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Copper-Mediated Aryl-Aryl Couplings for the Construction of Oligophenylenes and Related Heteroaromatics

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Dedicated to Professor Armin de Meijere on the occasion of his 70th birthday.

Abstract: Efficient methods for the syntheses of biaryls by the copper-mediated homocoupling of arylmetals are summarized. First, a smooth transmetallation between arylzinc halides and copper(II) salts has been employed for the selective homocoupling of arylzinc halides to produce either biphenylenes or tetraphenylenes. This reaction has been applied to the synthesis of cyclic oligothiophenes. Second, an efficient method for the homocoupling of aryl halides by the electron-transfer (ET) oxidation of Lipshutz cuprates [$Ar_2Cu(CN)Li_2$] with organic electron acceptors has been developed. The ET oxidation of cuprates with 1,4-benzoquinones proceeds smoothly to afford the corresponding coupling products in moderate to high yields. The ET oxidation of cuprates has been applied to the synthesis of either thiophene- or benzene-fused 10-membered ring cyclophanes. For the synthesis of macrocyclic cyclophanes, a linear C–Cu–C structure of Lipshutz cuprates should be maintained in the dimetallacyclic intermediates to efficiently produce large-ring cyclophanes. Moreover, nonaphenylenes and dodecaphenylenes have been synthesized using the ET oxidation of cuprates with duroquinone. Interestingly, hexadodecyloxynonaphenylene exhibits different nanostructures between fibrous materials in solution and cast films on a surface. Films of this compound can detect vaporized nitroaromatics such as dinitrobenzene and trinitrobenzene.

Keywords: arenes; C–C coupling; copper; electron transfer; ring construction

1 Introduction

The aryl-aryl bond forming reaction is one of the most important and powerful tools in modern organic synthesis.[1,2] Biaryls and their heteroaromatic analogues are some of the most attractive structural units in natural products, bioactive compounds, photonic materials, functional polymers, ligands in catalysts, and theoretically interesting molecules.[3] For aryl-aryl bond formation, transition metal-mediated coupling has been employed in most cases. Thus, the methodologies for homo- and cross-couplings using transition metals such as copper, nickel, palladium, and iron have been developed and widely used.[4,5] Among them, the homocoupling of substituted benzenes and aromatic heterocycles using copper as the reducing and coupling reagent is known as the Ullmann reaction.[6] Since the original Ullmann reaction[7] was reported in 1901 using metallic copper as the coupling reagent, a number of Ullmann-type couplings using activated metallic copper,[8] copper(I) salts,[9] and copper(II) salts[10] have been utilized for aryl-aryl bond formation. Diarylcopper(II) species prepared from aryl metals with copper(II) salts decompose at low temperatures to afford biaryls.[10,11] The reaction requires the transmetallation of arylmetal species such as aryllithiums and arylmagnesium halides with copper(II) salts,[12] followed by the reductive elimination

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of an organic copper(II) intermediate. Therefore, aryl-aryl bond formation in high yields with a high selectivity requires either a smooth transmetallation or an effective reductive elimination.

Arylzinc halides have been frequently employed for palladium-catalyzed cross-coupling reactions after the discovery of the Negishi reaction in 1977.[13] However, the copper-mediated homocoupling of arylzinc halides was not commonly employed for biaryl synthesis, when we started looking at the synthesis of oligophenylenes in 1998.[14] We expected that arylzinc intermediates may have different structures in solution compared with aryllithium and arylmagnesium intermediates and that the transmetallation of arylzinc halides by Cu(II) salts would proceed smoothly. With these ideas, we first synthesized oligophenylenes using arylzinc intermediates; this synthetic method has been applied to the synthesis of cyclic oligothiophenes.

For the effective reductive elimination of Cu(II) species, we investigated an efficient oxidative ligand coupling of organocuprates. In 1981, Lipshutz and coworkers reported a novel cuprate prepared by the addition of 2 equivalents of a lithium reagent to 1 equivalent of CuCN, the so-called "Lipshutz cuprate" [$R_2Cu(CN)Li_2$].[15] This cuprate has been reported to be an effective reagent for substitution reactions of alkyl halides and for conjugate additions of α,β-unsaturated ketones.[16,17] We expected that an oxidative 'decomposition' of organic cuprates (R_2CuLi) with oxidants would be a promising method for the homocoupling of ligands (R) on a copper atom. Concerning the oxidative coupling of Lipshutz cuprates, the oxidation of cuprates with molecular oxygen was reported to form coupling products *via* ligand coupling on a copper atom.[18,19] Recently, 1,3-dinitrobenzene has been used for the oxidation of Lipshutz cuprates to afford medium-sized ring compounds including the biaryl skeleton.[20] For this ligand coupling, we introduced electron transfer (ET) oxidation with 1,4-benzoquinones. The ET oxidation of Lipshutz cuprates with quinines proceeds smoothly to afford biaryls and oligophenylenes in moderate to high yields.

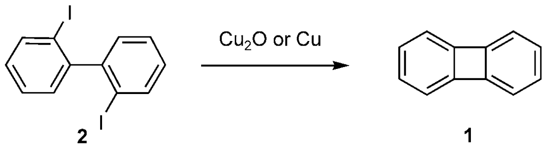
Here, copper-mediated aryl-aryl couplings and their application to the synthesis of oligophenylenes are summarized together with the novel molecular structures, electronic and optoelectronic properties, and supramolecular chemistry of oligophenylenes.

2 Copper-Mediated Coupling of Organozinc Halides

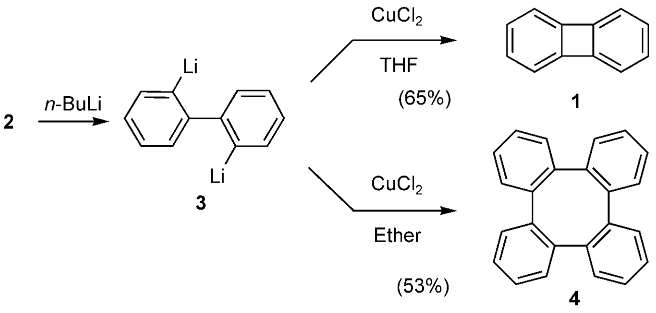
2.1 Synthesis of Biphenylenes and Tetraphenylenes

Since the first synthesis of biphenylene **1** in 1941,[21] considerable attention has been devoted to designing and constructing new analogues of this benzannelated cyclobutadiene system.[22] Recently, new carbon allotropes containing the biphenylene **1** as a unit have been considered as materials with attractive properties.[23] Furthermore, the derivatives of **1** can be used as spacers and building blocks for functionalized organic materials,[24] together with starting materials for organic synthesis.[25] Many synthetic methods, such as the dimerization of benzyne,[26] the Ullmann coupling of 2,2′-diiodobiphenyl **2** with Cu_2O or Cu (Scheme 1),[27] pyrolytic extrusion,[28] and the Vollhardt method using cobalt-catalyzed cyclization,[29] have been employed for the preparation of **1** and [n]phenylenes. However, only a few limited methods are known for the construction of functionalized biphenylenes with methyl, fluoro, and other functional groups owing to the difficulty in obtaining the appropriate starting materials.[30]

The copper-mediated coupling of 2,2′-dilithiobiphenyl **3** leads to the tetraphenylene **4** (53%) with a small amount of **1** (3%).[31] Since the yield of **1** can be



Scheme 1. Typical Ullmann reaction.

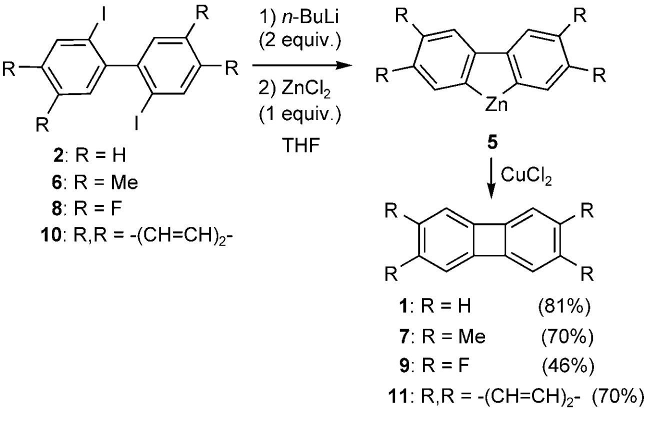


Scheme 2. Solvent effect on the copper-mediated cyclization of **3**.

improved to 36% together with **4** (24%) by changing the solvent from ether to a mixture of ether-THF (1:1),[31a] the yields of **1** and **4** depend on the structure of **3** in solution and/or of a copper intermediate derived from **3** and $CuCl_2$. As shown in Scheme 2, the copper-mediated coupling of **3** with $CuCl_2$ in THF selectively produces **1** in 65% yield.[14,32]

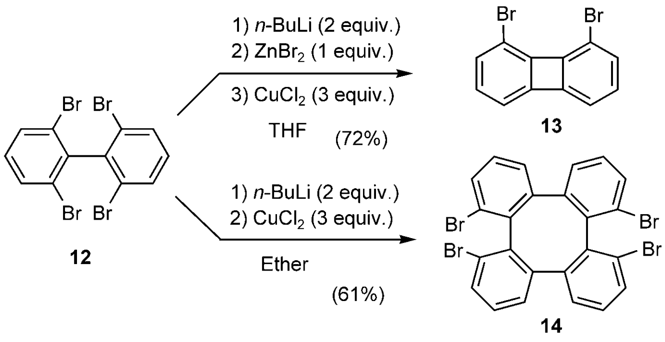
Interestingly, the copper-catalyzed coupling of the organozinc compound **5** prepared by the reaction of **3** with $ZnCl_2$ produces **1** and its derivatives selectively as shown in Scheme 3. The reaction of 2,2′-diiodobiphenyl **2** in THF with 2 equivalents of butyllithium in hexane, followed by treatment with 1 equivalent of $ZnCl_2$ gives the arylzinc derivative **5** in good yield. The reaction of **5** with 3 equivalents of $CuCl_2$ produced **1** (81%), together with 5% of **4**. The intramolecular coupling reaction of dibenzozincacyclopentadiene **5** with $CuC1_2$ can be applied to the synthesis of 2,3,6,7-tetrasubstituted biphenylenes (**7**, **9**, and **11**). The successive treatments of **6**, **8**, and **10** with 2 equivalents of butyllithium and 1 equivalent of $ZnCl_2$ produced the zincacyclopentadiene intermediates **5** which were reacted with 3 equivalents of $CuC1_2$ to produce **7** (70%), **9** (46%), and **11** (70%).

1,8-Dibromobiphenylene **13**[24f] and 1,8,9,16-tetrabromotetraphenylene **14** can be employed as either a spacer or a helical building block. Therefore, the selective synthesis of **13** and **14** was carried out (Scheme 4). The successive treatment of **12** with 2 equivalents of *n*-BuLi, 1 equivalent of $ZnBr_2$, and 3 equivalents of $CuCl_2$ in THF produced **13** in 72% total yield, whereas the reaction of **12** with 2 equivalents of *n*-BuLi, followed by treatment with 3 equivalents of $CuCl_2$ in THF resulted in the formation of **14**. The helical structure of **14** has been determined by X-ray analysis.[32]

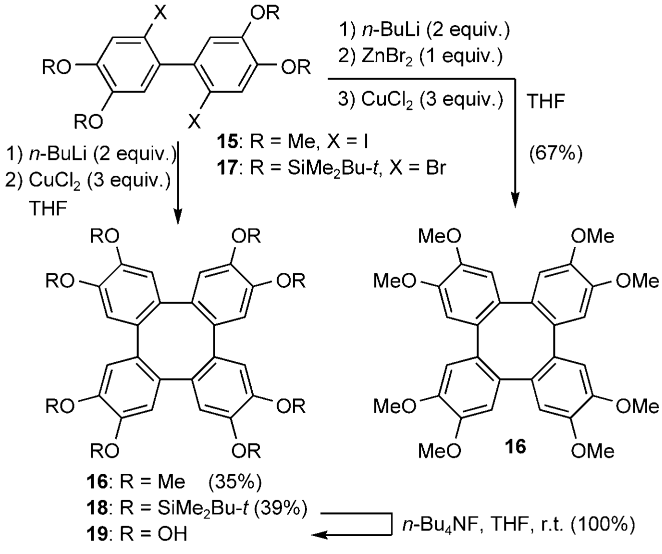


Scheme 3. Synthesis of biphenylenes.

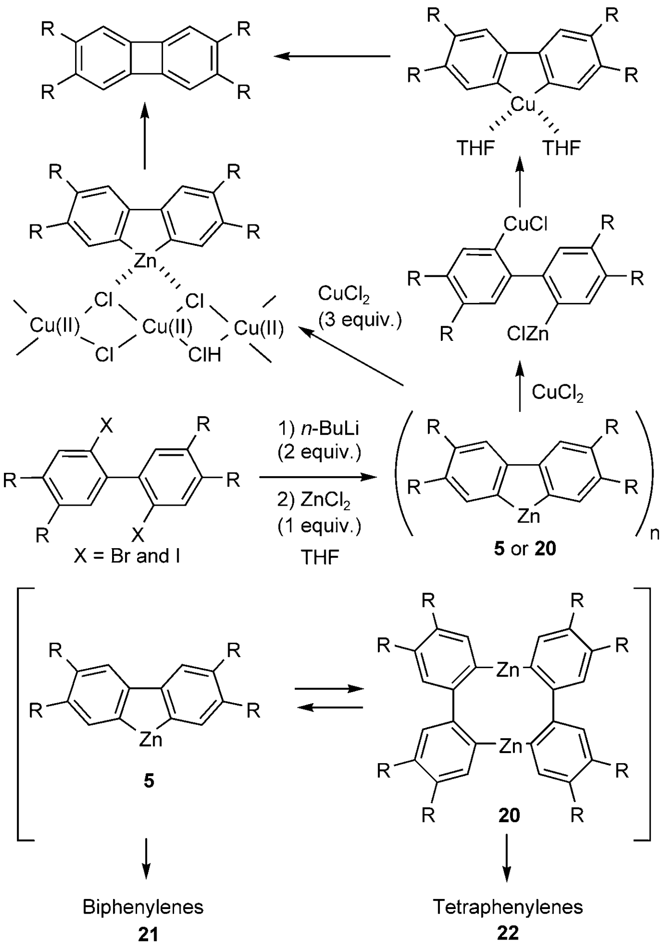
Although we succeeded in the selective synthesis of the biphenylenes **1**, **7**, **9**, **11**, and **13** using the copper-mediated ring closure of the zincacyclopentadiene intermediates **5**, a similar reaction of **15** produced only the corresponding tetraphenylene **16** in 67% yield.[32] Furthermore, **16** was prepared in 35% yield using the conventional reaction of dilithiobiphenyl with $CuCl_2$ (Scheme 5) Similarly, **17** can be converted into **18** (39%). Interestingly, octahydroxytetraphenylene **19** can be synthesized in quantitative yield by the treatment of either **18** with $(n\text{-Bu})_4NF$ or **16** with BBr_3.[33]



Scheme 4. Selective synthesis of the biphenylene **13** and the tetraphenylene **14**.



Scheme 5. Octamethoxytetraphenylene **16** and related compounds.



Scheme 6. Plausible pathways for the formation of the biphenylenes **21** and the tetraphenylenes **22**.

The two-electron oxidation of **16** has been reported to give a dication that exhibits a color change from yellow to dark red. This color change is observed to be reversible.[34]

Plausible pathways for the formation of biphenylenes and tetraphenylenes *via* diarylzinc intermediates are shown in Scheme 6. The diarylzinc species **5** and **20** react with $CuCl_2$ to give the corresponding **21** and **22**, respectively. Thus, the most thermodynamically stable species **5** is formed predominantly in solution, leading to the preferential formation of biphenylenes.

2.2 Synthesis of Cyclic Oligothiophenes

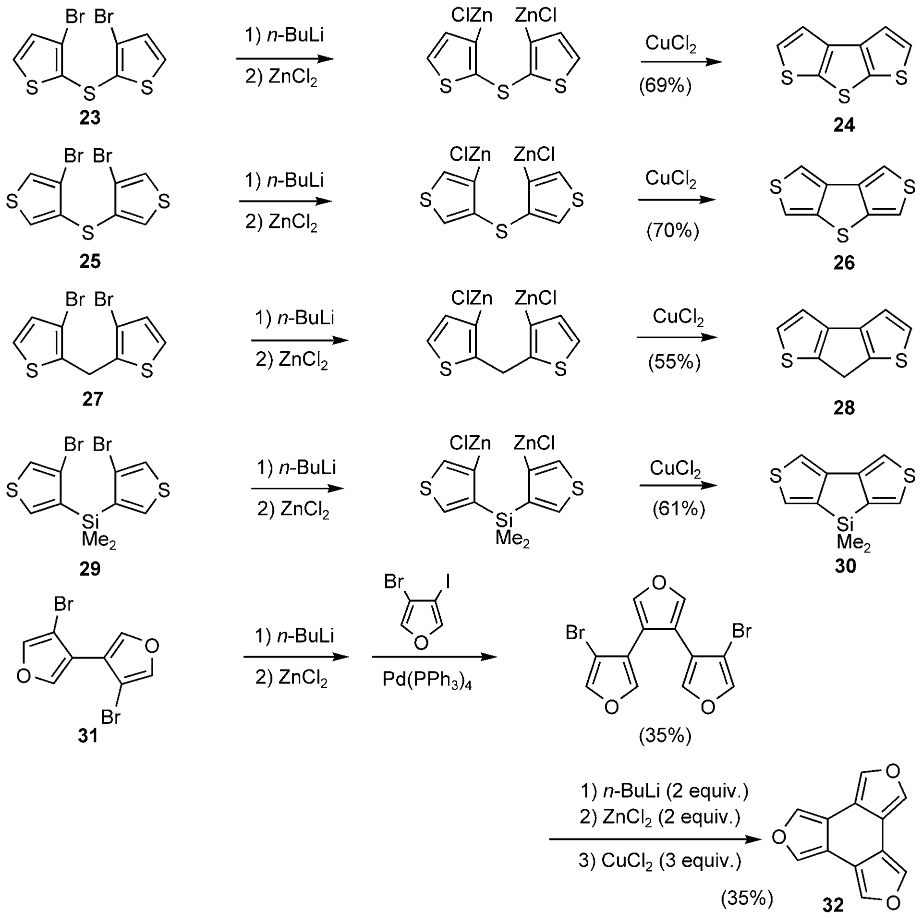
To apply the copper-mediated coupling of organozinc species to the synthesis of polycyclic thiophenes, we synthesized tricyclic thiophenes, cyclooctatetrathiophenes, cyclooctatetrafuran, and a related new cyclic systems (Scheme 7).[35] For the synthesis of the tricyclic thiophenes **24**, **26**, and **30**, the reported procedures employ the copper-mediated coupling of dilithio derivatives.[36] Although our procedure needs dilute conditions, the yields of **24**, **26**, and **30** are fairly high. Furthermore, the benzotrifuran **32** has been synthesized using the copper-mediated ring closure of organozinc species in 35% yield.[37–39]

The copper-mediated coupling of organozinc species can also be applied to the synthesis of cyclooctatetrathiophene, cyclooctatetrafuran, and their starting materials. As shown in Scheme 8, the dibromobithiophenes **33** and **35** and the dibromobifuran **31** have been prepared in moderate yields by the homocoupling of organozincates. For the synthesis of the cyclooctatetrathiophenes **34** and **36**, the homocoupling of the corresponding dilithiobithiophenes with $CuCl_2$ was reported to afford **34** and **36** in 18 and 23% yields, respectively.[11c] Therefore, our method produces **34** and **36** in much higher yields. However, the coupling of **31** afforded **37** in only 14% yield presumably owing to its instability. Recently, Marsella et al. suggested that linear oligothiophenes work as molecular springs, muscles, rheostats, and processing gyroscopes.[40] I think that our synthetic tools for linear and cyclic oligothiophenes can serve these purposes by providing synthetic methodologies.

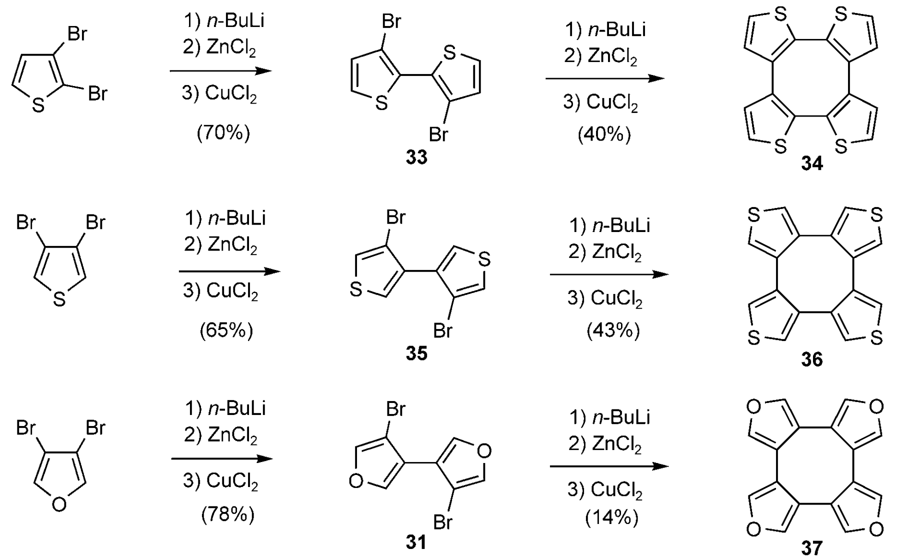
3 Copper-Mediated Coupling of Organotin Compounds

Although organotin compounds are frequently employed for transition metal-catalyzed cross-coupling reactions, only a few have been reported for transition metal-catalyzed homocoupling reactions. We are interested in the copper-mediated homocoupling reactions of organotins for the synthesis of oligophenylenes and their heteroaromatic analogues. In the coupling of organotins with $CuCl_2$, no reaction was observed at room temperature.[41] However, the homocoupling of organotins with $Cu(NO_3)_2$ proceeded smoothly to produce coupling products.[42] As shown in Scheme 9, we conducted the coupling of **38** with $Cu(NO_3)_2$ in THF at room temperature for 1 h. This reaction proceeded smoothly to afford **39** in moderate yield.[43] For this coupling, we also applied the copper-mediated coupling of organozinc derivatives. However, the yield of **39** was very low (4%).[44] For the coupling of **40**, $Cu(NO_3)_2$ is an effective reagent for producing **41** in 30% yield.[45]

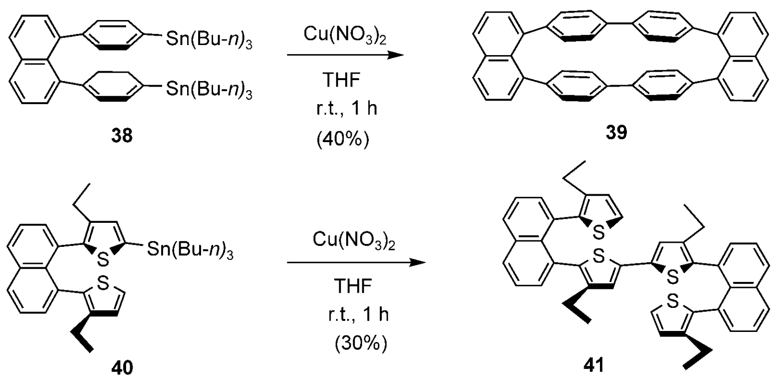
The coupling of organotins with $Cu(NO_3)_2$ can be applied to the dimerization of highly reactive π-donors. Thus, the reactions of the tin derivatives **42** and **44** of tetrathiafulvalene (TTF) and tetraselenafulvalene (TSF) produce the bi-TTF **43** (70%) and the bi-TSF **45** (75%) (Scheme 10).[46,47] The reaction of diaryldimethyltins with $Cu(NO_3)_2$ also proceeded smoothly in THF at room temperature to afford the biaryls **47a–47d**, **31**, and **35** in high yields.[10c]



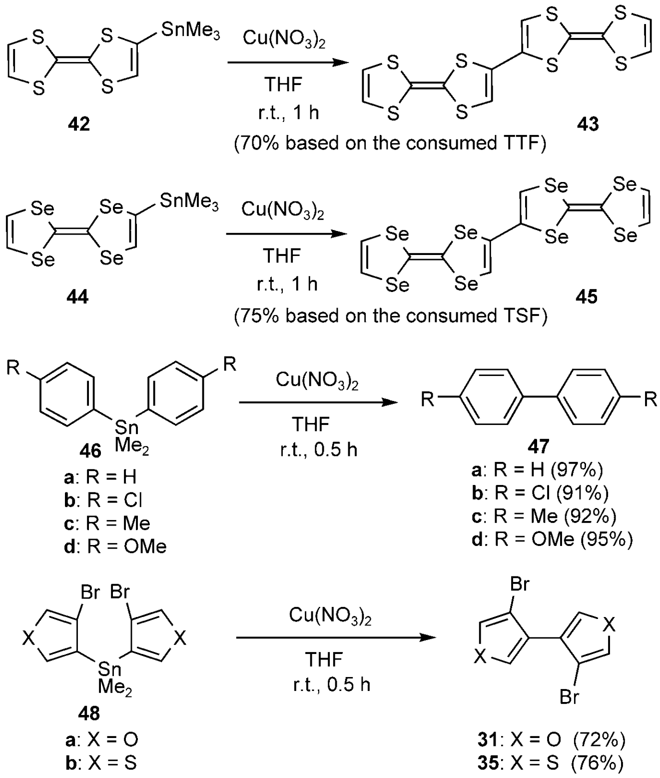
Scheme 7. Synthesis of polycyclic thiophenes.



Scheme 8. Cyclooctatetrathiophenes **34** and **36** and cyclooctatetrafuran **37**.



Scheme 9. Synthesis of **39** and **41**.

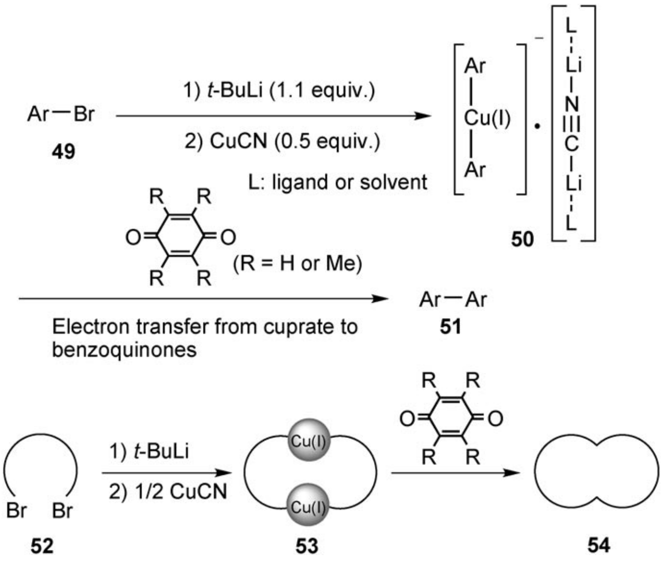


Scheme 10. Homocoupling of various organotin compounds with $Cu(NO_3)_2$.

4 ET Oxidation of Lipshutz Cuprates

4.1 Synthesis of Biaryls and 10-Membered Cyclophanes

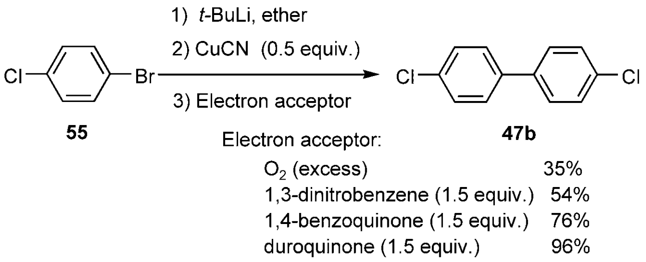
We recently found an efficient method for the homocoupling of aryl halides by the ET oxidation of Lipshutz cuprates [$Ar_2Cu(CN)Li_2$] with organic electron acceptors. Lipshutz cuprates [$R_2Cu(CN)Li_2$] show higher reactivity in chemical reactions than traditional Gilman cuprates ($R_2CuLi{\cdot}LiX$).[48] The unusual reactivity was considered to be due to the structure of Lipshutz cuprates, in which the cyano group bound to copper by a Cu–CN bond, resulting in the dianion species $R_2Cu(CN)^{2-}2Li^+$.[49] After much investigation and controversial discussion on the structure of Lipshutz cuprates,[50] X-ray structural determinations revealed that the cyano group in Lipshutz cuprates is located between two lithium atoms as a bridge, and that Lipshutz cuprates have a linear carbon-Cu(I)-carbon arrangement.[51] We expected that the carbon-Cu(I)-carbon linkage in Lipshutz cuprates would be easily oxidized by electron acceptors to give the corresponding carbon-Cu(II)-carbon structure, and that the oxidation of Lipshutz cuprates would finally produce homocoupling products under mild conditions. In this study, we established a novel ET oxidation of Lipshutz cuprates with *p*-benzoquinones to produce biaryls as homocoupling products (Scheme 11). Since various aryl bromides **49** can be converted into the Lipshutz cuprates **50**, our new methodology can produce a number of biaryls **51** in moderate to high yields. In addition, this methodology can be successfully applied



Scheme 11. Electron-transfer oxidation of Lipshutz cuprates.

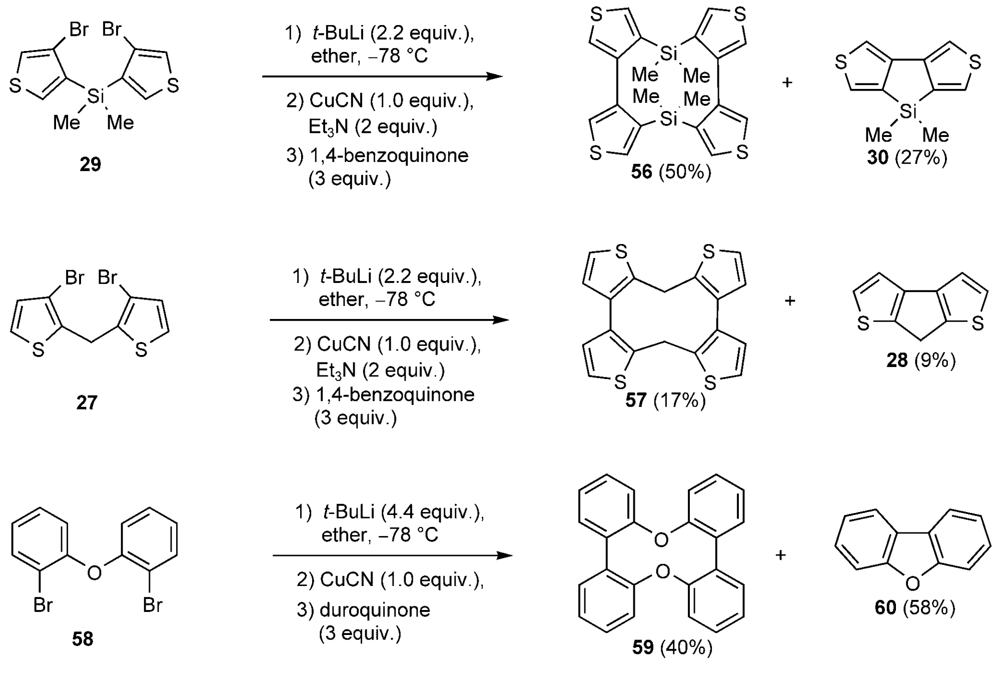
to the construction of macrocycles **54**.[52] Although the macrocyclizations such as intramolecular ring closure and intermolecular cyclooligomerization generally afford macrocyclic products in low yields owing to the preferable formation of linear oligomers and 5- and 6-membered rings in some cases, our novel ET oxidation of metallacyclic intermediates including the Lipshutz cuprates **53** results in the formation of macrocyclic dimers owing to the preferable formation of a dimetallacyclic intermediate with a linear Ar-Cu(I)-Ar arrangement.

Lipshutz cuprates can be oxidized with molecular oxygen or dinitrobenzene to afford the corresponding homocoupling products.[18,20,53,54] Thus, we first investigated the oxidation of the Lipshutz cuprate **50** prepared from the reaction of *p*-bromochlorobenzene **55** with 1.1 equivalents of *tert*-butyllithium, followed by treatment with 0.5 equivalents of CuCN (Scheme 12). Our preliminary experiments showed that the reactions of the cuprate with molecular oxygen and 1,3-dinitrobenzene gave 4,4′-dichlorobiphenyl **47b** in 35% and 54% yields, respectively. To increase the yield of **47b**, various electron acceptors were examined. After several attempts, 1,4-benzoquinones were found to be effective for the oxidation of **50**, and tetramethyl-*p*-benzoquinone (duroquinone) led to the highest yield of **47b** (96%). This biphenyl synthesis can be applied to the preparation of biphenyl derivatives, and various substrates with electron-deficient substituents, such as *p*-bromofluorobenzene and *p*-dibromobenzene, and those with electron-rich substituents, such as *p*-bromoanisole and *p*-bromotoluene furnished high yields of the biaryl products. Heteroaromatic halides were also successfully coupled under the present conditions, and 3,4-dibromothiophene was converted into 4,4′-dibromo-3,3′-bithiophene in 87% yield.



Scheme 12. Coupling of *p*-bromochlorobenzene **55** *via* ET oxidation of Lipshutz cuprate.

The above novel methodology for the aryl-aryl bond formation was applied to the construction of macrocyclic compounds in the following work. Metallacycles are one of the most important and available reaction intermediates in organometallic chemistry. The existence of equilibriums among monomeric, dimeric, and oligomeric metallacycles is well known and the reaction conditions, such as metals, solvents, and temperatures, are expected to affect the structures and distribution of oligomeric intermediates and the final products (Scheme 13).[14,55] Generally, modifications are necessary to induce the equilibrium to favor the formation of the desired product. Since a Lipshutz cuprate has a linear carbon-copper-carbon [C–Cu(I)–C] structure, a favorable formation of large



Scheme 13. Cyclization of **27**, **29**, **58** *via* aryl-aryl bond formation.

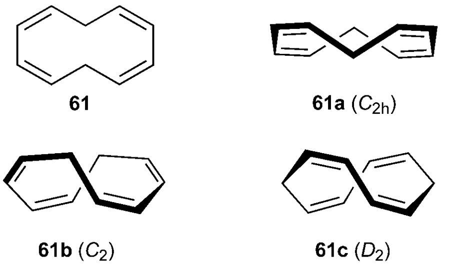


Figure 1. Three possible conformers **61a**–**61c** for *all-Z*-cyclodeca-1,3,6,8-tetraenes. The symmetry of each structure is shown in parentheses.

oligomeric metallacycles is expected. The preparation of thiophene-fused cyclophanes has always attracted our interest, and the synthesis of a methylene-bridged ten-membered ring (**57**) has already been carried out by the reaction of Lipshutz cuprate with oxygen.[56] However, it exhibited low reproducibility and could not be be applied to the construction of its analogues. The present method that involves an ET procedure can be applied to the formation of the three cyclophanes **56**, **57**, and **59**.[57]

The 10-membered ring cyclophanes **56**, **57**, and **59** are novel compounds with unique molecular structures. As shown in Figure 1, *all-Z*-cyclodeca-1,3,6,8-tetraene **61** has three possible conformations: one with a chairlike C_{2h} symmmetry, **61a**; one with a boat-like C_2 symmetry, **61b**; and one with a twisted D_2 symmetry; **61c**. The difference between **61a** and **61b** is in the relative arrangement of their two *cisoid*-butadiene units; **61c** has two *transoid*-butadiene moieties. The dihedral angles of butadiene units are estimated to be 54.2°, 47.5°, and 104.5° for **61a**, **61b**, and **61c**, respectively by B3LYP/6-31G(d) level DFT calculations. The most stable conformer of the macrocycle **61** is considered to be the chair-like C_{2h}-structure **61a**; the other two conformers **61b** and **61c** are less stable than **61a** by 3.9 and 15.4 kcal mol^{-1}, respectively. Interestingly, the three cyclophanes **56**, **57**, and **59** have different structures owing to the steric repulsion between their substituents and fused rings. X-Ray analyses showed that **56**, **57**, and **59** adopt the twisted D_2, chair-like C_{2h}, and boat-like C_2 symmetric structures.[52b]

To investigate the face-to-face interaction of planar π-conjugated systems, 1,8-diiodonaphthalene and 1,8-dibromobiphenylene **13** have been frequently employed as the spacer. As shown in Figure 2, 1,8-diarylnaphthalene **62** has a 2.6 Å distance between the ring carbons at the 1 and 8 positions.[58,59] Therefore, the distance is too small to show an optimum π-π interaction between the two aryl rings. In the case of 1,8-diarylbiphenylene **63**, the face-to-face distance of 3.9 Å between the two aryl rings seems to be large, and only a large π-system can show a through-space interaction.[24a] Interestingly, 3,4-disubstituted 7,7-dialkyl-7*H*-2,5-dithia-7-silacyclopenta[*a*]pentalene **64** is estimated to have 3.4–3.5 Å distances between the two aryl carbons.[60,61] Therefore, we first prepared the corresponding diiodides and converted them into **64**.

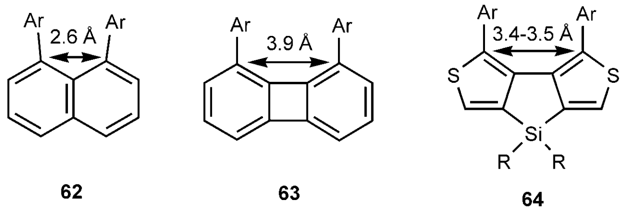


Figure 2. Three face-to-face systems **62**, **63**, and **64** and the distances between their two aryl groups.

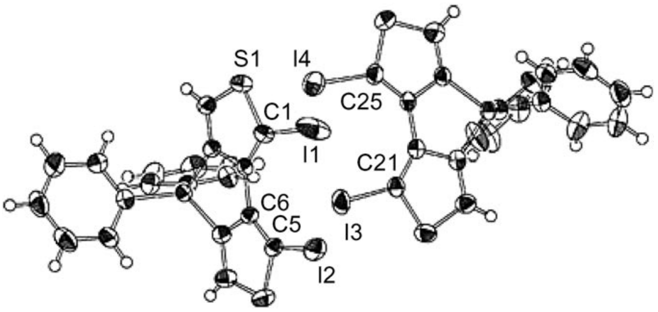


Figure 3. ORTEP drawing of **67**. The selected interatomic distances (Å) are as follows: I(1)···I(2) 3.6909(8); I(3)···I(4) 3.7194(8); C(1)···C(5) 3.487(6); C(21)···C(25) 3.505 (7); I(3)···C(6) 3.535(4); I(4) ··S(1) 3.638(2).

The reaction of **30** and **65** with *n*-BuLi in ether produced 3,4-dilithio derivatives, which were treated with $C_6F_{13}I$ to afford the diiodides **66** and **67** in 52 and 55% yields, respectively.[62] The X-ray structure of **67** is shown in Figure 3.[60] The crystal lattice includes two crystallographically independent molecules. Interestingly, there are very short I···S and I···C contacts less than the sum of van der Waals radii. The higher reactivity of the 3 and 4 positions in **30** and **65** depends on the stabilization of anions caused by the silicon atom at the 7 position. The Negishi coupling of **66** with 2-thienylzinc chloride produced **68** in 89% yield. The X-ray analysis of **68** (Figure 4) shows that the two thiophene rings are lined parallel, although the thiophene ring attached to the C(9)-carbon is disordered (*syn*/*anti* = 1/1).[61] The diiodides **66** and **67** were converted into the corresponding dimers **69**[35] and **70** in 42 and 20% yields, respectively, by successive treatment with *n*-BuLi and $CuCl_2$ (Scheme 14).[63]

4.2 Synthesis of Nonaphenylenes and Dodecaphenylenes

Cyclic oligophenylenes bearing medium-sized inner cavities are of interest in connection with the unusual

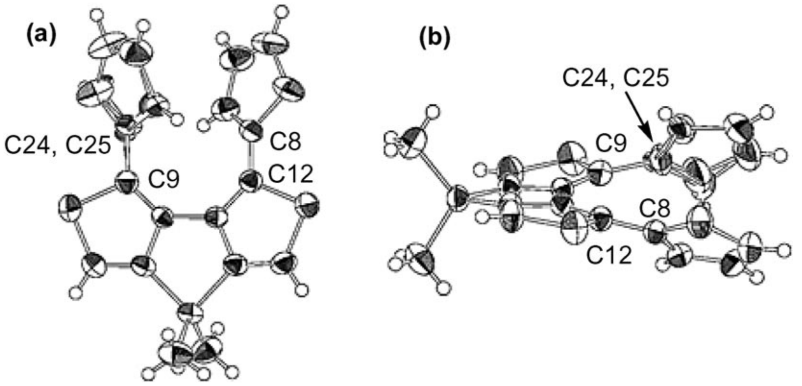
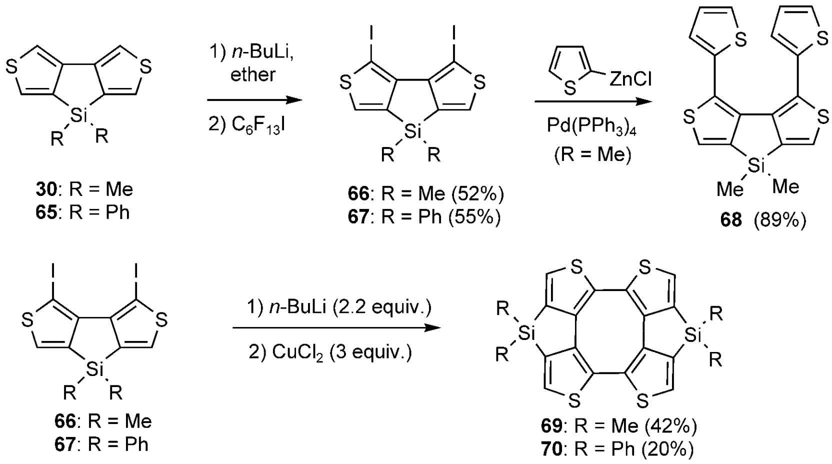


Figure 4. ORTEP drawing of **68**. **a**) Top view. **b**) Side view. The selected interatomic distances (Å) are as follows: C(9)···C(12) 3.402(5); C(8)···C(24) 3.44(2); C(8)···C(25) 3.37(3).

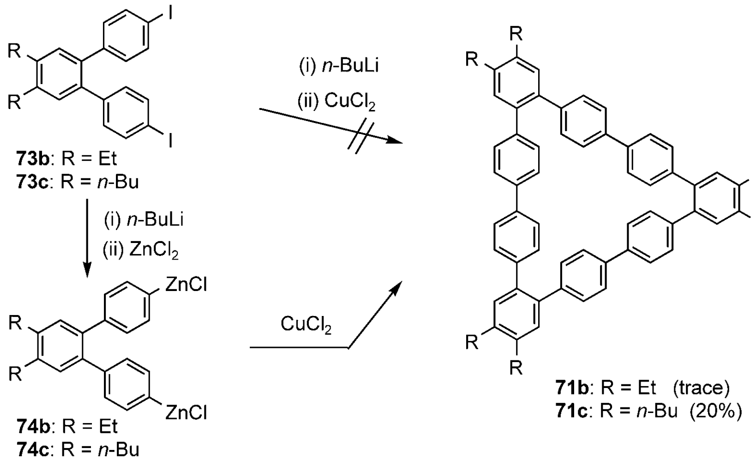


Scheme 14. Synthesis of 3,4-di(2-thienyl)-7,7-dimethyl-7*H*-2,5-dithia-7-silacyclopenta[*a*]pentalene **68** and the dithia-7-silacyclopenta[*a*]pentalene dimers **69** and **70**.

properties of open-cage fullerenes.[64] Furthermore, shape- and size-persistent macrocycles with large cavities are attractive targets for synthetic challenges and potential use for optoelectronics,[65,66] although many difficulties in the synthesis of hardly soluble macrocyclic oligophenylenes prevent detailed studies of their properties.[67,68] Among them, *o,p,p,o,p,p,o,p,p*-nonaphenylene (**71a**: R = H), a triangular molecule, was first synthesized by Meyer and Staab in 1969 by the $CuCl_2$-mediated coupling of a di-Grignard derivative of 4,4″-dibromo-*o*-terphenyl in low yield (0.97%).[69] In 1984,[70] Fujioka also obtained **71a** in 5% yield as a by-product during the intermolecular cross-coupling reaction of di-Grignard reagents of 4,4″-dibromo-*o*-terphenyl and 2,2″-dibromo-*p*-terphenyl with $CuCl_2$ and studied the formation of charge-transfer (CT) complexes of **71a** with either tetracyanoethylene (TCNE) or 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ).[71] Since nonaphenylenes can be expected to be prepared using copper-mediated reactions, we focused on the synthesis of nonaphenylenes and related macrocyclic oligoarylenes.

For the synthesis of hexabutylnonaphenylene **71c**, the $CuCl_2$-mediated cyclotrimerization of either the dilithio derivative of **73c** or the bis(chlorozinc) derivative **74c** was first attempted (Scheme 15).[32,35] The lithiation of **73c** with butyllithium (2 equiv.) followed by the reaction with $CuCl_2$ (excess) gave a trace amount of **71c**. In contrast, the treatment of **74c** (prepared from dilithio species of **73c** with excess $ZnCl_2$) with $CuCl_2$ (excess) produced hexabutylnonaphenylene **71c** in 20% yield. Although this reaction gave a number of side-products containing linear oligomers, no formation of octabutyldodecaphenylene **72c** was observed. However, a similar reaction of **73b** with butyllithium, followed by successive treatment with $ZnCl_2$ and $CuCl_2$ produced the corresponding **71b** in a trace yield.

As described above, we recently found a simple and convenient homocoupling of aryl lithium *via* the



Scheme 15. Synthesis of **1b** and **1c** using the copper-mediated coupling of an organozinc precursor.

ET oxidation of Lipshutz cuprates with duroquinone that produces biaryls in high yields.[52] Since this new coupling can be expected to have a wide applicability to the synthesis of large-membered oligophenylenes, we employed this procedure for the synthesis of **71a** and its hexaalkyl derivatives **71b**–**71d**. We also expected the formation of the dodecaphenylenes **72b**–**72d**, because the ET oxidation of Lipshutz cuprates tends to form larger cyclic oligomers than the $CuCl_2$-mediated homocoupling reaction of di-Grignard derivatives.[71] This selectivity depends on the structure of the intermediarily formed Lipshutz cuprates.[51]

For the synthesis of the nonaphenylenes **71** and the dodecaphenylenes **72** (Figure 5), we next carried out the ET oxidation of Lipshutz cuprates, because this reaction is a very strong tool for the formation of aryl-aryl bonds.[52] Thus, the reaction of **73a**–**73e** with 4 equivalents of *t*-BuLi at −78 °C, followed by treatment with 1 equivalent of CuCN in THF (for **73a**) or ether (for **73b**–**73e**) at −78 °C to room temperature produced the corresponding Lipshutz cuprates **75** and **76**.[73] For the coupling of the cuprate (R = H), the ET oxidation of **75** derived from **73a** with 3 equivalents of duroquinone in THF at room temperature proceeded smoothly to give the nonaphenylene **71a** in 46% yield (Scheme 16).

For **73b**–**73d** as the starting materials, the cyclooligomerization was carried out in ether owing to the higher solubility of **73**, **75**, **76**, and related compounds. The ET oxidation of a mixture of **75** and **76** derived from **73b** with 3 equivalents of duroquinone in ether at −5 °C to room temperature produced **71b** (25%) and **72b** (5%). Similarly, the oxidation of the Lipshutz cuprates **75** and **76** derived from **73c** and **73d** with duroquinone under similar conditions afforded **71c** (27%) and **71d** (34%), together with **72c** (4%) and **72d** (3%), respectively. However, the oxidation of Lipshutz cuprates derived from **73e** in ether or THF only produced **71e** in 18 and 14% yield, respectively (Scheme 16).[57] All the nonaphenylenes and dodecaphenylenes synthesized in this work are extremely stable to light, atmospheric oxygen, and prolonged heating.

The electron transfer oxidation of Lipshutz cuprates with excess amounts of duroquinone was examined by ESR measurements. The addition of duroqui-

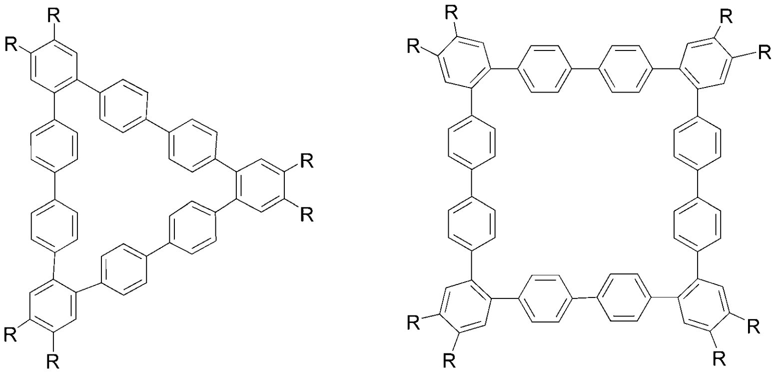
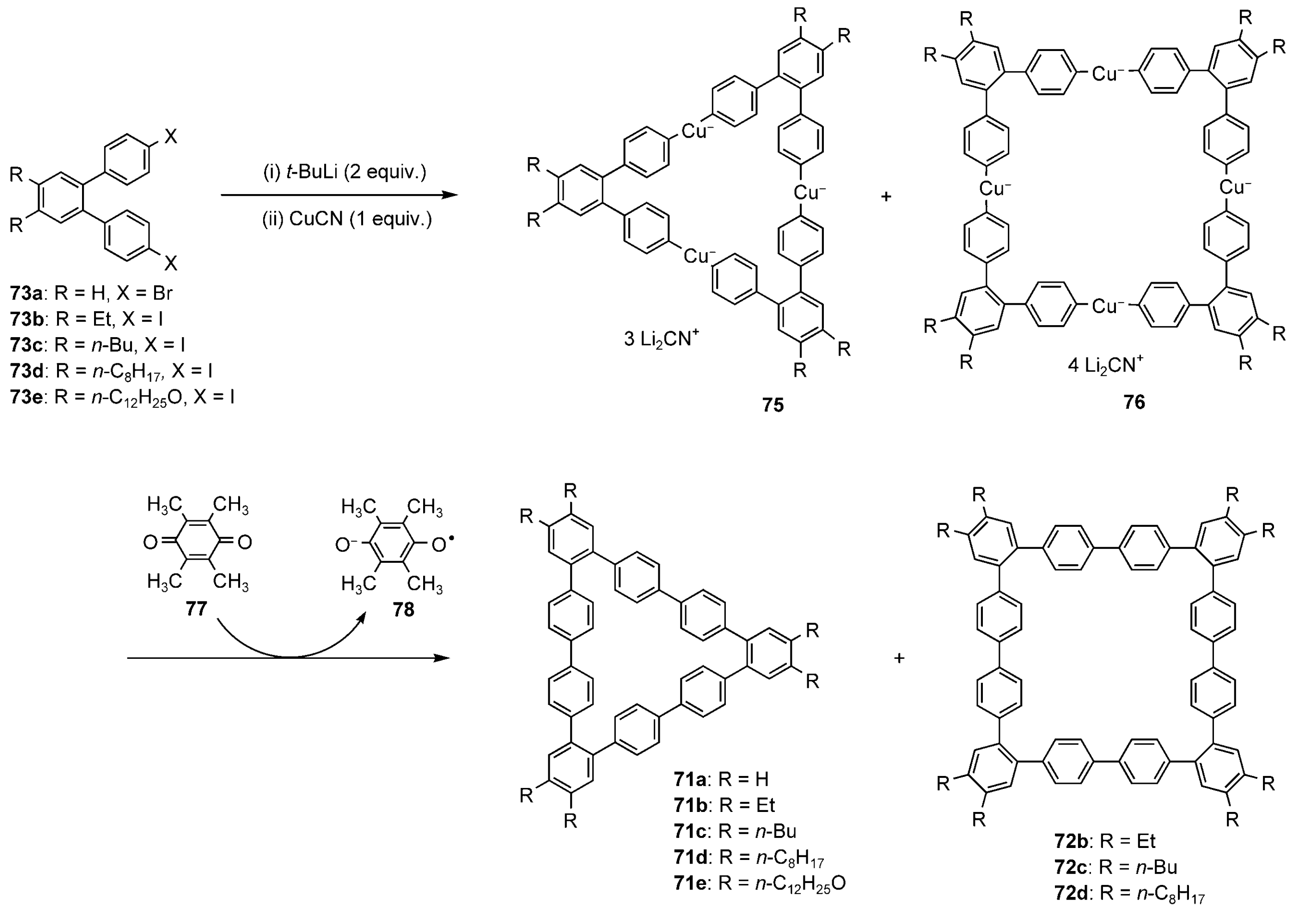

71 **72**

Figure 5. Nonaphenylenes **71** and dodecaphenylenes **72**.



Scheme 16. Syntheses of nonaphenylenes **71a**–**71e** and dodecaphenylenes **72b**–**72d**.

none to a yellow solution of the Lipshutz cuprates **75** and **76** resulted in a green solution that showed ESR signals due to the durosemiquinone radical **78**.[74,75]

The nonaphenylenes and dodecaphenylenes show strong UV absorption and fluorescent emission and exhibit some redox properties on CV analysis. Moreover, hexadodecyloxynonaphenylene **71e** exhibits different nanostructures on the surface and in solution to form a film by casting a solution of **71e** in cyclohexane, benzene, chloroform, THF or diisopropyl ether (IPE) and nanofibers from IPE-MeOH (1:1), indicating different absorption and emission spectra and XRD patterns.[73] The absorption maxima of THF solution, fiber, and film are in the order of **71e** film > fiber > solution, whereas the emission maxima are in the order of **71e** fiber > solution > film. XRD analysis revealed that **1e** aligns laterally on a glass or silicon surface to form a thin film with a lamella structure; however, it forms a nanofiber with a Lego-like stacking structure without π-π stacking interaction of the aromatic rings. Reflecting the different nanostructures of the **71e** film and fiber, a spin-coated **71e** film is found to be effective in detecting the vapor of explosives due to the intercalation of nitroaromatics to the cracked surface of the loosely stacked **71e**. In contrast, the **71e** fiber is not effective in the detection of nitroaromatics but exhibits fluorescence anisotropy. The maximum fluorescence intensity is obtained in a direction perpendicular to the longitudinal axis of the fiber, indicating the stacking direction to be parallel to the longitudinal axis of the fiber.[73]

5 Conclusions

Copper is a coinage metal, and copper-mediated organic reactions have already been explored in detail. However, copper-mediated carbon-carbon bond formation maintains practical importance, and a number of communications and articles have been published to date. On the other hand, the Ullmann coupling is a well-known reaction for synthesizing symmetrical biaryls, although this reaction can produce coupling products in only limited yields compared with transition metal-catalyzed biaryl syntheses. In connection with our research interest, we needed an effective synthetic procedure for constructing biaryls and oligophenylenes. Oligophenylenes and their heteroaromatic analogues have remarkable photo- and electrophysical properties, and are either extremely robust or unreactive to heat, light, and air oxidation. Therefore, these compounds have potential applications in molecular devices, switches, and actuators.

We have developed new synthetic methodologies to access oligophenylenes and their heteroaromatic analogues by combining organozincs, organotins, and Lipshutz cuprates with copper(II) species or organic π-acceptors. First, the ring-size control of organozinc intermediates can be successfully applied to the selective synthesis of biphenylenes and tetraphenylenes. Second, the copper(II)-mediated oxidative coupling of organotin species can be applied to the synthesis of extremely strained cyclophanes. Third, the ET oxidation of Lipshutz cuprates with 1,4-benzoquinones can be used for the synthesis of conformationally rigid nonaphenylenes and dodecaphenylenes. Since these cuprates have a linear carbon-Cu(I)-carbon arrangement, their reactions tend to produce larger cyclic products. Oligophenylenes are extremely stable functional materials, and our new approach to the construction of nanostructures could be extended to interesting multifunctional materials through the control of structural, optoelectric, and device properties.

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