12H), 0.89 (t,  $J = 6.9$  Hz, 6H);  $^{13}C$ -NMR (125 MHz,  $CDCl_3$ ): 139.33, 137.78, 135.06, 132.85, 130.24, 128.48, 125.59, 31.69, 30.57, 29.38, 29.23, 24.57, 22.60, 15.26, 14.09; UV-vis ( $CH_2Cl_2$ ):  $\lambda_{max}/nm$  (log  $\epsilon$ ) 361 (4.53); HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{32}H_{40}S_4$ , 552.2007; found, 552.2013 ( $[M]^+$ ); Elemental analysis: calcd for  $C_{32}H_{40}S_4$ , C 69.51, H 7.29; found, C 69.32, H 7.16.

### 5,5-Dimethyl-2-(thiophen-2-yl)-1,3,2-dioxaborinane (3.22) <sup>[13]</sup>

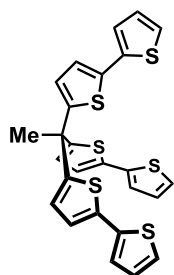


To a solution of thiophene (5.0 mL, 63.0 mmol) in diethyl ether (100 mL) was added dropwise a solution of *n*-BuLi (1.5 M in *n*-hexane, 46.0 mL, 69.0 mmol) at  $-78$  °C. After stirring for 1 h at  $0$  °C,  $B(Oi-Pr)_3$  (17.0 mL, 74.1 mmol) was added in one portion at  $-78$  °C. The resulting mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (9.858 g, 94.7 mmol) was added, then the reaction mixture was stirred for additional 1 h. After addition of a saturated aqueous solution of  $NH_4Cl$  (50 mL), the aqueous layer was extracted with diethyl ether ( $5 \times 50$  mL). The combined organic

extracts were washed with water (1 × 50 mL) and brine (1 × 50 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by reprecipitation from CH<sub>2</sub>Cl<sub>2</sub>/MeOH to afford the title compound (11.059 g, 90%) as colorless crystals.

mp: 94.4–95.2 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.58–7.56 (m, 2H), 7.17 (dd, *J* = 3.4, 4.7 Hz, 1H), 3.76 (s, 4H), 1.03 (s, 6H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 135.61, 131.31, 128.04, 72.39, 32.04, 21.89; MS (EI, rel intensity): *m/z* 196/195 (100/26, [M]<sup>+</sup>); Elemental analysis: calcd for C<sub>9</sub>H<sub>13</sub>BO<sub>2</sub>S, C 55.13, H 6.68; found, C 54.98, H 6.75.

### 1,1,1-Tris(2,2'-bitiophen-5-yl)ethane (3.23)



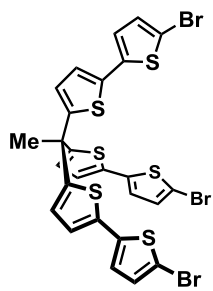
**3.23**

A mixture of 1,1,1-tris(5-bromo-2-thienyl)ethane **3.21** (5.140 g, 10.0 mmol), 2-thienylboronic acid neopentyl glycol ester **3.22** (8.824 g, 45.0 mmol), K<sub>2</sub>CO<sub>3</sub> (8.303 g, 60.1 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (1.173 g, 0.0372 mmol) in THF/toluene/water (3/3/1, 105 mL) was heated to reflux and stirred for 2 days. After cooling to room temperature, water (30 mL) was added and the resulting mixture was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were washed with water (1 × 50 mL) and brine (1 × 50 mL) then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica-gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/6) to afford the title compound **3.23** (5.166 g,

99%) as a colorless solid.

Mp: 96.2–98.0 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.19 (dd, *J* = 1.1, 5.1 Hz, 3H), 7.12 (dd, *J* = 1.1, 3.6 Hz, 3H), 7.01 (d, *J* = 3.7 Hz, 3H), 6.98 (dd, *J* = 3.6, 5.1 Hz, 3H), 6.81 (d, *J* = 3.7 Hz, 3H), 2.32 (s, 3H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 151.55, 137.30, 136.80, 127.73, 126.56, 124.32, 123.62, 122.86, 46.73, 33.45; IR (KBr):  $\nu$ /cm<sup>-1</sup> 3102 (w) 3067 (w), 2981 (w), 2930 (w), 2355 (w), 1789 (w), 1751 (w), 1509 (w), 1464 (w), 1423 (m), 1373 (w), 1309 (w), 1229 (m), 1206 (m), 1082 (w), 1046 (w), 1008 (w), 907 (w), 887 (w), 839 (s), 801 (s), 756 (w), 696 (s); MS (EI, rel. intensity): *m/z* 522 ([M]<sup>+</sup>, 52), 507 ([M-Me]<sup>+</sup>, 100); HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>26</sub>H<sub>18</sub>S<sub>6</sub>Na, 544.9625; found, 544.9632 ([M+Na]<sup>+</sup>); Elemental analysis: calcd for C<sub>26</sub>H<sub>18</sub>S<sub>6</sub>, C 59.73, H 3.47; found, C 60.01, H 3.61.

### 1,1,1-Tris(5'-bromo-2,2'-bitiophen-5-yl)ethane (3.24)



**3.24**

To a solution of tris(2,2'-bitiophen-5-yl)ethane **3.23** (5.235 g, 10.0 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (15 mL) was added dropwise a solution of NBS (5.914 g, 33.2 mmol) in DMF (15 mL) at 0 °C. After completion of the addition, the reaction mixture was warmed up to room temperature and stirred for 1 h. After addition of water (20 mL), the precipitates were collected by filtration and then washed with water, ethanol and diethyl ether successively to obtain the title compound **3.24** (4.748 g) as a colorless crystals. The organic layer of the filtrate was separated from the aqueous layer and then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography

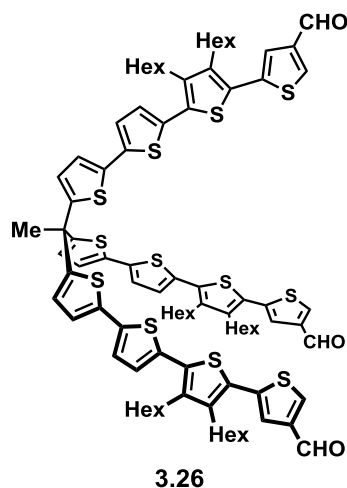
(silica gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/10) to afford the title compound **3.24** (2.367 g) as a colorless crystals.

Mp: 96.1–96.9 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 6.94 (d, *J* = 3.8 Hz, 3H), 6.93 (d, *J* = 3.8 Hz, 3H), 6.85 (d, *J* = 3.8 Hz, 3H), 6.78 (d, *J* = 3.8 Hz, 3H), 2.29 (s, 3H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 151.79, 138.69, 135.90, 130.59, 126.66, 123.78, 123.19, 111.01, 46.74, 33.35; IR (KBr):  $\nu$ /cm<sup>-1</sup> 3068 (w), 2973 (w), 2925 (w), 1739 (w), 1514 (m), 1462 (m), 1425 (m), 1372 (w), 1320 (w), 1237 (m), 1216 (m), 1200 (m), 1060 (w), 1016 (w), 969 (m), 903 (w), 871 (m), 790 (s), 755 (w), 638 (w); MS (EI, rel. intensity): *m/z* 756/758/760/762 ([M]<sup>+</sup>, 13/48/54/28),



741/743/745/747 ([M–Me]<sup>+</sup>, 26/85/100/50); HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>26</sub>H<sub>15</sub>Br<sub>3</sub>S<sub>6</sub>, 755.7043; found, 755.7052 ([M]<sup>+</sup>); Elemental analysis: calcd for C<sub>26</sub>H<sub>15</sub>Br<sub>3</sub>S<sub>6</sub>, C 41.12, H 1.99; found, C 41.14, H 1.94.

### 1,1,1-Tris(4'''-formyl-3'',4''-dihexyl-2,2':5',2'':5'',2'''-quaterthiophen-5-yl)ethane (3.26)

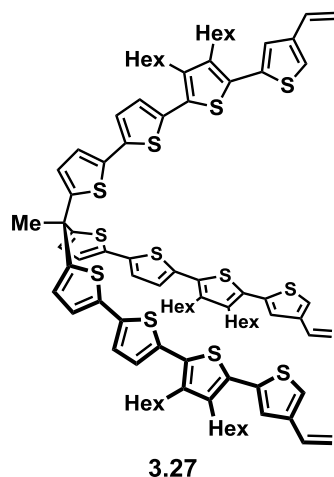


A mixture of 1,1,1-tris(5'-bromo-2,2'-bitiophen-5-yl)ethane **3.24** (2.034 g, 2.68 mmol), 2,2'-bithenylboronic acid neopentyl glycol ester **3.25** (6.236 g, 12.0 mmol), K<sub>2</sub>CO<sub>3</sub> (2.270 g, 16.4 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (284 mg, 0.246 mmol) in THF/toluene/water (3/3/1, 70 mL) was heated to reflux and stirred for 2 days. After cooling to room temperature, water (30 mL) was added and the resulting mixture was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were washed with water (1 × 50 mL) and brine (1 × 50 mL) then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was dissolved in THF (20 mL). A 6 M aqueous solution of HCl (20 mL) was then added at room temperature and the resulting mixture was stirred overnight. The aqueous layer was extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (5 × 20 mL) and

brine (1 × 20 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica gel, EtOAc/*n*-hexane = 2/7) to afford the title compound **3.26** (3.659 g, 85%) as a yellow orange oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 9.88 (s, 3H), 8.06 (d, *J* = 1.3 Hz, 3H), 7.51 (d, *J* = 1.3 Hz, 3H), 7.08 (d, *J* = 3.7 Hz, 3H), 7.04 (d, *J* = 3.7 Hz, 3H), 7.02 (d, *J* = 3.7 Hz, 3H), 6.85 (d, *J* = 3.7 Hz, 3H), 2.73–2.67 (m, 12H), 2.35 (s, 3H), 1.60–1.51 (m, 12H), 1.44–1.29 (m, 36H), 0.91–0.87 (m, 18H); <sup>13</sup>C-NMR (500 MHz, CDCl<sub>3</sub>): δ 184.75, 151.72, 143.09, 141.49, 140.31, 138.48, 137.27, 136.52, 136.08, 134.71, 130.88, 128.23, 126.75, 126.68, 123.93, 123.23, 122.90, 46.87, 33.45, 31.46, 31.44, 30.67, 30.61, 29.53, 29.49, 28.19, 28.07, 22.59, 22.57, 14.05, 14.02; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>89</sub>H<sub>102</sub>O<sub>3</sub>S<sub>12</sub>Na, 1625.4370; found, 1625.4392 ([M+Na]<sup>+</sup>).

### 1,1,1-Tris(4'''-formyl-3'',4''-dihexyl-2,2':5',2'':5'',2'''-quaterthiophen-5-yl)ethane (3.27)

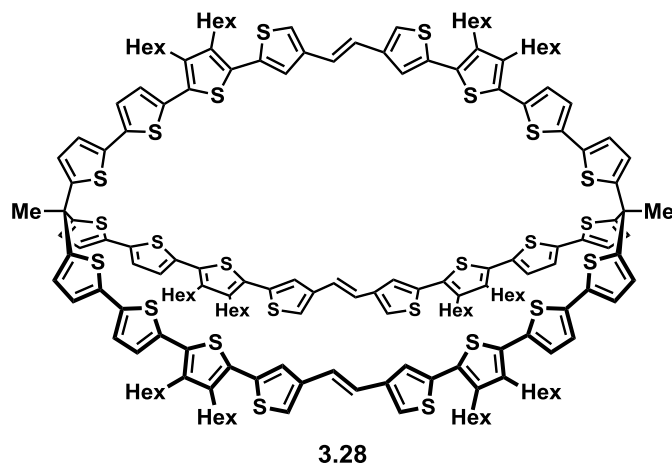


A mixture of trialdehyde **3.26** (3.383 g, 2.11 mmol), KO<sup>*tert*</sup>-Bu (3.601 g, 32.1 mmol) and methyltriphenylphosphonium iodide (12.830 g, 31.7 mmol) was suspended in THF (30 mL) and stirred overnight at room temperature. After addition of a saturated aqueous solution of NH<sub>4</sub>Cl (10 mL), the aqueous layer was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were washed with water (1 × 50 mL) and brine (1 × 50 mL), then dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>. After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica-gel, CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/9) to afford the title compound **3.27** (3.013 g, 89%) as a yellow oil.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.24 (d, *J* = 1.3 Hz, 3H), 7.14 (d, *J* = 1.3 Hz, 3H), 7.08 (d, *J* = 3.7 Hz, 3H), 7.04 (d, *J* = 3.9 Hz, 3H), 7.01 (d, *J* = 3.9 Hz, 3H), 6.84 (d, *J* = 3.7 Hz, 3H), 2.72–2.67 (m, 12H), 2.35 (s, 3H), 1.60–1.53 (m, 12H), 1.45–1.29 (m, 36H), 0.91–0.88 (m, 18H); <sup>13</sup>C-NMR (500 MHz, CDCl<sub>3</sub>): δ 151.61, 140.60, 140.50, 140.21, 136.91, 136.63, 136.62, 135.16, 130.92, 129.81, 129.80, 126.72, 126.34, 123.89, 123.45, 122.76, 122.34, 113.90,

46.86, 33.46, 31.49, 31.48, 30.74, 30.61, 29.56, 28.21, 28.12, 22.61, 14.07, 14.05; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{92}H_{108}S_{12}$ , 1596.5094; found, 1596.5115 ( $[M+Na]^+$ ).

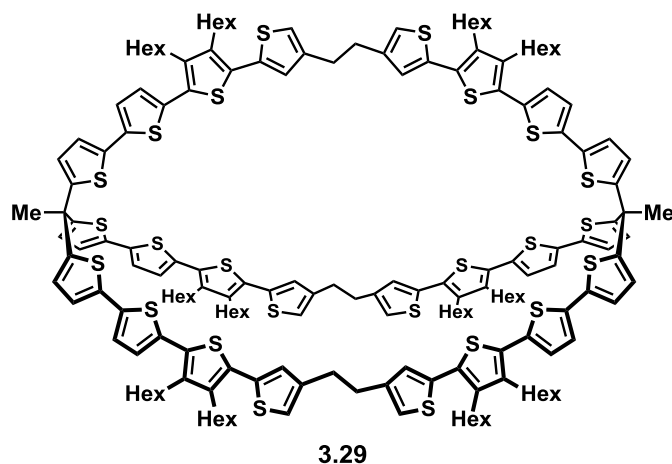
### $\beta$ -Etheno-linked hexakis(quarterthiophene)-bridged cage (3.28)



A solution of tris(quarterthienyl)methane **3.27** (72 mg, 0.0450 mmol) and Grubbs 2nd generation catalyst (3.3 mg, 0.00527 mmol) in  $CH_2Cl_2$  (90 mL) was heated to reflux and stirred for 24 h. After cooling to room temperature, ethyl vinyl ether (0.2 mL) was added to the reaction mixture. The resulting solution was concentrated, then filtered through silica gel short plug ( $CH_2Cl_2/n$ -hexane = 1/1). The filtrate was concentrated and the crude product was purified by GPC to afford the title compound **3.28** (10 mg, 14%) as a brown solid.

Mp: 117.8–119.2 °C;  $^1H$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  7.27–7.25 (m, 12H), 7.08 (d,  $J = 3.9$  Hz, 6H), 7.04 (d,  $J = 3.9$  Hz, 6H), 7.02 (d,  $J = 3.9$  Hz, 6H), 6.92 (s, 6H), 6.89 (d,  $J = 3.9$  Hz, 6H), 2.74–2.69 (m, 24H), 2.36 (s, 6H), 1.60–1.53 (m, 24H), 1.45–1.26 (m, 72H), 0.91–0.88 (m, 36H);  $^{13}C$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  151.86, 140.37, 140.21, 139.74, 136.87, 136.70, 136.41, 135.22, 129.89, 129.61, 126.33, 126.16, 125.09, 124.04, 122.96, 122.86, 120.73, 46.64, 32.63, 31.50, 31.49, 30.76, 30.59, 29.59, 29.57, 28.22, 22.63, 22.62, 14.07; IR (KBr):  $\nu_{cm^{-1}}$  3065 (w), 2952 (s), 2923 (s), 2852 (s), 2360 (w), 1539 (w), 1508 (w), 1458 (m), 1375 (w), 1223 (w), 1203 (w), 1186 (w), 1059 (w), 951 (w), 872 (w), 832 (w), 794 (m), 729 (w), 637 (w); UV-vis ( $CH_2Cl_2$ ):  $\lambda_{max}/nm$  (log  $\epsilon$ ) 384 (5.25), 303 (5.04), 264 (5.05), 227 (4.99); HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{178}H_{204}S_{24}Na$ , 3131.9152; found, 3131.9089 ( $[M+Na]^+$ ); Elemental analysis: calcd for  $C_{178}H_{204}S_{24}$ , C 68.68, H 6.61; found, C 68.37, H 6.76.

### $\beta$ -Ethano-linked hexakis(quarterthiophene)-bridged cage (3.29)



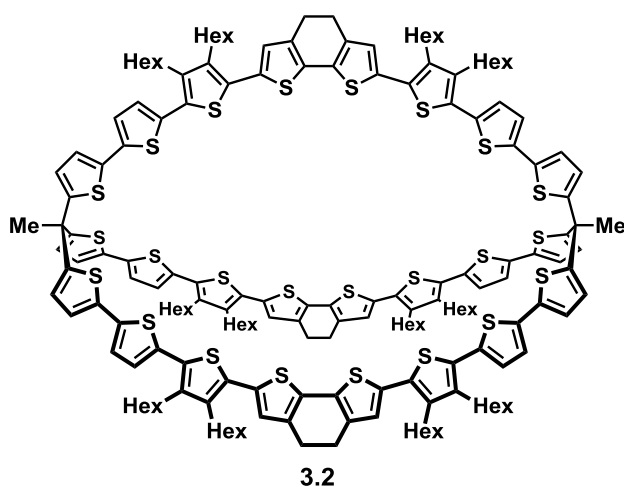
A solution of  $\beta$ -etheno-linked hexakis(quarterthiophene)-bridged cage **3.28** (369 mg, 0.118 mmol), *p*-toluenesulfonyl hydrazide (340 mg, 1.83 mmol) and  $NaHCO_3$  (161 mg, 1.92 mmol) in toluene/2-methoxyethanol (3/1, 20 ml) was heated up to 100 °C and stirred for 12 h. Additional *p*-toluenesulfonyl hydrazide (333 mg, 1.79 mmol) and  $NaHCO_3$  (151 mg, 1.80 mmol) were then added and stirring was continued for further 12 h. After cooling to room temperature, water (20 mL) was added and then extracted with diethyl

ether ( $3 \times 20$  mL). The combined organic extracts were washed with water ( $3 \times 10$  mL) and brine ( $1 \times 10$  mL), then dried over sodium sulfate. After removal of solvents *in vacuo*, the crude product was purified by silica-gel

column chromatography ( $\text{CH}_2\text{Cl}_2/n\text{-hexane} = 2/13$ ) to afford the title compound **3.29** (282 mg, 77%) as yellow solid.

Mp: 70.7–72.3 °C;  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.92–6.87 (m, 24H), 6.75 (d,  $J = 3.7$  Hz, 6H), 6.63 (d,  $J = 1.4$  Hz, 6H), 2.92 (s, 12H), 2.66–2.60 (m, 24H), 2.32 (s, 6H), 1.56–1.47 (m, 24H), 1.41–1.25 (m, 72H), 0.89–0.85 (m, 36H);  $^{13}\text{C-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  151.27, 141.86, 139.91, 139.72, 136.67, 136.44, 135.69, 135.33, 130.41, 129.50, 127.89, 126.88, 126.18, 123.90, 122.77, 120.85, 46.86, 33.63, 31.81, 31.47, 30.60, 30.51, 29.58, 29.57, 28.23, 28.14, 22.62, 14.08, 14.07; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $\text{C}_{178}\text{H}_{210}\text{S}_{24}\text{Na}$ , 3137.9622; found, 3137.9622 ( $[\text{M}+\text{Na}]^+$ ); Elemental analysis: calcd for  $\text{C}_{178}\text{H}_{210}\text{S}_{24}$ , C 68.54, H 6.79; found, C 68.35, H 6.72.

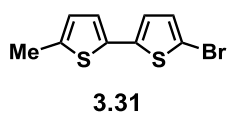
### Attempt of $\beta$ -Ethano-linked tris(octithiophene)-bridged cage (3.2)



To a solution of  $\beta$ -ethano-linked hexakis(quarterthiophene)-bridged cage **3.29** (293 mg, 0.0939 mmol) in THF (25 mL) was added dropwise a solution of *n*-BuLi (1.5 M in hexane, 0.95 mL, 1.43 mmol) at  $-78$  °C. After stirring for 1 h, a THF solution of  $\text{CuCl}_2 \cdot 2\text{LiCl}$ , which was freshly prepared from  $\text{CuCl}_2$  (381 mg, 2.83 mmol), LiCl (241 mg, 5.69 mmol) and THF (25 mL), was added dropwise and stirring was continued for 3 h at  $-78$  °C. After addition of methanol (10 mL), the reaction mixture was filtered through alumina short plug ( $\text{CH}_2\text{Cl}_2/n\text{-hexane} = 1/1$ ) and then concentrated *in vacuo*.

The crude product was purified by GPC followed by silica-gel column chromatography ( $\text{CH}_2\text{Cl}_2/n\text{-hexane} = 1/5$ ) to afford the red powder (183 mg.), which have not be able to be identified yet.

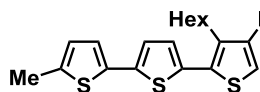
### 5-Bromo-5'-methyl-2,2'-bithiophene (3.31)<sup>[14]</sup>



A mixture of 2,5-dibromothiophene (2.418 g, 9.99 mmol), 5,5-dimethyl-2-(5-methylthiophen-2-yl)-1,3,2-dioxaborinane (1.049 g, 4.99 mmol),  $\text{K}_2\text{CO}_3$  (2.087 g, 15.1 mmol) and  $\text{Pd}(\text{PPh}_3)_4$  (176 mg, 0.152 mmol) in THF/toluene/water (3/3/1, 14 mL) was heated to reflux and stirred for 3 days. After cooling to room temperature, water (10 mL) was added to the reaction mixture. The aqueous layer was extracted with diethyl ether ( $3 \times 15$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL), then dried over anhydrous  $\text{Na}_2\text{SO}_4$ . After filtration and removal of solvent *in vacuo*, the crude product was purified by column chromatography (silica-gel, *n*-hexane) to afford the title compound **3.31** (491 mg, 38%) as a colorless crystals.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  6.93 (d,  $J = 3.7$  Hz, 1H), 6.89 (d,  $J = 3.4$  Hz, 1H), 6.82 (d,  $J = 3.7$  Hz, 1H), 6.65–6.64 (m, 1H), 2.47 (d,  $J = 1.0$  Hz, 3H);  $^{13}\text{C-NMR}$  (125 MHz,  $\text{CDCl}_3$ ): 139.71, 139.37, 134.04, 130.47, 125.96, 123.93, 123.08, 110.18, 15.31; MS (EI, rel intensity):  $m/z$  258/260 (94/100,  $[\text{M}]^+$ ).

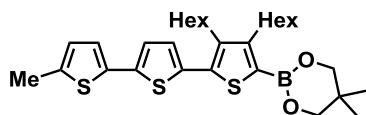
### 3,4-Dihexyl-5''-methyl-2,2':5'2''-terthiophene (3.33)



To a solution of 5-bromo-5'-methyl-2,2-bithiophene **3.31** (446 mg, 1.72 mmol),  $K_2CO_3$  (482 mg, 3.49 mmol) and  $Pd(PPh_3)_4$  (67 mg, 0.0580 mmol) in toluene/water (3/1, 8 mL) was added a solution of 3,4-dihexyl-2-thienylboronic acid neopentyl glycol ester **3.32** (940 mg, 2.58 mmol) in THF (6 mL). The reaction mixture was heated to reflux and stirred for 2 days. After cooling to room temperature, water (10 mL) was added and the resulting mixture was extracted with diethyl ether ( $3 \times 20$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL), and then dried over sodium sulfate. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (*n*-hexane) to afford the title compound (693 mg, 94%) as yellow oil.

$^1H$ -NMR (500 MHz,  $CDCl_3$ ):  $\delta$  7.02 (d,  $J = 3.7$  Hz, 1H), 6.97–6.96 (m, 2H), 6.84 (s, 1H), 6.67–6.66 (m, 1H), 2.70–2.67 (m, 2H), 2.53–2.50 (m, 2H), 2.48 (d,  $J = 1.0$  Hz, 3H), 1.68–1.62 (m, 2H), 1.56–1.50 (m, 2H), 1.41–1.29 (m, 12H), 0.92–0.87 (m, 6H);  $^{13}C$ -NMR (125 MHz,  $CDCl_3$ ):  $\delta$  140.28, 139.92, 139.31, 137.47, 135.42, 134.86, 134.57, 132.58, 130.71, 130.20, 129.50, 126.18, 126.06, 126.00, 123.50, 123.26, 31.50, 31.48, 30.64, 30.56, 29.59, 29.56, 28.25, 24.54, 22.63, 22.60, 15.34, 14.08, 14.07; HRMS (ESI-Orbitrap):  $m/z$  calcd for  $C_{25}H_{34}S_3$ , 430.1817; found, 430.1823 ( $[M]^+$ ).

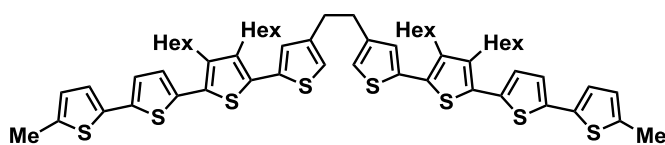
### 3,4-Dihexyl-5''-methyl-2,2':5'2''-terthiophen-5-ylboronic acid neopentyl glycol ester (3.34)



To a solution of 3,4-dihexyl-5''-methyl-2,2':5'2''-terthiophene **3.33** (693 mg, 1.61 mmol) in diethyl ether (10 mL) was added dropwise a solution of *tert*-BuLi (1.5 M in pentane, 1.6 mL, 2.40 mmol) at  $-78$  °C, then the reaction mixture was stirred for 1 h at this temperature. After  $B(Oi-Pr)_3$  (0.75 mL, 3.27 mmol) was added in one portion, the resulting mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (507 mg, 4.87 mmol) was then added and stirring was continued for further 1 h. Water (10 mL) was added, then the aqueous layer was extracted with diethyl ether ( $3 \times 15$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL), and then dried over sodium sulfate. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (ethyl acetate/*n*-hexane = 1/9) to afford the title compound (656 mg, 75%) as yellowish red oil.

$^1H$  NMR (500 MHz,  $CDCl_3$ )  $\delta$  7.02 (d,  $J = 3.7$  Hz, 1H), 7.01 (d,  $J = 3.7$  Hz, 1H), 6.96 (d,  $J = 3.7$  Hz, 1H), 6.66–6.65 (m, 1H), 3.75 (s, 4H), 2.76 (t,  $J = 7.9$  Hz, 2H), 2.69 (t,  $J = 8.3$  Hz, 2H), 2.48 (d,  $J = 0.7$  Hz, 3H), 1.56–1.47m (m, 4H), 1.43–1.25 (m, 12H), 1.02 (s, 6H), 0.93–0.87 (m, 6H);  $^{13}C$  NMR (125 MHz,  $CDCl_3$ )  $\delta$  153.51, 140.41, 139.15, 137.39, 136.01, 135.59, 134.98, 126.15, 125.94, 123.40, 123.22.72.32, 32.28, 31.95, 31.59, 30.69, 29.58, 28.94, 27.79, 22.61, 21.89, 15.33, 14.10, 14.06; HRMS (ESI-Orbitrap): Calcd for  $C_{30}H_{43}BO_2S_3Na$ , 565.2410; Found, 565.2415.

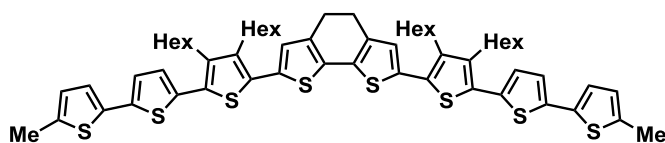
### 1,2-Bis(3,4-dihexyl-5''-methyl-2,2':5'2''-terthiophen-4-yl)ethane (3.28)



To a solution of 1,2-bis(2-bromo-4-thienyl)ethane **3.17** (142 mg, 0.403 mmol),  $K_2CO_3$  (235 mg, 1.70 mmol) and  $Pd(PPh_3)_4$  (43 mg, 0.0372 mmol) in toluene/water (3/1, 8 mL) was added a solution of 3,4-dihexyl-5''-methyl-2,2':5'2''-terthiophen-5-ylboronic acid neopentyl glycol ester **3.34** (656 mg, 1.21 mmol) in THF (6 mL). The reaction mixture was heated to reflux and stirred for 2 days. After

cooling to room temperature, water (10 mL) was added and the resulting mixture was extracted with diethyl ether (3 × 20 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL) then dried over sodium sulfate. After removal of solvents *in vacuo*, the crude product was purified by silica-gel column chromatography (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/9) to afford the title compound **3.28** (324 mg, 76%) as yellow orange oil. <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.03 (d, *J* = 3.9 Hz, 2H), 7.01 (d, *J* = 3.9 Hz, 2H), 6.97 (d, *J* = 3.6 Hz, 2H), 6.95 (s, 2H), 6.68–6.67 (m, 2H), 2.92 (s, 4H), 2.74–2.70 (m, 8H), 2.49 (d, *J* = 1.0 Hz, 6H), 1.63–1.56 (m, 8H), 1.49–1.31 (m, 24H), 0.93–0.89 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 142.11, 140.04, 140.01, 139.23, 137.42, 136.12, 134.88, 134.59, 130.29, 129.58, 127.00, 126.18, 125.97, 123.46, 123.21, 120.56, 31.51, 31.49, 31.35, 30.67, 29.58, 28.22, 28.14, 22.63, 22.62, 15.34, 14.07, 14.06; HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>60</sub>H<sub>74</sub>S<sub>8</sub>, 1050.3551; found, 1050.3571 ([M]<sup>+</sup>).

### β-Ethano-liked octithiophene (**3.4**)



To a solution of 1,2-bis(3'-hexyl-5'-methyl-2,2'-bithiophen-4-yl)ethane **3.28** (317 mg, 0.301 mmol) in THF (25 mL) was added dropwise a solution of *n*-BuLi (1.5 M in hexane, 1.0 mL,

1.50 mmol) at –78 °C. After stirring for 1 h, a THF solution of CuCl<sub>2</sub>·2LiCl, which was freshly prepared from CuCl<sub>2</sub> (434 mg, 3.23 mmol), LiCl (264 mg, 6.23 mmol) and THF (25 mL), was added dropwise and stirring was continued for 3 h at –78 °C. After addition of methanol (10 mL), the reaction mixture was filtered through alumina short plug (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/1) and then concentrated *in vacuo*. The crude product was purified by GPC followed by silica-gel column chromatography (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/8) to give yellow oil. Recrystallization from CH<sub>2</sub>Cl<sub>2</sub> and methanol at –20 °C afforded the title compound **3.4** (157 mg, 50%) as a dark red powder.

mp: 70.2–72.1 °C; <sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>): δ 7.03 (d, *J* = 3.9 Hz, 2H), 7.01 (d, *J* = 3.9 Hz, 2H), 6.97 (d, *J* = 3.6 Hz, 2H), 6.95 (s, 2H), 6.68–6.67 (m, 2H), 2.92 (s, 4H), 2.74–2.70 (m, 8H), 2.49 (d, *J* = 1.0 Hz, 6H), 1.63–1.56 (m, 8H), 1.49–1.31 (m, 24H), 0.93–0.89 (m, 12H); <sup>13</sup>C-NMR (125 MHz, CDCl<sub>3</sub>): δ 140.28, 139.92, 139.31, 137.47, 135.42, 134.86, 134.57, 132.58, 130.71, 130.20, 129.50, 126.18, 126.06, 126.00, 123.50, 123.26, 31.50, 31.48, 30.64, 30.56, 29.59, 29.56, 28.25, 24.54, 22.63, 22.60, 15.34, 14.08, 14.07; UV-vis (CH<sub>2</sub>Cl<sub>2</sub>): λ<sub>max</sub>/nm (log ε) 453 (4.51), 352 (sh); HRMS (ESI-Orbitrap): *m/z* calcd for C<sub>60</sub>H<sub>72</sub>S<sub>8</sub>, 1048.3394; found, 1048.3406 ([M]<sup>+</sup>); Elemental analysis: calcd for C<sub>60</sub>H<sub>72</sub>S<sub>8</sub>, C, 68.65; H, 6.91; found, C, 68.27; H, 6.82.

### 3.6. References

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- [5] Crystal Data of **3.1**: Monoclinic,  $P 2_1/n$ ,  $a = 16.4578(8) \text{ \AA}$ ,  $b = 28.8430(15) \text{ \AA}$ ,  $c = 18.6411(8) \text{ \AA}$ ,  $\beta = 100.3096(12)^\circ$ ,  $V = 8705.9(7) \text{ \AA}^3$ ,  $Z = 4$ ,  $D_{\text{calc}} = 1.211 \text{ g/cm}^3$ ,  $R1 (I > 2s(I)) = 0.1012$ ,  $wR2 (\text{all data}) = 0.2716$ ,  $\text{Refl./Param.} = 6357/1122$ ,  $\text{GOF} = 1.042$ ,  $T = 150 \text{ K}$ .
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## Chapter 4

### Optical and Electronic Properties of Cage-Shaped Compounds

#### 4.1 Introduction

In the previous two chapters, I presented the successful synthesis of the series of oligothiophenes with various topologies such as cage, cycle and linear oligothiophenes, which can be considered as a novel structurally-defined oligothiophenes. The efficient and scalable synthesis of these compounds will make these oligothiophenes one of the promising candidates for oligothiophene-based organic semiconductors. In this chapter, I describe the optical and redox properties of the cages and with comparison to the corresponding derivatives. First I carried out the spectroscopic investigation to reveal the topological effect on the oligothiophene properties. These investigation will give deep insight into the electronic states of curved and closely-congested thiophene systems, which can provide the new entry for the creation of oligothiophene-based materials.

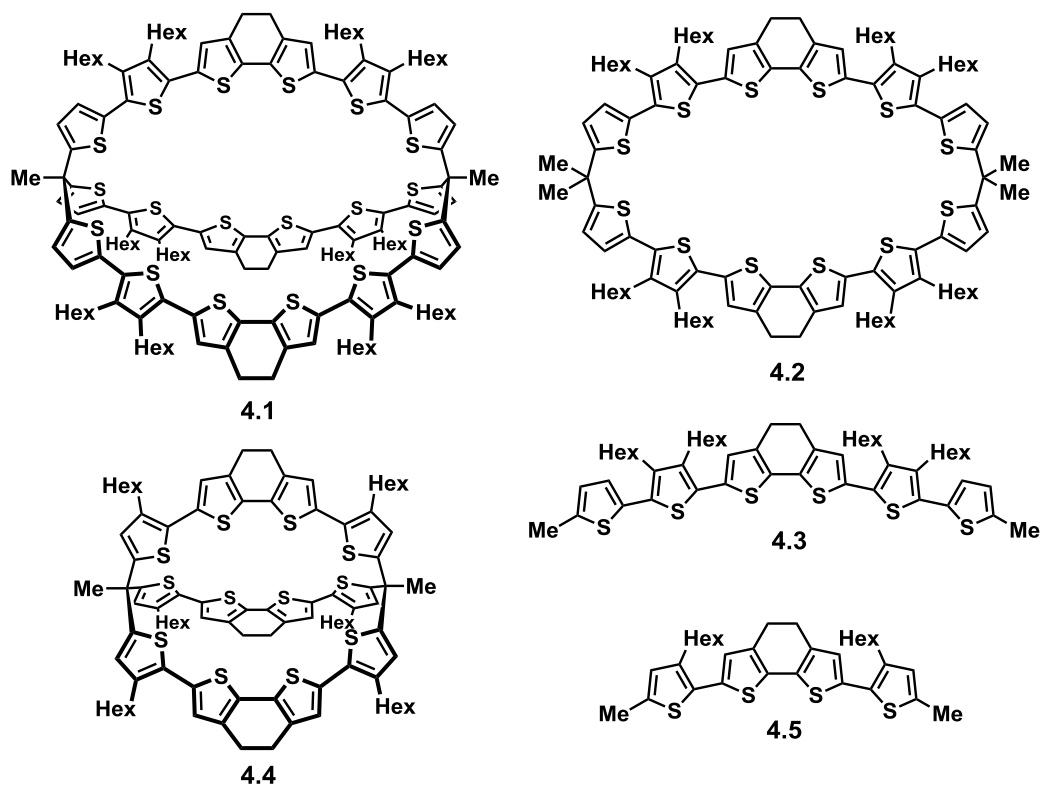


Chart 4.1.

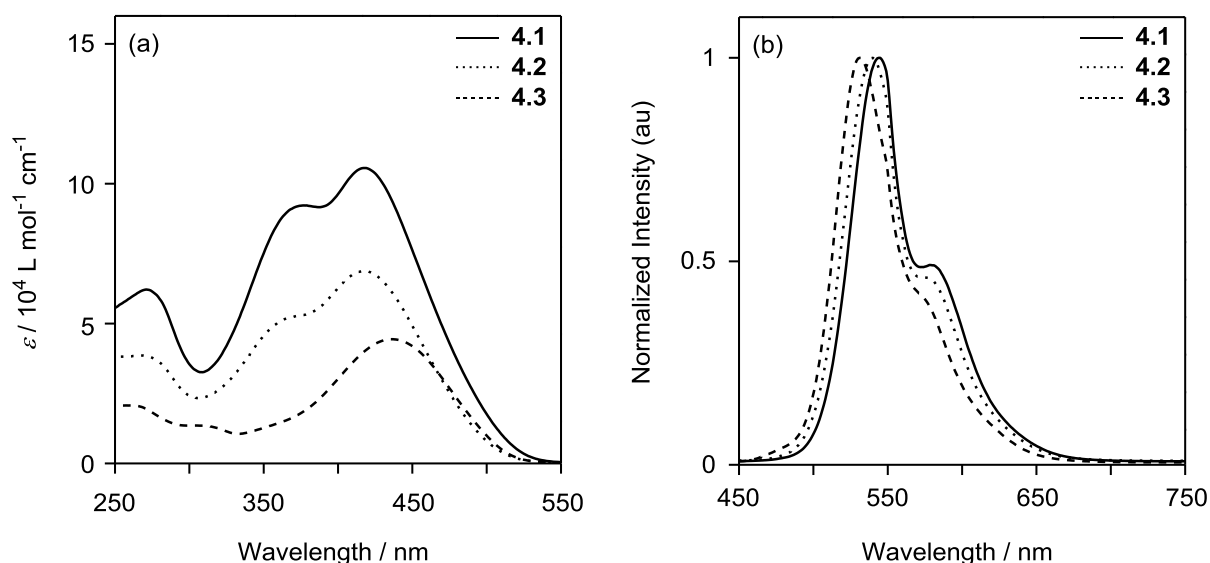
## 4.2. Results and discussions

### 4.2.1. UV-vis spectral measurement of cage, cycle and linear sexithiophenes

The optical properties of cage, cycle and linear sexithiophenes **4.1**, **4.2** and **4.3** are performed in dichloromethane solution (Figure 4.1a). Cage **4.1** showed absorption maximum at 418 nm, at which is blue-shifted compared to linear **4.3**. In addition, **4.1** exhibited additional absorption band at 377 nm (Table 4.1). Such an observable peak close to the long wavelength region could not be detected in the spectrum of **4.3**. The cyclic analogue **4.2** also exhibited blue-shifted and two absorption bands at 418 and 367 nm. These two spectral features are discussed in the latter section. It should be also mentioned that the molar extinction coefficient ( $\epsilon$ ) at the absorption maximum of **4.1** is not proportional to the increase of sexithiophene units from linear **4.3**, or only 2.4 times larger than that of **4.3** (Table 4.1). The same unproportional  $\epsilon$  value was also observed in **4.2** as 1.5 times larger one. On the other hand, good correlation between the number of thiophene units and  $\epsilon$  values was found in **4.1** and **4.2** as 1.5 times larger  $\epsilon$  value in **4.1** than in **4.2**.

One of the other common structural features of these compounds is the presence of  $\beta$ -ethano linkage at central bithiophene moiety, of which the effect on absorption behavior could be assessed by the comparison of **4.3** with linear sexithiophene derivatives. It is reported that non-substituted sexithiophene shows one strong absorption band at 432 nm.<sup>[1]</sup> This value is similar to the observed value in **4.3** rather than the alkylated sexithiophenes on 3',3''',4',4'''-positions, which causes hypsochromic shift due to steric congestion of the alkyl groups.<sup>[2]</sup> Thus, the  $\beta$ -ethano linker would cause planar conformation in the sexithiophenes, which would bring about bathochromic shift in absorption spectrum compared to the corresponding substituted oligothiophenes but not possessing such the linker.

Figure 4-2b illustrates the fluorescence spectra of **4.1**–**4.3**. On the contrary to the absorption spectra, the emission maximum of **4.1** is very close to that of **4.3**. As a result, Stokes shift in **4.1** is larger than that of **4.3**. The similar tendency could be observed in cyclic **4.2** as the intermediate emission maximum and Stokes shift between **4.1** and **4.3**.



**Figure 4.1.** (a) UV-vis absorption and (b) emission spectra of **4.1**–**4.3** (in  $\text{CH}_2\text{Cl}_2$ ).



**Table 4.1.** Spectral data of **4.1–4.3**.

compound	$\lambda_{abs} / \text{nm}$ ( $\epsilon / 10^4 \text{ L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$ )	$\lambda_{em} / \text{nm}$	Stokes shift / $\text{cm}^{-1}$
<b>4.1</b>	418 (10.56), 377 (9.22)	544	5541
<b>4.2</b>	418 (6.88), 367 (5.21)	540	5404
<b>4.3</b>	437 (4.44)	531	4050

To clarify the absorption spectra of **4.1–4.3**, the assignment of the absorption band was carried out with the aid of time-dependent density functional theory (TD-DFT) calculation at the B3LYP/6-31G\* level of theory with Gaussian 03.<sup>[3]</sup> Five structural isomers were tested in this experiment. One is calculated structure of sexithiophene chain depicted as **4.6a** (Chart 4.2) by DFT calculation, where the thiophene rings arrange *transoid* manner except for the central bithiophene. One of the others is optimized *cisoid* conformer **4.6b**. The other three are dimethyl substituted sexithiophenes (**4.6c** and **4.6d**) found in the crystal of **4.1**, two of which possess one inverted thiophene out of six thiophene rings, and one of which is all-*cisoidal* chain (see Chapter 3). The oscillator strength of lowest 10 excitations are calculated for each compound (Figure 4.2). The lowest energy transitions of all the calculated structures are predicted to correspond to HOMO→LUMO transition for each sexithiophene with large oscillator strength ( $f_{calc} \sim 2.0256\text{--}1.1724$ ) at 532–418 nm. The lowest transition energy was found in **4.6a**, and those decrease in the order of **4.6b**, **4.6c** and **4.6d**. This decrease should be partly due to loss of planarity of the sexithiophenes since the dihedral angle of optimized **4.6a** are calculated to be less than 15°. However, not only the planarity, but also *cisoid* thiophene arrangement is suggested to cause high energy shift by comparing **4.6a** to **4.6b–4.6d**. Furthermore, it was found that *cisoid*-fixed thiophenes **4.6b** and **4.6c** show relatively strong transition at higher energy region than strongest HOMO→LUMO transition. These could be assigned mainly to HOMO–1→LUMO and HOMO→LUMO+1 transition. The ratio of calculated oscillator strength is 3:1 and 2:1, respectively. These results suggest that the *syn*-fixation of the thiophene arrangement should cause two phenomena. One is high energy shift of lowest excited state corresponding to HOMO→LUMO transition. The other is enhancement of intensity of slightly higher energy absorption assigned to HOMO–1→LUMO and HOMO→LUMO+1 transition. On the other hand, the absorption behavior of **4.6d** is predicted to show highly blue-shifted peak without any other intense peaks even though **4.6d** has *cisoid* conformation. This can be attributed to highly twisted thiophene array in **4.6d**, which results in quite different orbital distribution from **4.6b** and **4.6c**.

The TD calculation could give an insight into the observed spectra. As shown in Figure 4.1, cage **4.1** exhibited two absorption bands, which were hypsochromically shifted relative to linear **4.3**. The blueshift can be rationalized by distorted conformation of the bridged sexithiophene chain. The appearance of the two bands can be ascribed to the effect of fixation of the thiophene arrangement in *cisoid* manner. These two structural characters should be first realized by the fixation of oligothiophene chains by carbon atoms at the both ends. The observed spectral features found in cyclic analogue **4.2** can be also explained by the same discussion. Therefore, it can be said that the absorption spectral data reflect the electronic state of each thiophene chain in solution state.

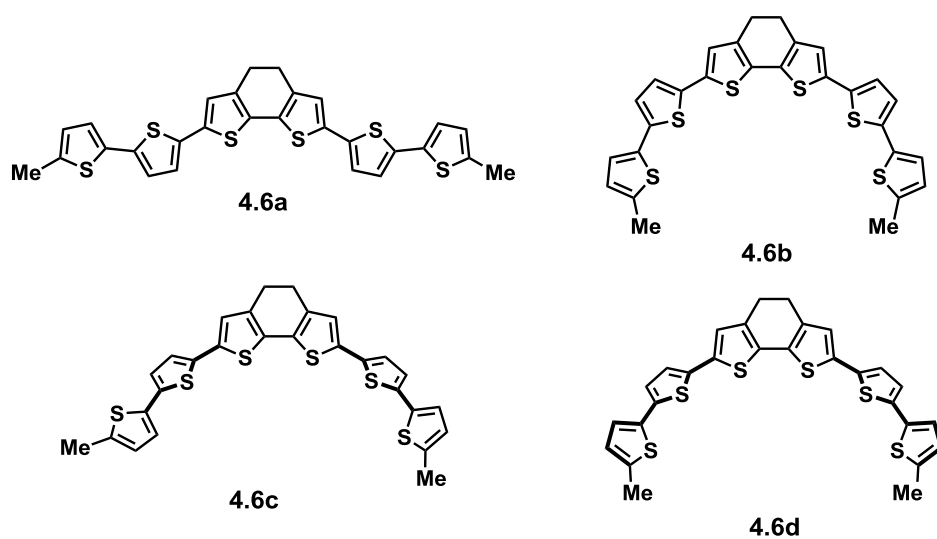


Chart. 4.2

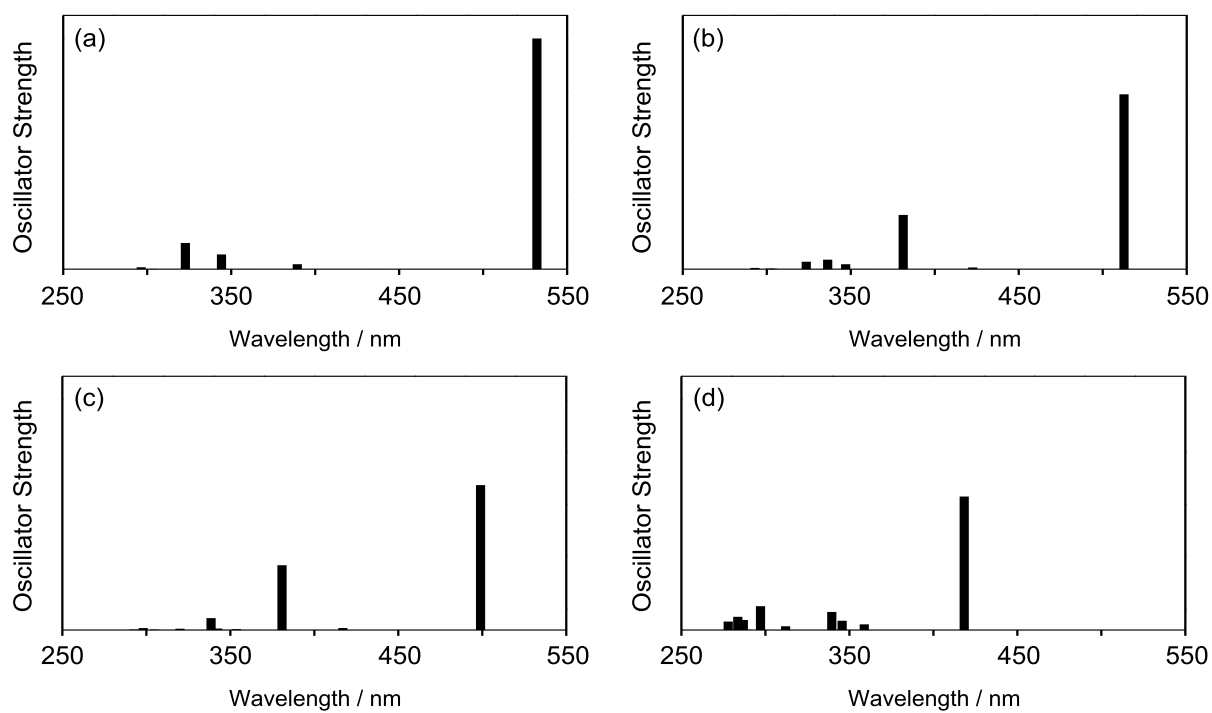
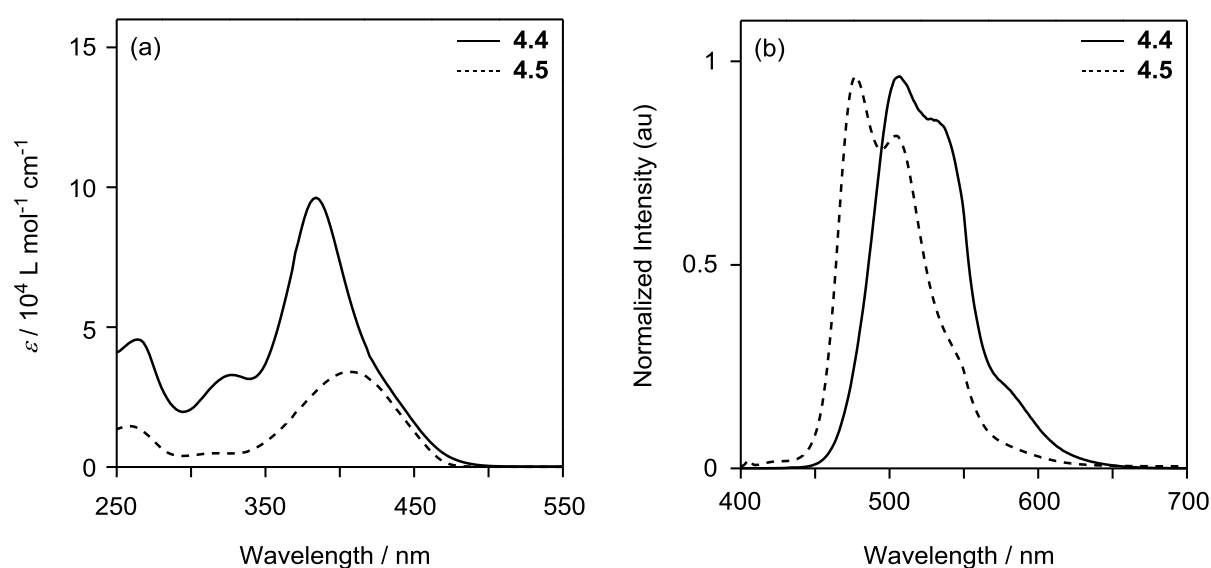


Figure 4.2. Calculated oscillator strength of (a) 4.6a, (b) 4.6b, (c) 4.6c and (d) 4.6d (TD-DFT at B3LYP/6-31G\*).

#### 4.2.2. UV-vis spectral measurement of cage and linear sexithiophenes

To obtain deep insight into the cage fixation effect of oligothiophenes, UV-vis spectroscopic measurements of quarterthiophene-based compounds **4.4** and **4.5** were carried out. The absorption maximum of **4.4** (384 nm) was hypsochromically shifted compared to linear **4.5** (408 nm). As mentioned above, similar tendency was also observed between **4.1** and **4.3**, but the energy differences in quarterthiophenes ( $153\text{ cm}^{-1}$ ) was larger than that of sexithiophenes ( $104\text{ cm}^{-1}$ ). On the other hand, the fluorescent spectrum of **4.4** was bathochromically shifted than that of **4.5**, which was qualified as a large Stokes shift ( $6317\text{ cm}^{-1}$ ). This value is also larger than that of sexithiophene cage **4.4** ( $5541\text{ cm}^{-1}$ ). The similar fluorescence shifts accompanied by smaller ring system are also observed in the case of cycloparaphenylenes<sup>[4]</sup>, so that the observed spectral change might be explained by the larger structural relaxation from the Franck–Condon state in **4.4**.



**Figure 4.3.** (a) UV-vis absorption and (b) emission spectra of **4.4** and **4.5** (in  $\text{CH}_2\text{Cl}_2$ ).

**Table 4.2.** Spectral data of **4.4** and **4.5**.

compound	$\lambda_{abs} / \text{nm}$ ( $\epsilon / 10^4 \text{ L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$ )	$\lambda_{em} / \text{nm}$	Stokes shift / $\text{cm}^{-1}$
<b>4.4</b>	384 (9.63), 328 (3.29)	506	6278
<b>4.5</b>	408 (3.40)	477	3545

This absorption spectra of these quarterthiophene derivatives could also be rationalized by TD-DFT calculation of model compounds **4.7a–4.7d** (Chart 4.3) at B3LYP/6-31G\* level of theory. The structurally optimized model compound **4.7a**, possessing *anti-syn-anti* arranged thiophenes, is predicted to show one strong peak at longest wavelength region. On the other hand, the absorption of **4.7b**, bearing optimized structure of all-*syn* quarterthiophene, is estimated to have two peaks corresponding to HOMO→LUMO and a set of HOMO-1→LUMO/HOMO→LUMO+1 excitations, respectively. The ratio of the oscillator strength of these two is 8:1, which qualitatively agree with observed spectra. The other model compound **4.7c**, which was dimethyl capped quarterthiophene bridge found in the crystal of **4.4**, is also calculated to show strong HOMO→LUMO and weak HOMO-1→LUMO/HOMO→LUMO+1 absorption. These results suggest that the dominant contribution to

the UV spectroscopy is the electronic state of each thiophene chain as is observed in sexithiophene derivatives.

It should be noted that **4.4** exhibited highly broaden shoulder around 450 nm. This could be attributed to the forbidden transition involving the charge transfer (CT) absorption between quaterthiophene bridges. Therefore, it can be said that the intramolecular interaction became observable by incorporation of oligothiophenes in small and rigid cage scaffold, even though the effect would be not significant. The same phenomena might appear in the spectrum of **4.1**, however, such an interaction would be too small to detect by absorption spectroscopy technique.

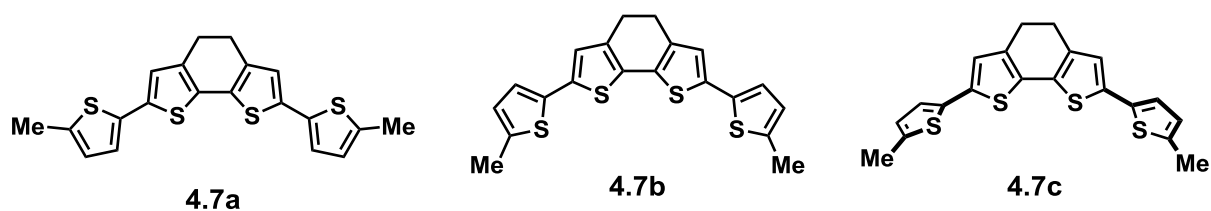
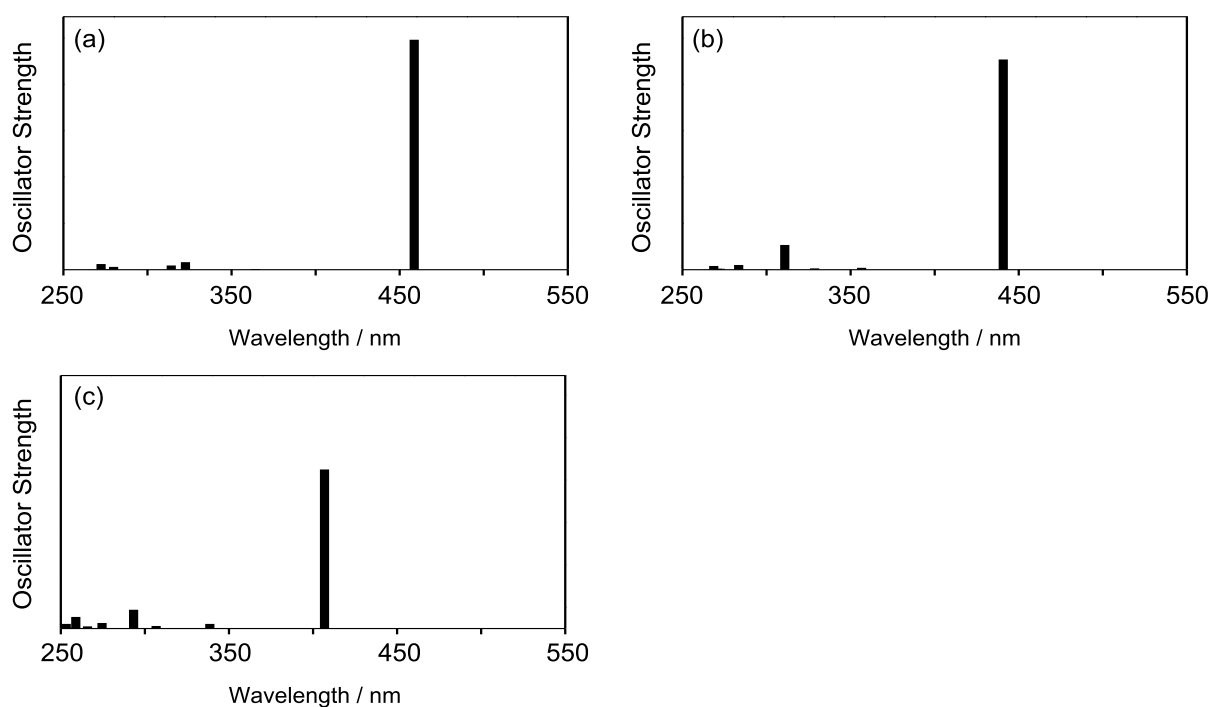


Chart 4.3.

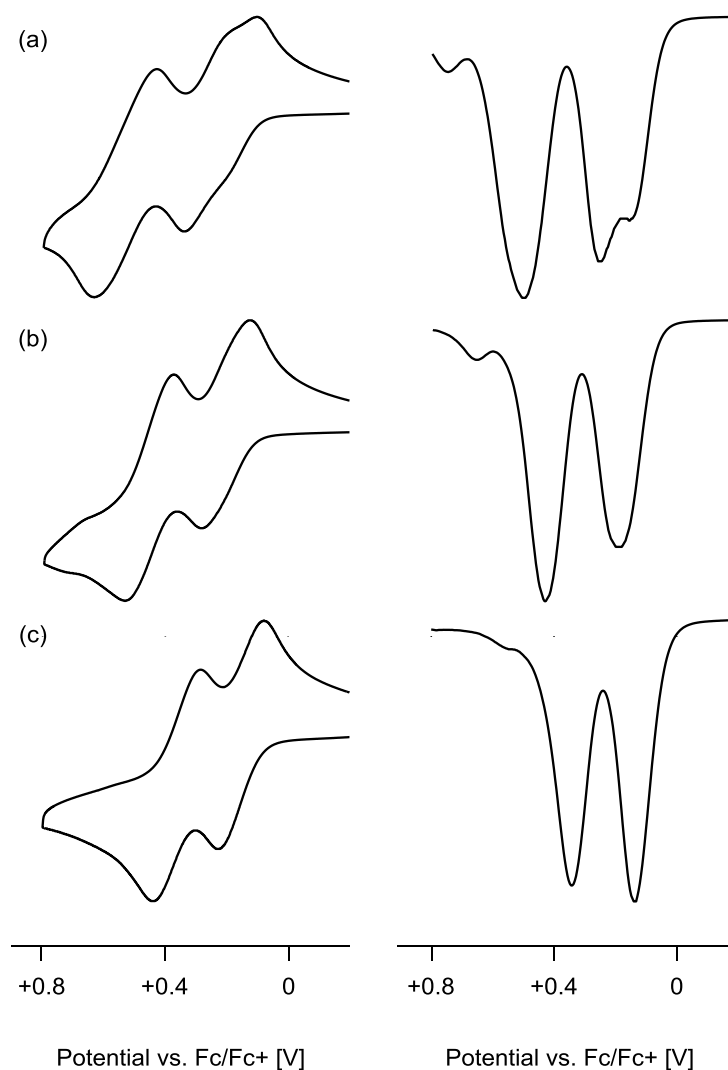


**Figure 4.4.** Calculated oscillator strength of (a) **4.7a**, (b) **4.7b** and (c) **4.7c** (TD-DFT at B3LYP/6-31G\*).

#### 4.2.3. Cyclic voltammetry measurement of cage, cycle and linear sexithiophenes

Since the oxidation potentials provide helpful information on the electronic interactions between the bridged sexithiophenes in the oxidized states, voltammetry measurements were performed in dichloromethane ( $\text{CH}_2\text{Cl}_2$ ) solution with tetra-*n*-butylammonium hexafluorophosphate (*n*- $\text{Bu}_4\text{NPF}_6$ ) as a supporting electrolyte. As a result, a unique electronic interaction in cage **4.1** was observed in cyclic voltammetry (CV) and differential pulse voltammetry (DPV) measurements (Figure 4.5). All the sexithiophene derivatives **4.1–4.3** exhibit two reversible redox waves, which correspond to monocation and dication formation for each sexithiophene moiety. However,

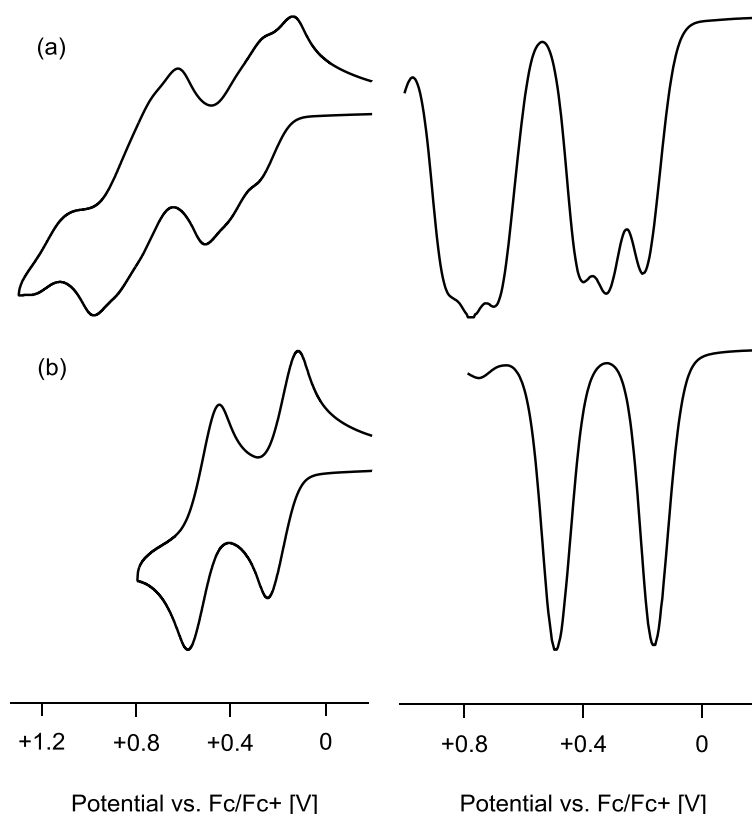
as can be seen in Figure 4.2a, the first oxidation peak of **4.1** is broadened and a new peak appears as a shoulder. This peak broadening could be ascribed to stepwise oxidation of one electron (**4.1<sup>•+</sup>**) followed by two-electron transfer (**4.1<sup>3(•+)</sup>**). This redox behavior indicates an intramolecular interaction between three oligothiophenes in the mono(radical cation) species **4.1<sup>•+</sup>**. Appearance of the electronic interaction at the mono(radical cation) state is different from that observed in alkylene-bridged cyclophane-type oligothiophenes,<sup>[5]</sup> but is similar to those linked by other spacers.<sup>[6]</sup> The higher potential of the second oxidation wave of **4.1<sup>3(•+)</sup>** compared to **4.3<sup>•+</sup>** is due to increased Coulomb repulsion in the formation of the hexacation species. The first oxidation wave of **4.2** is also broadened, but the extent of the peak broadening is smaller than that observed in **4.1**. This indicates that tight fixation and/or incorporation of a larger number of oligothiophene units enhances the electronic communication between the bridged thiophene chains.



**Figure 4.5.** Cyclic voltammograms (left) and differential pulse voltammograms (right) of (a) **4.1**, (b) **4.2** and (c) **4.3** in CH<sub>2</sub>Cl<sub>2</sub> solution containing 0.1 M *n*-Bu<sub>4</sub>NPF<sub>6</sub>.

#### 4.2.4. Cyclic voltammetry measurement of cage and linear quaterthiophenes

The investigation of electronic interaction in **4.4** at the oxidized state was also carried out with CV and DPV measurement (Figure 4.6). As was the same as oxidation process of sexithiophenes, quaterthiophenes **4.4** and **4.5** showed two reversible redox waves. However, the peak broadening of **4.4** in Figure 4.6a was found to be more pronounced than that observed in **4.1** (cf. Figure 4.5a). DPV measurement revealed that the each oxidation process includes three electron transfer steps possessing distinct oxidation potentials. Considering the redox potentials, the first wave is composed of the three peaks corresponding to formation of mono-trication and second one consists of the three peaks from the generation of tetra-hexacation. This one-by-one electron transfer is suggestive of the retainment of intramolecular interaction at any oxidized states in **4.4**. Considering the molecular structure, such the interaction in **4.4** should be caused by not  $\pi$ -dimer formation but homo-conjugation, or orbital overlap between the neighboring thiophenes around the bridge head carbon atoms. Therefore, the enhanced intramolecular interaction in **4.4** compared to **4.1** would reflect the tightly fixed thiophene bridges, which cause effective orbital interaction at the thiophene rings of both ends.



**Figure 4.6.** Cyclic voltammograms (left) and differential pulse voltammograms (right) of (a) **4.4** and (b) **4.5** in  $\text{CH}_2\text{Cl}_2$  solution containing 0.1 M  $n\text{-Bu}_4\text{NPF}_6$ .

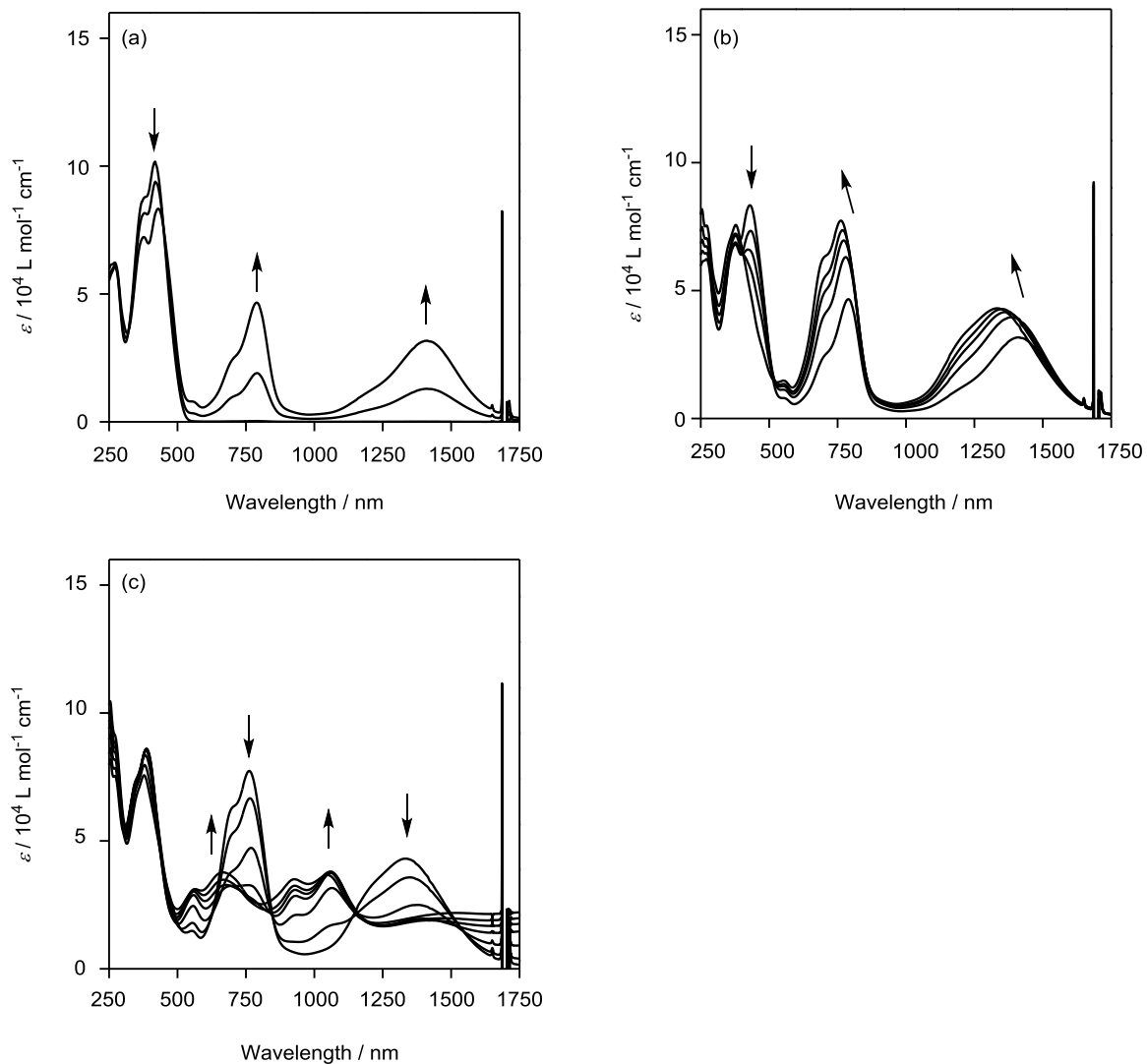
#### 4.2.5. Oxidation titration of cage and linear sexithiophenes

As discussed above, the intramolecular interaction in the oligothiophene-based cage is pronounced in the oxidized state. Especially, oxidation potential of mono(radical cation) species could be observed as distinct peak

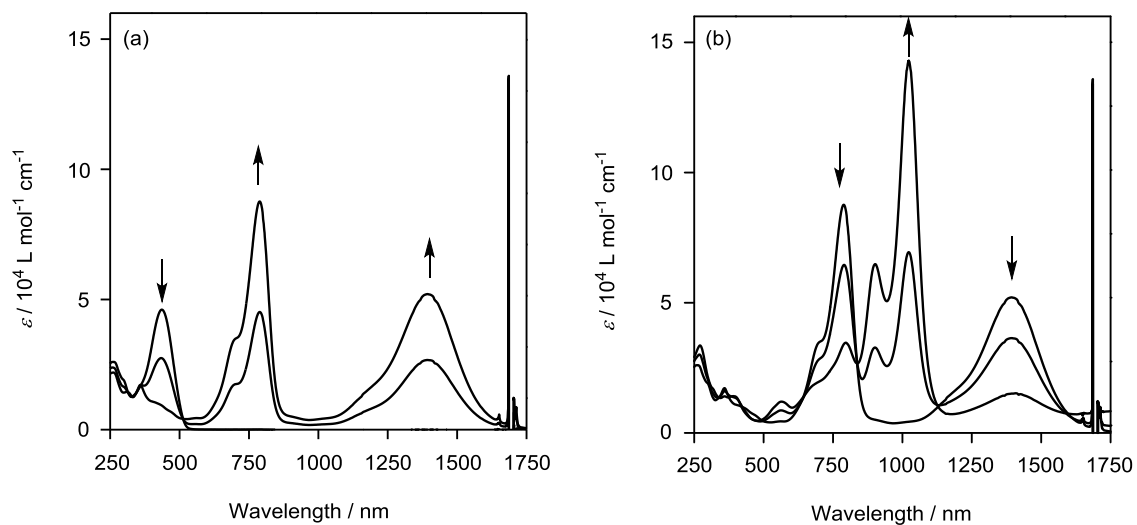
in both cases of **4.1**<sup>+</sup> and **4.4**<sup>+</sup>, which suggests high stability at this state. This fact indicates the possibility of isolation of the one-electron oxidized state. To obtain the electronic states of the oxidized species more deeply, oxidation titration experiment was carried out with antimony pentachloride (SbCl<sub>5</sub>) as an oxidant. It should be noted that SbCl<sub>5</sub> can remove one electron from a substrate when using 1.5 equivalents excess amount of SbCl<sub>5</sub> through the electron transfer described in eq 1.



The titration of sexithiophene cage **4.1** was performed by successive addition of 0.75 equivalents (0.5 electron oxidation) of CH<sub>2</sub>Cl<sub>2</sub> solution of SbCl<sub>5</sub> to the solution of **4.1**. For comparison, the oxidation titration with linear analogue **4.3** was also carried out. In the spectra of **4.1**, the intensities of two peaks at 790, 1400 nm were perpendicularly increased up to the addition of 1.5 equivalents. of SbCl<sub>5</sub> (Figure 4.7a). The same phenomena was also observed in the oxidation spectrum of **4.1**, which can be assigned to mono(cation radical) species formation (Figure 4.8). Further addition of SbCl<sub>5</sub> up to 4.5 equivalents of SbCl<sub>5</sub> to the solution caused peak shift toward higher energy region (29, 77 nm, respectively) whereas such a spectral shift could not be observed in the oxidation of **4.3**. This spectral change can be explained by polaron-polaron interaction between the bridges in the triply oxidized species.<sup>[7]</sup> However, the lack of isosbestic points suggests that the oxidation proceeds through the mixture of various oxidation state. This fact implies that the electronic interaction as observed in cyclic voltammetry measurement is so little that the chemical oxidation could not detect stepwise oxidation as expected in the CV and DPV measurement. Further addition of SbCl<sub>5</sub> from 4.5 to 9.0 equivalents caused monotonous spectral changes, that is, decrease of two bands around 790 and 1400 nm and increase of one broadened band around 1000 nm. However, addition of 10 equivalents of SbCl<sub>5</sub> did not enough to furnish the spectral change. Addition of hydrazine monohydrate did not recover neutral one, which suggest decomposition of the oxidized species at this stage even though such instability is inconsistent with CV measurement.



**Figure 4.7.** Electronic absorption spectra of oxidized **4.4** with the addition of (a) 0–1.5 eq. (b) 1.5–4.5 eq. and (c) 4.5–9.0 eq. of  $\text{SbCl}_5$ .



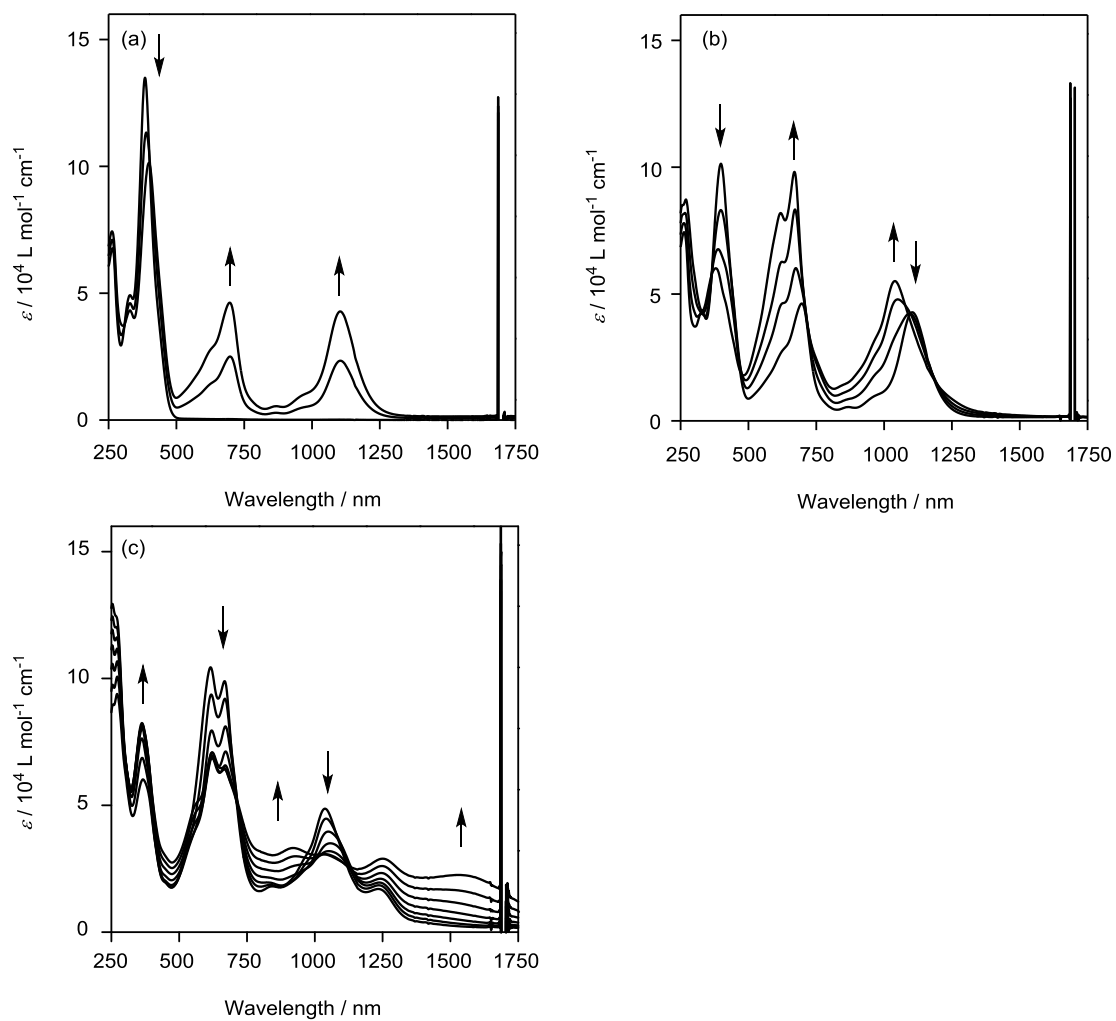
**Figure 4.8.** Electronic absorption spectra of oxidized **4.5**. (a) 0–1.5 eq. and (b) 1.5–3.0 eq. of  $\text{SbCl}_5$ .



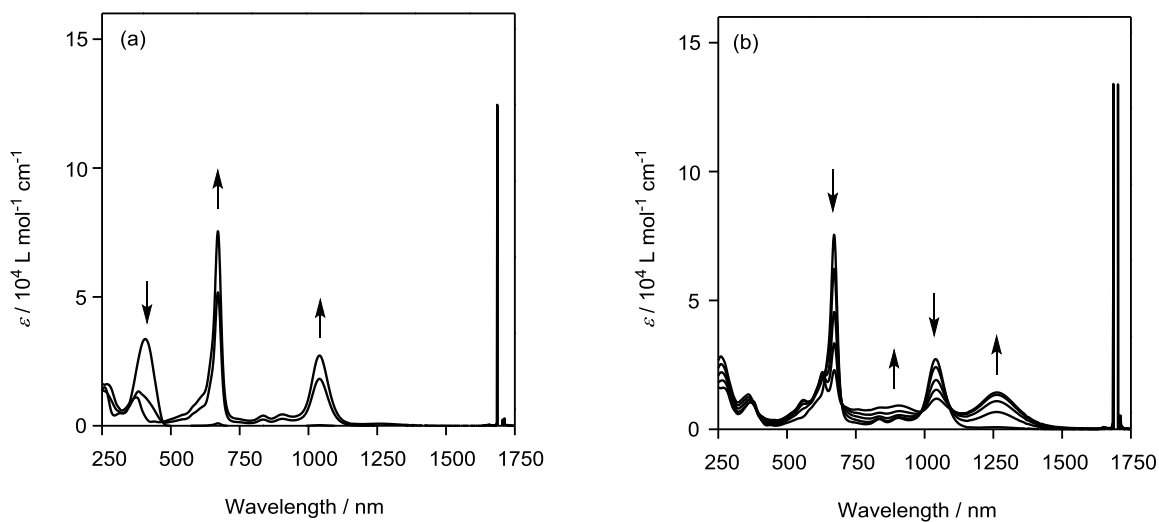
#### 4.2.6. Oxidation titration of cage and linear quaterthiophenes

Considering the results of voltammetry measurement, the enhanced interchain interaction of **4.4** compared to **4.1** will allow the observation of stepwise oxidation process in **4.4** by chemical oxidation method. Thus, I examined the oxidation titration with  $\text{SbCl}_5$  (Figure 4.9). Up to the addition of 1.5 equivalents of  $\text{SbCl}_5$ , decrease of one neutral absorption at 399 nm and increase of two absorption at 697 and 1103 nm were observed. Successive addition of  $\text{SbCl}_5$  caused dramatic change of increase of three peaks at 616, 667 and 1037 nm. These peak shifts involved isosbestic points at 476, 711 and 1092 nm. This suggests that the clean conversion from mono(radical cation) **4.4<sup>•+</sup>** to tri(radical cation) species **4.4<sup>3(•+)</sup>**. Large difference of absorption region of these two species enable us to distinguish the two oxidized species and to confirm the stepwise conversion by electronic spectroscopic technique. The spectral change by oxidation of linear **4.5** is almost the same as **4.3** except for the wavelength (Figure 4.10). Therefore, the spectral differences between **4.1** and **4.4** comes from the difference of not just thiophene conjugation length but the interaction of thiophene bridges. This experimental result should reflect the enhanced intrachain electronic interaction between the three bridges in **4.4**, reflecting the structure of fixed and neighbored thiophene chains.

Further oxidation by  $\text{SbCl}_5$  led to decrease of two bands at 711 and 1094 nm, which was saturated upon addition of 9.0 equivalents of  $\text{SbCl}_5$ . However, new appeared bands were so broadened that those could not be assigned easily. In addition, the increase of the intensity of new bands did not furnished even though the spectral change of first two bands are saturated. As is the same as the sexithiophene cage, addition of hydrazine did not recover the original spectrum, which suggests conversion of **4.4<sup>3(•+)</sup>** into some structurally distinctive species rather than higher oxidized species, such as **4.4<sup>6(•+)</sup>**.



**Figure 4.9.** Electronic absorption spectra of oxidized **4.4** with the addition of (a) 0–1.5 eq. (b) 1.5–4.5 eq. and (c) 4.5–9.0 eq. of  $\text{SbCl}_5$ .



**Figure 4.10.** Electronic absorption spectra of oxidized **4.5**. (a) 0–1.5 eq. and (b) 1.5–3.0 eq. of  $\text{SbCl}_5$ .

### 4.3 Conclusion

I investigated the optical and electrochemical properties of the series of cage compounds and the analogues. In the UV spectra cage compounds **4.1** and **4.4** exhibited hypsochromically shifted peak relative to linear analogues **4.3** and **4.5** with changing the spectral shape. TD-DFT calculation suggested that these spectral features can be assigned to the effect of twisted and *cisoid*-fixed oligothiophenes. Such a highly distorted and specific conformational oligothiophenes can be first realized by incorporation of oligothiophenes in cage architectures. Highly strained structural feature of the oligothiophene bridges could be also observed in emission spectra as bathochromically shifted emission of the cages. The voltammetry measurements succeeded to detect intramolecular interaction between the bridged oligothiophenes both in cage **4.1** and **4.4**. Electrochemical oxidation with  $\text{SbCl}_5$  also support the presence of the electronic communication between the  $\pi$ -bridges, which was enhanced in **4.4** relative to **4.1**.

These results highlight the importance of tight fixation and congestion of  $\pi$ -moieties for 3D electronic communications. In addition, such tight fixation of oligothiophenes also causes structural distortion, which will be reflected in optical properties of higher energy absorption and lower energy emission compared to the corresponding  $\pi$ -fragments. These characteristic properties derived from cages architecture will give helpful information to rationalize the properties of other 3D  $\pi$ -systems and hopefully be a good guideline for tailoring other various 3D molecular systems in the future.

## 4.4 Experimental Section

### 4.4.1 General

All experiments with moisture- or air-sensitive compounds were conducted in anhydrous solvents under a nitrogen atmosphere in well-dried glassware. Anhydrous dichloromethane was purchased from Kanto Chemical Co., Inc. and used without further purification. Dichloromethane solution of antimony pentachloride was purchased from Sigma-Aldrich. UV-vis absorption spectra were measured on a JASCO V-570 spectrometer. Fluorescence spectra were measured on a JASCO FP-6300 spectrofluorometer. Cyclic voltammetry measurement was conducted with a BAS CV-50W electrochemical analyzer in a 0.1 M *n*-Bu<sub>4</sub>NPF<sub>6</sub> dichloromethane solution at room temperature.

### 4.4.2 General procedure for the electronic spectral measurements

To the solution of 3.0 mL of dichloromethane solution of substrate (*ca.*  $10^{-6} \sim 10^{-5}$  M) in a quartz cell .equipping a cap sealed with septum added a solution of dichloromethane solution of SbCl<sub>5</sub> (*ca.*  $10^{-3} \sim 10^{-4}$  M). Each spectrum was measured soon after mixing (within 1 minute).

#### 4.5. References

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## Chapter 5.

### Synthetic Attempt of Tetrahedral Oligothiophene

#### 5.1. Introduction

Tetrahedrane, or tricyclo[1.1.0.0<sup>2,4</sup>]butane, is a tetrahedral-shaped polyhedral hydrocarbons and consists of four carbons and four protons (C<sub>4</sub>H<sub>4</sub>). Although much efforts have been paid for the synthesis of such a structurally fascinating molecule, the parent compound itself is still unknown probably due to the high molecular strain. Tetra-*tert*-butyl substituted<sup>[1]</sup> and tetrakis(trimethylsilyl)ethynyl substituted tetrahedranes<sup>[2]</sup> have been successfully synthesized and characterized. On the other hand,  $\pi$ -expanded tetrahedranes could be synthesized by utilizing metal-ligand coordination chemistry.<sup>[3]</sup> Recently, Yamago and co-workers reported the successful synthesis of C-C bond based tetrahedral shaped molecule by employing platinum complex as a key precursor.<sup>[4]</sup> Zhang reported their trial toward tetrahedral shaped molecule from three-fold symmetric acetylene monomer. However, on the contrary to their initial expectation, the metathesized product was tetramer with  $D_{2h}$  symmetry as a single isolable isomer, but not  $T_d$  symmetric tetrahedral compound.<sup>[5]</sup>

I suppose that  $\pi$ -expanded tris(2-thienyl)methanes meet the requirements for using as a monomer unit of such  $\pi$ -conjugated tetrahedranes. Since the three thiophenes are attached directly to carbon atom, such the compounds is reminiscent of the tetrahedrane just replacement of C-C bond by thiophene chains. However, as shown in the previous chapter, tetramerization of tris(2-thienyl)derivatives could not be isolable but only dimer could be obtained. This should not be due to molecular strain because possibly more strained or congested dimers were formed. The reason of unsuccessful synthesis of tetrameric cages through metathesis reaction of tris(2-thienyl)methanes should be quite small amount of production of tetramer, which gave small and overlapped peak on those of other oligomers in GPC analysis. Thus, for construction of tetrahedral cage, a new strategy aimed at both preventing the formation of bicycle-type dimer and higher oligomers are required. In this chapter, I describe the synthetic attempt toward tetrahedral cage **5.1** starting from dimer of tris(2-thienyl)methane derivative. This synthetic attempt can provide the scope and limitation of the cage synthesis strategy for the construction of  $\pi$ -expanded 3D oligothiophene-based molecular architecture. Furthermore, the accommodation behavior of the sphere-like sulfur-rich cavity in **5.1** will be interesting, which will give significant impact on host-guest chemistry.

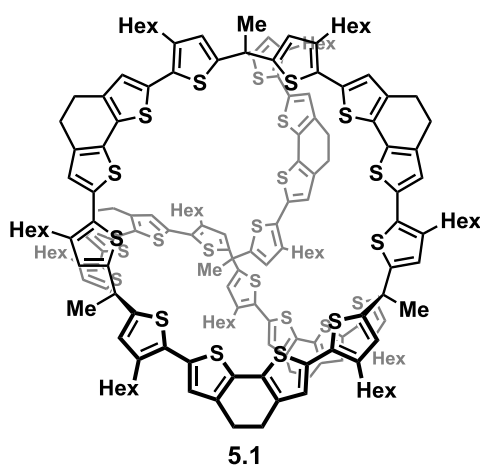
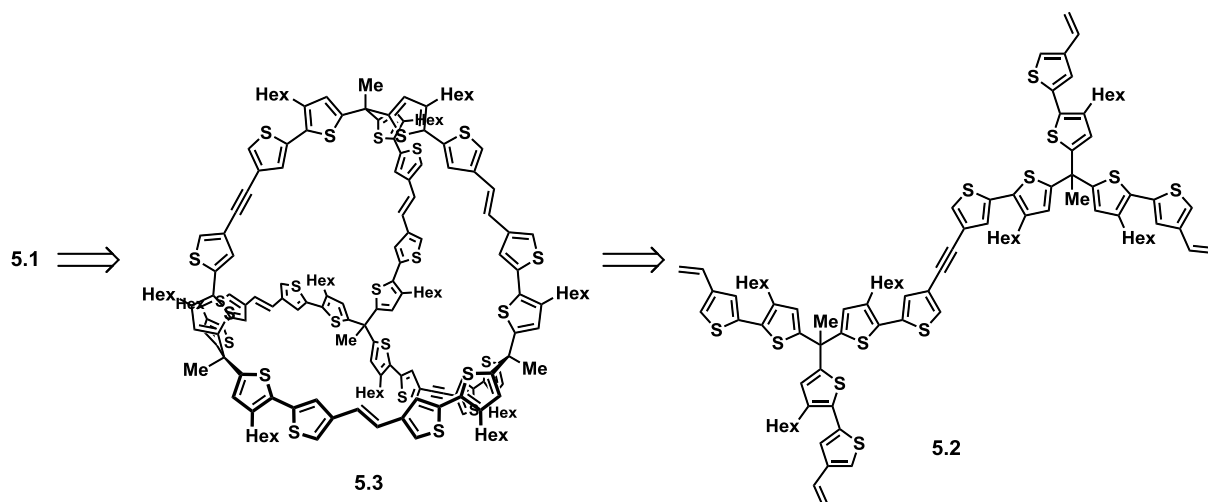


Chart 5.1

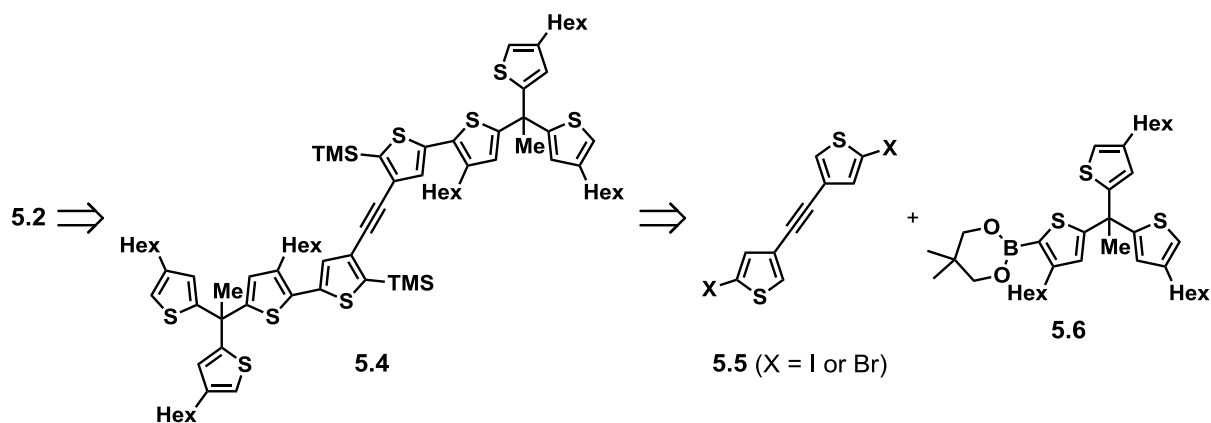
## 5.2. Synthetic strategy

The synthetic difficulty should be how to tetramerize 3D molecular platforms. My first attempt to synthesize such molecules was separation by GPC, or size exclusion chromatography as a by-product of cage-shaped dimer. However, it has already demonstrated that the metathesis reaction only gave dimerized compound as a sole isolable product. Tetramer or higher order molecular composites could not be isolated in the purification process. This fact indicates that the synthetic strategy should involve an appropriate monomer unit that prevents cage formation. To satisfy this requirement, I designed new monomer unit **5.2**, where two tris(2-thienyl)methanes are connected by acetylene linker at the one of the three  $\beta$ -position of each tris(bithienyl)methane. I expected that the acetylene linker would be enough rigid to interfere the formation of cage-like structure, or intramolecular coupling in **5.3**. If this strategy works, tetramer of tris(2-thienyl)methane units, or dimer of **5.2** will be able to be isolated by GPC method as a smallest metathesized product. The acetylene linker will be able to be reduced into the same saturated alkyl linkers by hydrogenation. Subsequent oxidative coupling reaction can afford the all-thiophene chain bridged tetrahedrane **5.1**.



**Scheme 5.1.**

With this strategy in mind, I next seek for the way to synthesize the key monomer **5.2**. Although various synthesis routes are possible, I first planned the reaction as shown below. The key fragment is dithienylacetylene **5.4** and unsymmetrical substituted tris(2-thienyl)methane **5.5**. In the next section I present the synthesis of **5.2** and the attempt of construction of tetrahedral oligothiophene.

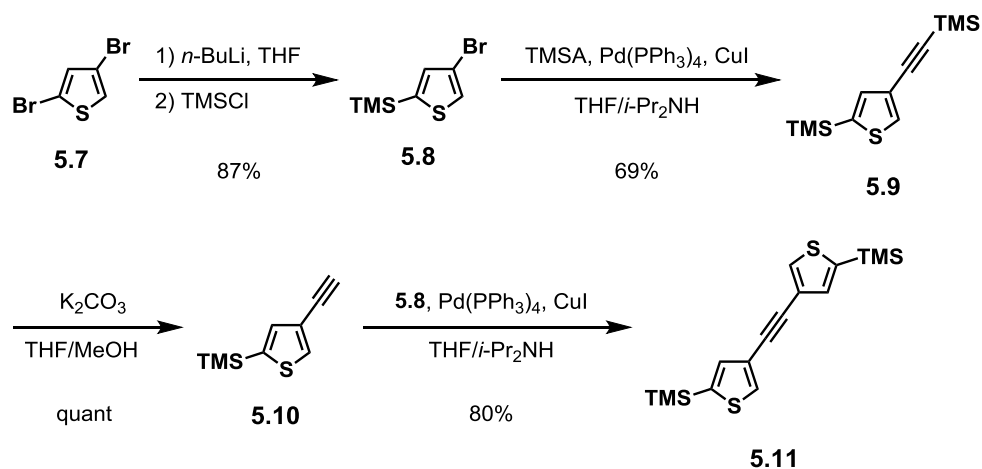


Scheme 5.2.

### 5.3 Results and discussions

#### 5.3.1. Synthesis of dithienylacetylene moiety

The synthesis of **5.5** was first started from 2,4-dibromothiophene **5.7** (Scheme 5.3). Thus, TMS protection of  $\alpha$ -position followed by Sonogashira coupling with trimethylsilylacetylene (TMSA) afforded **5.9**. After deprotection of TMS group at only acetylene moiety, resulting **5.10** was coupled with **5.8** to form **5.11**.

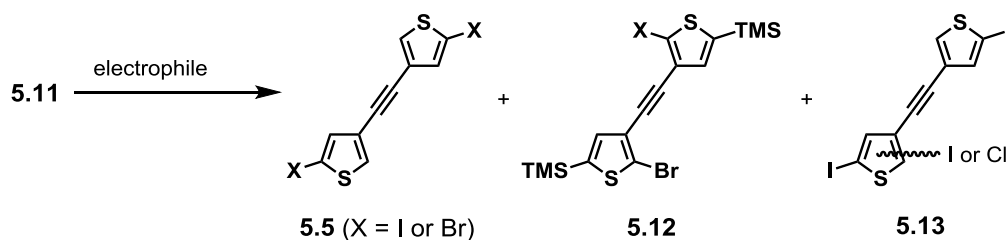


Scheme 5.3.

TMS group at the  $\alpha$ -position of the thiophene is known to be selectively substituted by electrophiles such as NBS<sup>[6]</sup> or ICl<sup>[7]</sup>. However, this substitution reaction failed to introduce the halogen atoms at the TMS substituted position (Scheme 5.4, Table 5.1). For example, addition of NBS in CHCl<sub>3</sub> solution of **5.11** resulted in recovery of the starting material. Replacing the solvent by DMF resulted in bromination at the opposite side of TMS group to produce **5.12**, suggested by EI-MS (entry 2). By using ICl instead of NBS, *ipso*-substitution at the TMS substituted carbon would be proceeded, but the EI-MS also suggested that the over-introduction iodine or chlorine atoms (**5.13**) (entry 3). Quite complicated <sup>1</sup>H-NMR spectrum of the resulting mixture made it difficult to assign the molecular structure. Lowering reaction temperature led to partial substitution with not only iodine but also chlorine



atoms (entry 4). This fact indicates that the side-reaction of chlorination was accompanied by desired iodination even at low temperature.

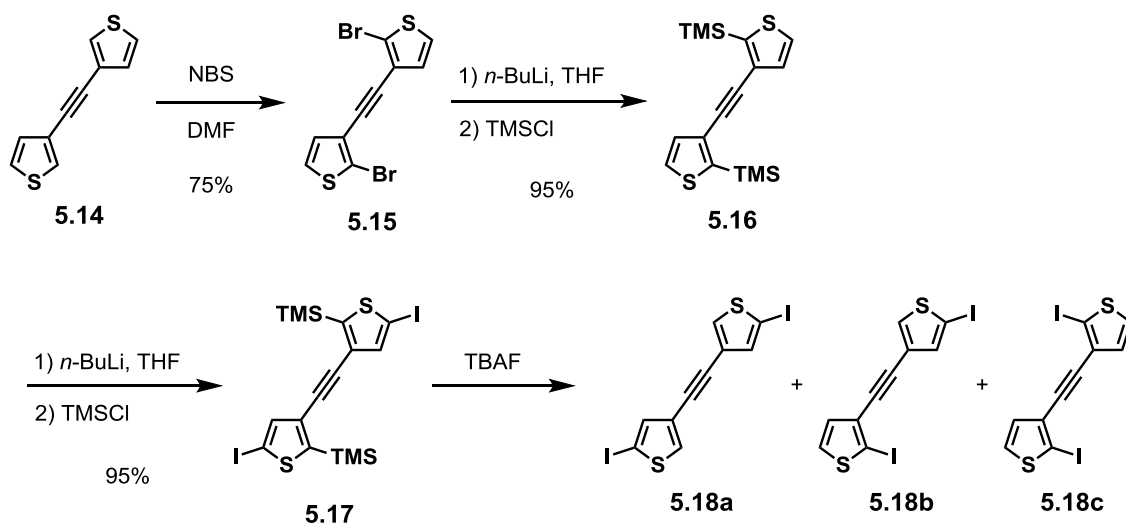


Scheme 5.4..

Table 5. 1. Reaction conditions of Scheme 5.4.

entry	reagents	solvents	temp and time	results
1	NBS	THF	rt, overnight	recovery of <b>5.11</b> (90%)
2	NBS	DMF	rt, overnight	mixture of mono- and dibrominated compound ( <b>5.12</b> )
3	ICl	CH <sub>2</sub> Cl <sub>2</sub>	-78 °C to rt, overnight	Iodo- and chlorinated compound ( <b>5.13</b> )
4	ICl	CH <sub>2</sub> Cl <sub>2</sub>	-78 °C, 4 h	Partial substitution of iodo- and chlorine atoms

As an alternative pathway, I secondly examined the reactions depicted below (Scheme 5.5). First bis(3-thienyl)acetylene **5.14**<sup>[8]</sup> was brominated and silylated to generate **5.15** and **5.16**. Lithiation followed by iodination afforded **5.17**, which is corresponding to trimethylsilylated derivative of **5.5**. Surprisingly the attempt of removal of TMS group by tetrabutylammonium fluoride (TBAF) lead to iodine partial migration to opposite  $\alpha$ -position of the thiophene. This migration can be easily detected different *J* value between the protons on 2,3 position and 2,4 position (see <sup>1</sup>H NMR spectra in Figure 5.1). It was found that the addition of acetic acid could solve the migration problem, although the quantitative desilylation have not been achieved yet (Table 5.2 entries 3–8). Because of this deprotection difficulty, I decided to employ **5.17** for tetrahedral oligothiophene construction as an acetylene fragment.



Scheme 5.5.

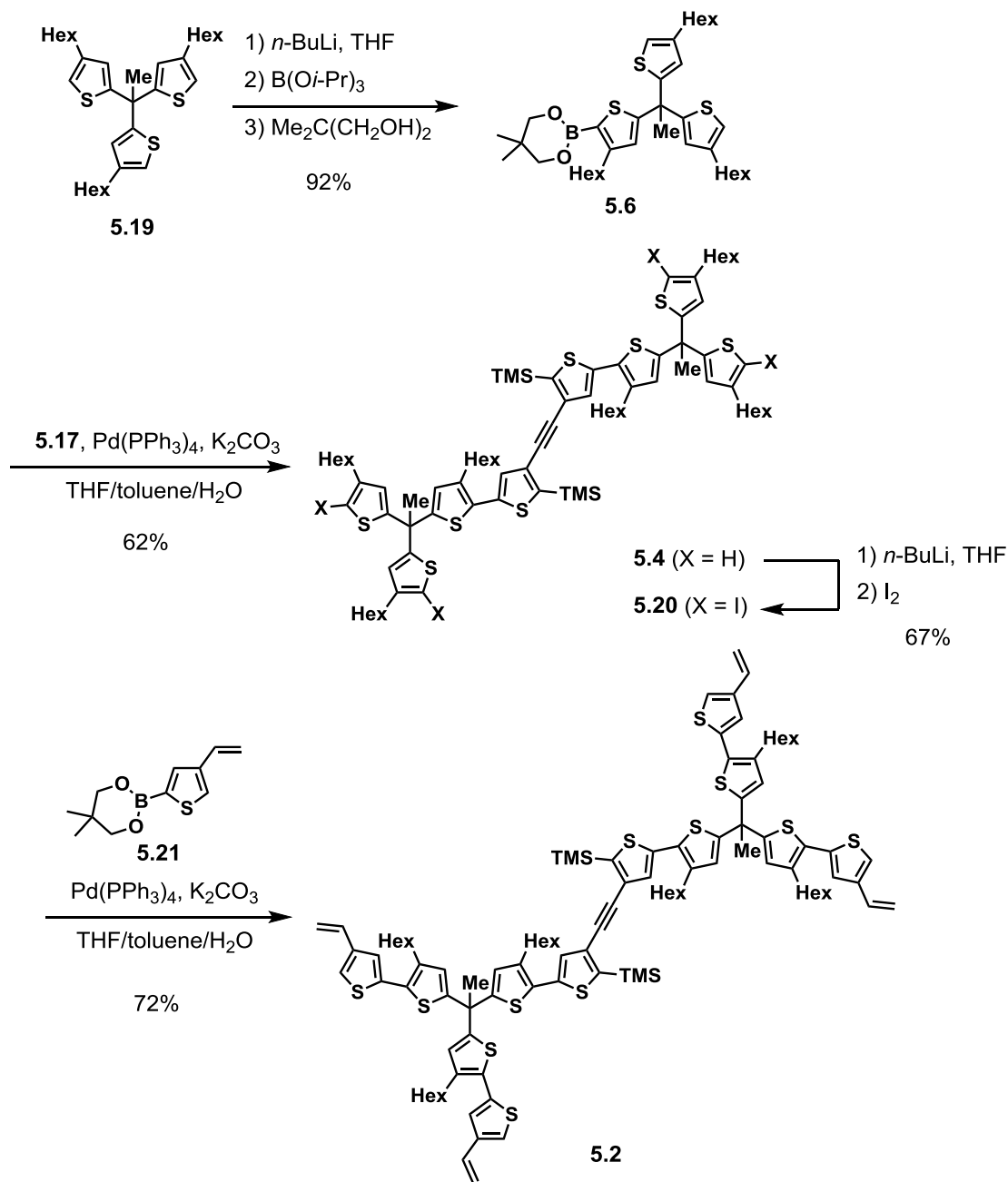
**Table 5.2.** Reaction conditions of Scheme 5.5.

entry	additive	temp and time	ratio of products <sup>[a]</sup> ( <b>5.18a</b> : <b>5.18b</b> : <b>5.18c</b> )	isolated yield of <b>5.18a</b> [%]
1	none	rt, overnight	1.1 : 1.0 : 0.9	Not isolated
2	none	-78 °C, 30 min	1.4 : 1.0 : 0.2	Not isolated
3	AcOH ( 2 eq.)	rt, 10 min	4.3 : 1.0 : 0	58
4	AcOH ( 4 eq.)	rt, 10 min	4.4 : 1.0 : 0	72
5	AcOH (100 eq.)	rt then reflux, overnight	recovery of <b>5.17</b>	0
6	AcOH ( 2 eq.)	0 °C, 10 min	3.8 : 1.0 : 0	78
7	AcOH ( 2 eq.)	-78 °C, 10 min	recovery of <b>5.17</b>	0
8	AcOH ( 2 eq.)	-78 °C to rt, overnight	4.0 : 1.0 : 0	66

[a] The ratio was calculated from that of integral values in the NMR spectrum.

### 5.3.2. Synthesis of unsymmetrically substituted tris(2-thienyl)methane moiety

The coupling counterpart **5.6** was then synthesized from **5.19** (Scheme 5.6). Lithiation and borylation of **5.19** with small excess amount of reagents can isolate boronic acid ester **5.6** after silica-gel column chromatographic work-up. Suzuki coupling of **5.17** with **5.6** gave **5.4** in moderate yield. This reaction could not proceed when using thiophene boronic acid ester both with and without formyl group at 4-position. Subsequent iodination and Suzuki-Miyaura coupling also proceeded smoothly to produce **5.2**.

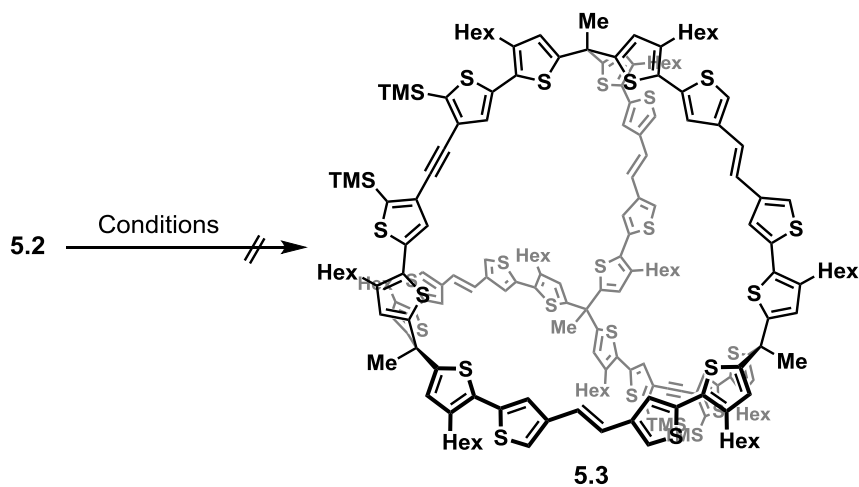


Scheme 5.6.

### 5.3.3. Synthetic attempt for the construction of tetrahedral-shaped molecule

Since the initially designed precursor could be prepared, metathesis reaction of **5.2** was carried out under high dilution condition describe as cage synthesis protocol. However, the reaction resulted in recovery of **5.2** (Scheme 5.7, Table 5.3, entry 1). Both replacement of solvent (entry 2) and catalyst (entry 3) caused production of undefiable mixture with remained **5.2**. Surprisingly, metathesis reaction also did not proceed even at 10-fold higher concentration and **5.2** was just recovered (entry 4). It can be ruled out that the presence of acetylene linker interrupt metathesis reaction.<sup>[9]</sup> So far the reason for inactivity of **5.2** toward Grubbs catalyst is still unclear, and it should be needed to examine other strategies, such as replacement of monomer unit from **5.2**, for the construction

of oligothiophene-based tetrahedral topologies.



Scheme 5.7.

Table 5.3. Reaction conditions of metathesis reaction in Scheme 5.7.

entry	solvent	catalyst	temp and time	conc. / mM	results
1	CH <sub>2</sub> Cl <sub>2</sub>	Grubbs II	40 °C, 24 h	1.0	recovery
2	toluene	Grubbs II	110 °C, 24 h	1.0	recovery with unidentifiable mixture
3	toluene	Hoveyda-Grubbs II	110 °C, 24 h	1.0	recovery with unidentifiable mixture
4	CH <sub>2</sub> Cl <sub>2</sub>	Grubbs II	40 °C, 24 h	10	recovery

#### 5.4. Conclusion

In this chapter, I attempted to construct quaterthiophene-based tetrahedral molecular architecture by utilizing the cage synthesis protocol. Although I succeeded in preparing the tetravinyl precursor **5.2**, the metathesis reaction to form ethylene and acetylene tethered tetrahedral molecule did not proceed under the employed condition. Unfortunately I could not have clarified the optimized reaction conditions or structural requirement to realize tetrahedral oligothiophene. However, the construction of such sophisticated 3D molecular architectures has not been fully explored research topic and the various synthetic methodology should be challenged to achieve the creation of novel molecular architectures, which can, not only offer the synthetic way of the construction of the molecule, but also bring development in the field of synthetic chemistry.

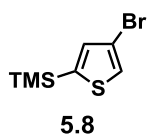
## 5.5. Experimental Section

### 5.5.1 General

All experiments with moisture- or air-sensitive compounds were conducted in anhydrous solvents under a nitrogen atmosphere in well-dried glassware. Anhydrous dichloromethane and tetrahydrofuran (THF) were purchased from Kanto Chemical Co., Inc. and used without further purification. Other anhydrous solvents were prepared by distillation over calcium hydride. Column chromatography were performed on a silica gel (Silica gel 60N, Kanto Chemical Co., Inc.) or alumina (Aluminium oxide 90, Merck). Melting points were taken on a Yanako MP 500D apparatus and are uncorrected. Preparative gel permeation chromatography (GPC) was performed on a recycling HPLC (JAI LC-9201 equipped with JAIGEL 1H and JAIGEL 2 H columns) with using chloroform as an eluent. Infrared spectra were recorded on a JASCO FT/IR-660M spectrometer. UV-vis absorption spectra were measured on a JASCO V-570 spectrometer. Fluorescence spectra were measured on a JASCO FP-6300 spectrofluorometer.  $^1\text{H-NMR}$  and  $^{13}\text{C-NMR}$  spectra were recorded on a JEOL ECA500 spectrometer. The chemical shifts were recorded by using tetramethylsilane (0.00 ppm) as an internal reference for  $^1\text{H-NMR}$  spectra and  $\text{CDCl}_3$  (77.00 ppm) for  $^{13}\text{C-NMR}$  spectra. Mass spectra were recorded on a Shimadzu GCMS-QP2010, a Shimadzu AXIMA-CFR and a ThermoFisher Scientific LTQ Orbitrap-XL mass spectrometer for EI, MALDI-TOF and ESI-Orbitrap MS, respectively. The high-resolution mass spectra (HRMS) were analyzed by using ThermoXcalibur 2.1.0.1140 software. Data collection for X-ray crystal analysis was performed on a Rigaku/Varimax diffractometer (Mo-K $\alpha$ ,  $\lambda = 0.71075 \text{ \AA}$ ). The structure was solved with direct methods and refined with full-matrix least-squares (teXsan). Cyclic voltammetry measurement was conducted with a BAS CV-50W electrochemical analyzer in a 0.1 M *n*-Bu $_4$ NPF $_6$  dichloromethane solution at room temperature. Elemental analyses were performed at the Elemental Analysis Center in the Faculty of Science, Osaka University.

### 5.5.2. Synthetic procedures

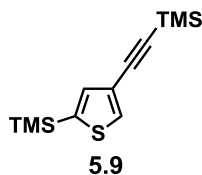
#### 4-Bromo-2-trimethylsilylthiophene (**5.8**)



To a solution of 2,4-dibromothiophene **5.7** (1.591 g, 6.58 mmol) in ether (10 mL) was added a solution of *n*-BuLi (1.5 M in *n*-hexane, 4.4 mL, 6.60 mmol) dropwise at  $-78 \text{ }^\circ\text{C}$  under nitrogen atmosphere and stirred for 10 minutes. TMSCl (1.0 mL, 7.88 mmol) was added dropwise to the reaction mixture at  $-78 \text{ }^\circ\text{C}$  and stirred for 1 h at room temperature. Water (10 mL) was added then the aqueous layer was extracted with ether ( $3 \times 15 \text{ mL}$ ). The combined organic layer was washed with water ( $1 \times 10 \text{ mL}$ ) and saturated aqueous solution of NaCl ( $1 \times 10 \text{ mL}$ ) then dried over  $\text{Na}_2\text{SO}_4$ . After filtration and concentration, the residue was purified by column chromatography (silica-gel; *n*-hexane) to afford the title compound **5.8** (1.344 g, 87%) as colorless oil.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ) 7.22 (d,  $J = 5.6 \text{ Hz}$ , 2H), 7.04 (d,  $J = 5.6 \text{ Hz}$ , 2H), 0.31 (s, 9H).

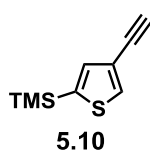
#### 4-(Trimethylsilyl)ethynyl-2-trimethylsilylthiophene (5.9)



To a suspension of 4-bromo-2-trimethylsilylthiophene **5.8** (578 mg, 2.46 mmol), CuI (11 mg, 0.0577 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (61 mg, 0.0528 mmol) in THF/*i*-Pr<sub>2</sub>NH (1/1 10 mL) was added trimethylsilylacetylene (0.68 mL, 4.92 mmol) under nitrogen atmosphere. The resulting mixture was stirred at 40 °C overnight. After cooling to room temperature, the reaction mixture was filtered through celite pad. The filtrate was concentrated and purified by silica-gel column chromatography (silica-gel; *n*-hexane) to afford the title compound **5.9** (427 mg, 69%) as colorless oil.

<sup>1</sup>H-NMR (300 MHz, CDCl<sub>3</sub>) 7.68 (d, *J* = 0.9 Hz, 1H), 7.24 (d, *J* = 0.9 Hz, 1H), 0.30 (s, 9H), 0.23 (s, 9H).

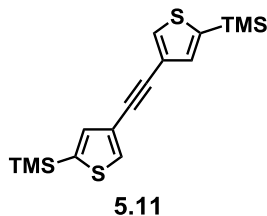
#### 4-Ethynyl-2-trimethylsilylthiophene (5.10)



To a solution of 4-(Trimethylsilyl)ethynyl-2-trimethylsilylthiophene **5.9** (1.633 g, 6.47 mmol) in THF/MeOH (1/1, 20 mL) was added K<sub>2</sub>CO<sub>3</sub> (1.866 g, 13.5 mmol) in one portion at room temperature. After stirring at room temperature for 30 minutes, water (10 mL) was added. The aqueous layer was extracted with ether (3 × 30 mL). The combined organic layer was washed with water (1 × 20 mL) and brine (1 × 20 mL) then dried over Na<sub>2</sub>SO<sub>4</sub>. After filtration and concentration, almost pure **5.10** (1.199 g, quant) was obtained as yellow oil.

<sup>1</sup>H-NMR (300 MHz, CDCl<sub>3</sub>) 7.72 (d, *J* = 0.9 Hz, 1H), 7.25 (d, *J* = 0.9 Hz, 1H), 0.31 (s, 9H).

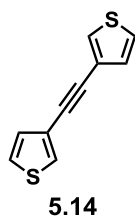
#### Bis-(5,5'-trimethylsilyl-3-thienyl)ethyne (5.11)



To a suspension of 4-bromo-2-trimethylsilylthiophene **5.8** (1.386 g, 5.89 mmol), CuI (24 mg, 0.126 mmol) and Pd(PPh<sub>3</sub>)<sub>4</sub> (154 mg, 0.133 mmol) in *i*-Pr<sub>2</sub>NH (10 mL) was added a solution of 4-Ethynyl-2-trimethylsilylthiophene **5.10** (1.166 g, 6.47 mmol) in THF (10 mL) under nitrogen atmosphere. The resulting mixture was heated to reflux, and stirred overnight. After cooling to room temperature, the reaction mixture was filtered through celite pad. The filtrate was concentrated and purified by silica-gel column chromatography (silica-gel; *n*-hexane) to afford the title compound **12** (1.587 g, 80%) as colorless crystals.

<sup>1</sup>H-NMR (300 MHz, CDCl<sub>3</sub>) 7.69 (d, *J* = 0.9 Hz, 2H), 7.29 (d, *J* = 0.9 Hz, 2H), 0.31 (s, 18H).

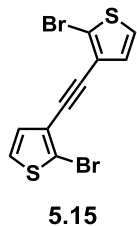
#### 1,2-Bis(3-thienyl)acetylene (5.14)



To a solution of 3-(trimethylsilyl)ethynylthiophene, prepared from 3-bromothiophene and trimethylsilylacetylene by a standard method<sup>[10]</sup> (7.014 g, 38.9 mmol) in THF (7 mL) was added a solution of TBAF (1.0 M in THF, 43.0 mL, 43.0 mmol) dropwise at room temperature under nitrogen atmosphere. After stirring for 10 minutes, *i*-Pr<sub>2</sub>NH (50 mL), CuI (940 mg, 0.813 mmol), Pd(PPh<sub>3</sub>)<sub>4</sub> (159 mg, 0.835 mmol) and 3-bromothiophene (4.5 mL, 47.5 mmol) were added successively. The resulting mixture was heated to reflux and stirred overnight. After cooling to room temperature, the reaction mixture was filtered through celite pad. The filtrate was concentrated and purified by column chromatography (silica-gel; CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/50) to afford the title compound **5.14** (5.621 g, 76%) as colorless crystals.

<sup>1</sup>H-NMR (500 MHz, CDCl<sub>3</sub>) 7.50 (dd, *J* = 1.1, 3.0 Hz, 2H), 7.29 (dd, *J* = 3.0, 5.0 Hz, 2H), 7.18 (dd, *J* = 1.1, 5.0 Hz, 2H).

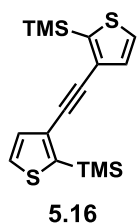
### 1,2-Bis(2-bromo-3-thienyl)acetylene (5.15)



To a solution of 1,2-bis(3-thienyl)acetylene **5.14** (1.909 g, 10.0 mmol) in DMF (10 mL) was added dropwise a solution of NBS (3.776 g, 21.2 mmol) in DMF (20 mL) at 0 °C. The resulting mixture was stirred at room temperature. The reaction mixture was quenched with water (30 mL) then extracted with ether (5 × 40 mL). The combined organic layer was washed with water (3 × 20 mL) and brine (1 × 20 mL) then dried over Na<sub>2</sub>SO<sub>4</sub>. After filtration and concentration, the residue was purified by silica-gel column chromatography (CH<sub>2</sub>Cl<sub>2</sub>/*n*-hexane = 1/9) to afford the title compound **5.15** (2.608 g, 75%) as yellow oil.

<sup>1</sup>H-NMR (300 MHz, CDCl<sub>3</sub>) 7.22 (d, *J* = 5.6 Hz, 2H), 7.04 (d, *J* = 5.6 Hz, 2H).

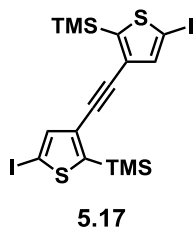
### 1,2-Bis(2-(trimethyl)silyl-3-thienyl)acetylene (5.16)



To a solution of 1,2-bis(2-bromo-3-thienyl)acetylene **5.15** (2.608 g, 7.49 mmol) in THF (20 mL) was added a solution of *n*-BuLi (1.5 M in *n*-hexane, 10.5 mL, 15.8 mmol) dropwise at -78 °C under nitrogen atmosphere and stirred for 10 minutes. TMSCl (2.3 mL, 18.1 mmol) was added dropwise to the reaction mixture at -78 °C and stirred for 1 h at room temperature. Water (10 mL) was added then the aqueous layer was extracted with ether (3 × 20 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL) then dried over Na<sub>2</sub>SO<sub>4</sub>. After

filtration and concentration, the residue was purified by column chromatography (silica-gel; *n*-hexane) to afford the title compound **5.16** (2.387 g, 95%) as colorless powder.

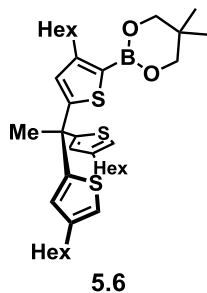
### 1,2-Bis(2-(trimethyl)silyl-3-iodo-5-thienyl)acetylene (5.17)



To a solution of 1,2-bis(2-(trimethyl)silyl-3-thienyl)acetylene **5.16** (2.379 g, 7.11 mmol) in THF (20 mL) was added dropwise *n*-BuLi (1.5 M in *n*-hexane, 11.5 mL, 17.3 mmol) at -78 °C under nitrogen atmosphere and stirred for 1 h. A solution of iodine (5.486 g, 21.6 mmol) in THF (10 mL) was added dropwise to the reaction mixture at -78 °C and stirred for 1 h at room temperature. Saturated aqueous NaHSO<sub>3</sub> (20 mL) was added then the resulting mixture was extracted with ether (3 × 20 mL). The combined organic layer was washed with

water (1 × 10 mL) and brine (1 × 10 mL) then dried over Na<sub>2</sub>SO<sub>4</sub>. After filtration and concentration, the residue was purified by column chromatography (silica-gel; *n*-hexane) to afford **5.17** (3.822 g, 92%) as colorless powder. <sup>1</sup>H-NMR (300 MHz, CDCl<sub>3</sub>) 7.28 (s, 2H), 0.39 (s, 18H).

### Mono-borylated tris(4-hexyl-2-thienyl)methane (5.6)



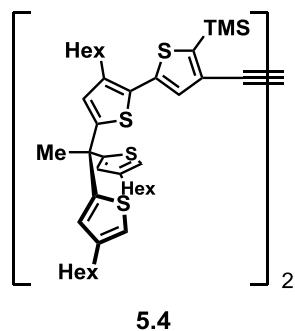
To a solution of tris(4-hexyl-2-thienyl)ethane **5.6** (274 mg, 0.518 mmol) in THF (5 mL) was added a solution of *n*-BuLi (1.5 M in *n*-hexane, 0.50 mL, 0.750 mmol) at -78 °C under nitrogen atmosphere then stirred for 1 h at -78 °C. B(O*i*-Pr)<sub>3</sub> (0.25 mL, 1.08 mmol) was added in one portion. The reaction mixture was warmed up to room temperature and stirred for 1 h. Neopentyl glycol (166 mg, 1.59 mmol) was added at room temperature and stirred for further 1 h. Water (5 mL) was added then the aqueous layer was extracted with diethyl

ether (3 × 20 mL). The combined organic extracts were washed with water (1 × 10 mL) and brine (1 × 10 mL) then dried over Na<sub>2</sub>SO<sub>4</sub>. After filtration and concentration, the residue was purified by silica-gel column chromatography (ethyl acetate/*n*-hexane = 1/8) to afford the title compound **5.6** (339 mg, quant) as

pale yellow oil.

$^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ) 6.78-6.77 (m, 3H), 6.75-6.74 (m, 3H), 5.90 (s, 1H), 2.53 (t,  $J = 7.4$  Hz, 6H), 1.60-1.54 (m, 6H), 1.34-1.26 (m, 18H), 0.89-0.86 (m, 9H).

#### $\beta$ -Acetylene-linked tris(2-thienyl)methane dimer (5.4)



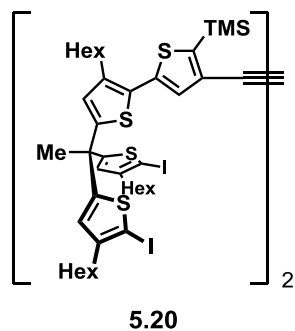
5.4

A solution of bis(3-thienyl)acetylene **5.17** (138 mg, 0.235 mmol), boronate ester **5.20** (332 mg, 0.518 mmol),  $\text{K}_2\text{CO}_3$  (144 mg, 1.04 mmol) and  $\text{Pd}(\text{PPh}_3)_4$  (17 mg, 0.147 mmol) in THF/toluene/ $\text{H}_2\text{O}$  (3/3/1, 14 mL) was heated to reflux and stirred for 1 day. After cooling to room temperature, water (20 mL) was added to the reaction mixture then the aqueous layer was extracted with diethyl ether ( $3 \times 20$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL) then dried over  $\text{Na}_2\text{SO}_4$ . After filtration and removal of the solvents, the residue was purified by column chromatography (silica gel;  $\text{CH}_2\text{Cl}_2/n$ -hexane (1/20)) to

afford the title compound **5.4** (203 mg, 62%) as yellow oil.

$^1\text{H-NMR}$  (300 MHz,  $\text{CDCl}_3$ ) 7.16 (s, 2H), 6.79 (d,  $J = 1.2$  Hz, 4H), 6.69 (d,  $J = 1.2$  Hz, 4H), 6.64 (s, 2H), 2.70-2.64 (m, 4H), 2.56-2.51 (m, 8H), 2.24 (s, 6H), 1.63-1.50 (m, 12H), 1.37-1.15 (m, 36H), 0.91-0.81 (m, 18H), 0.41 (s, 18H).

#### $\beta$ -Acetylene-linked tris(2-thienyl)methane dimer tetraiodide (5.20)



5.20

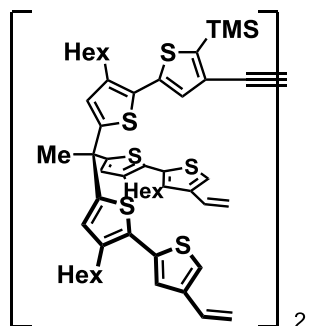
To a solution of **5.4** (303 mg, 0.218 mmol) in THF (5 mL) was added a solution of  $n$ -BuLi (1.5 M in  $n$ -hexane, 2.9 mL, 4.35 mmol) dropwise at  $-78$  °C under nitrogen atmosphere. The resulting mixture was stirred at  $0$  °C for 30 minutes. A solution of iodine (5.486 g, 21.6 mmol) in THF (10 mL) was added dropwise to the reaction mixture at  $-78$  °C and stirred for 1 h at room temperature. Saturated aqueous solution of  $\text{NaHSO}_3$  (20 mL) was added then the resulting mixture was extracted with ether ( $3 \times 20$  mL). The combined organic layer was washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL) then dried over  $\text{Na}_2\text{SO}_4$ . After filtration and concentration, the

residue was purified by column chromatography (silica-gel;  $\text{CH}_2\text{Cl}_2/n$ -hexane (1/50)) to afford the title compound **5.20** (277 mg, 67%) as yellow oil.

$^1\text{H-NMR}$  (300 MHz,  $\text{CDCl}_3$ ) 7.17 (s, 2H), 6.64 (s, 2H), 6.52 (s, 4H), 2.68 (t,  $J = 7.7$  Hz, 4H), 2.47 (t,  $J = 7.6$  Hz, 8H), 2.16 (s, 6H), 1.63-1.50 (m, 12H), 1.36-1.23 (m, 36H), 0.89-0.86 (m, 18H), 0.42 (s, 18H).



### $\beta$ -Acetylene-linked tris(bithienyl)methane dimer (**5.2**)



**5.2**

To a solution of tetraiodide **5.20** (410 mg, 0.217 mmol),  $K_2CO_3$  (253 mg, 1.83 mmol) and  $Pd(PPh_3)_4$  (53 mg, 0.0459 mmol) in toluene/water (3/1, 8 mL) was added a solution of boronate ester **28** (314 mg, 1.41 mmol) in THF (6 mL) heated to reflux and stirred for 1 day. After cooling to room temperature, water (10 mL) was added to the reaction mixture then the aqueous layer was extracted with diethyl ether ( $3 \times 20$  mL). The combined organic extracts were washed with water ( $1 \times 10$  mL) and brine ( $1 \times 10$  mL) then dried over  $Na_2SO_4$ . After filtration and removal of the solvents, the residue was purified by column chromatography (silica gel;  $CH_2Cl_2/n$ -hexane (1/10)) to afford the title compound **5.2** (286 mg, 72%) as yellow orange oil.

$^1H$ -NMR (300 MHz,  $CDCl_3$ ) 7.34 (s, 2H), 7.19 (s, 4H), 7.18 (s, 2H), 7.10 (s, 4H), 6.73 (s, 4H), 6.64 (dd,  $J = 11.0, 17.7$  Hz, 4H), 5.56 (d,  $J = 17.7$  Hz, 4H), 5.19 (d,  $J = 11.0$  Hz, 4H), 2.73-2.68 (m, 12H), 2.26 (s, 6H), 1.61-1.53 (m, 12H), 1.37-1.19 (m, 36H), 0.91-0.86 (m, 18H), 0.42 (s, 18H).

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Kazuhiko Adachi

March, 2015

## List of Publication

"Synthesis of sexithiophene-bridged cage compound: a new class of three-dimensionally expanded oligothiophenes"

Adachi, K.; Hirao, Y.; Matsumoto, K.; Kubo, T.; Kurata, H.

*Org. Lett.* **2014**, *16*, 5870–5873.