中央大学博士論文

Studies on Cross-coupling Reactions Using Trialkylsilyl-type Reagents

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Preface

The present dissertation is concerned with cross-coupling reactions using trialkylsilyl-type reagents. The studies described here have been carried out under the guidance of Professor Tamejiro Hiyama at Research and Development Initiative, Chuo University, during April 2013–January 2019. I would like to express my cordial gratitude to Professor Tamejiro Hiyama, who always encouraged me with enthusiasm by showing a variety of possible future research directions.

I am deeply grateful to Associate Professor Yasunori Minami for his pertinent encouragements and discussions for the duration of my Ph.D. program.

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All members in the Hiyama group, Dr. Kenta Shimizu, Yuki Shiraishi, Hirofumi Yoshiyasu, Mayuko Kanda, Kotomi Yamada, Tomohiro Anami, Chisato Tsuruoka, Tatsuro Kodama, Shu-ichi Uno, Megumi Sakai, Yuta Noguchi, Mayu Yamada, Yuki Furuya, and Takumi Sakamaki are appreciated for their friendships, and secretaries, Tomoko Yoshida and Hideko Sekiguchi for their assistances.

I am deeply indebted to Professor Martin Oestreich at Technische Universität Berlin for giving me an opportunity to study in Berlin for a month.

Financial support by JSPS is acknowledged during my Ph.D. program.

The course was finished owing to constant assistance and encouragement by my parents, Akihiro and Yukari, along with his younger brother, Koji.

Lastly, I show warm appreciation to my wife, Yukiko, for her continuous kindness.

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Contents

Abbreviation List

18C6	18-crown-6 ether
2,4,7-Me_3phen	2,4,7-trimethyl-1,10-phenanthroline
Ac	acetyl
APCI	atmospheric pressure chemical ionization
Ar	aryl
Ar^F	3,5-bis(trifluoromethyl)phenyl
BHT	di-*tertiary*-butylhydroxytoluene
Boc	*tertiary*-butylcarbonyl
bpy	2,2'-bipyridyl
n-Bu	*normal*-butyl
t-Bu	*tertiary*-butyl
bp	boiling point
cod	1,4-cycoctadiene
Cp	η^5-cyclopentadienyl
CPME	cyclopentyl methyl ether
Cy	cyclohexyl
DART	direct analysis in real time
Davephos	2-dicyclohexylphosphino-2'-dimethylaminobiphenyl
dba	dibenzylydeneacetone
Dec	*n*-decyl
DMA	*N*,*N*-dimethylacetamide
DME	1,2-dimethylethane
DMF	*N*,*N*-dimethylformamide
DMI	*N*,*N'*-dimethyl-2-pyroridinone
DMPU	*N*,*N*'-dimethylpropyreneurea
DMSO	dimethylsulfoxide
dppb	1,4-bis(diphenylphosphino)butane
dppf	1,1'-bis(diphenylphosphino)ferrocene
dtbpy	4,4'-di-*tertiary*-butylbipyrydyl
Et	ethyl
EI	electron ionization
ESI	electrospray ionization
GPC	gel permeation chromatography

LDA	lithium di-*iso*-propylamide
Hex	*normal*-hexyl
HOMSi	[2-(hydroxymethyl)phenyl]dimethylsilane
HRMS	high-resolution mass spectrometry
i	*iso*
JonPhos	2-di-*tertiary*-butylphosphinobiphenyl
LED	light emitting diode
Me	methyl
Me_4phen	3,4,7,8-tetramethyl-1,10-phenanthroline
$(MeO)_8$-BIPHEP	6,6'-dimethoxy-2,2'-bis[bis(3,4,5-trimethoxyphenyl)phosphino]-biphenyl
M_n	number average molecular weight
MOM	methoxymethyl
mp	melting point
Ms	methane sulfonyl
M_w	weight average molecular weight
n	*normal*
NMP	*N*-mehtyl-pyrroridone
NMR	nuclear magnetic resonance
Oct	*normal*-octyl
phen	1,10-phenanthlorine
PDI	polydispersity index
PG	protecting group
Ph	phenyl
Ph-DavePhos	2-diphenylphosphino-2'-dimethylaminobiphenyl
pin	pinacolato
Piv	pivaloyl
i-Pr	*iso*-propyl
PTFE	polytetrafluoroethylene
Py	pyridyl
R	substituent
RuPhos	2-dicyclohexylphosphino-2',6'-di-*i*-propoxybiphenyl
SEM	2-(trimethylsilyl)ethoxymethyl
SET	single electron transfer
t	*tertiary* (*tert*)
TASF	tris(dimethylamino)sulfonium difluorotrimethylsilicate

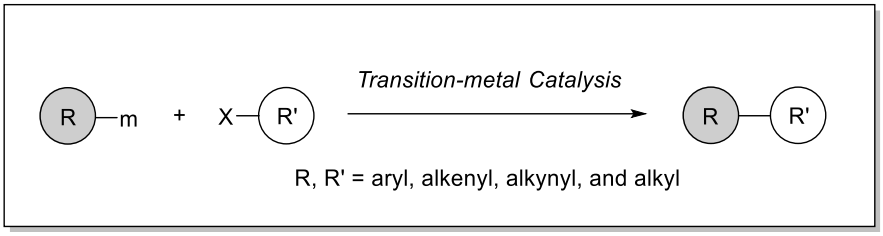
TBAF	tetrabutylammonium fluoride
TBS	*tertiary*-butyldimethylsilyl
TEMPO	*N,N-N',N'*-tetramethylpiperidine 1-oxyl
Tf	trifluoromethane sulfonyl
THF	tetrahydrofuran
THP	2-tetrahydropyranyl
TMU	*N,N-N',N'*-tetramethylurea
Ts	toluene sulfonyl (tosyl)
TS	transition state
TTMPP	tris(2,4,6-trimethoxyphenyl)phosphine
X	halogen or pseudohalogen
XPhos	2-dicyclohexylphosphino-2',4',6'-tri-*iso*-propylbiphenyl

Chapter 1

General Introduction

1-1. Cross-coupling Reaction

Organic synthesis supports our healthy and productive lives by means of providing helpful molecules toward pharmaceuticals, agrochemicals, and a wide range of chemicals from plastics and fibers to liquid crystals and electron transportation materials. To access such valuable molecules, one of the most common ways is the cross-coupling reaction where organometallic reagents couple with organic (pseudo)halides with the aid of transition-metal catalysis (following scheme).[1] The reaction allows us to connect desired carbon–carbon or carbon–heteroatom bonds with high efficiency and excellent selectively. In this section, the author briefly reviews the cross-coupling reactions.



In 1971, Kochi initially found alkyl Grignard reagents coupled with vinyl bromides in the presence of a catalytic amount of ferric chloride.[2] In the following year, Tamao/Kumada and Corriu independently reported a prototype of the cross-coupling reaction using Grignard reagents and aryl/alkenyl halides with nickel catalysis.[3,4] It should be noted that Tamao and Kumada first proposed the well-accepted reaction mechanism of the cross-coupling reaction in their communication (*vide infra*).[3] Murahashi disclosed organolithium reagents were partially applicable to the reaction with a palladium catalyst.[5] Although such organomagnesium and -lithium reagents show high reactivity for the coupling, they also react with electrophilic functional groups like carbonyl or cyano groups and are quenched by acidic proton. Subsequently, Negishi revealed organozinc reagents underwent the palladium-catalyzed reaction, showing wide functional group tolerance.[6] Unfortunately, zinc reagents are also air sensitive, making them hard to store like magnesium and lithium reagents. Organotin compounds were later shown to have enough reactivity for the reaction by Kosugi/Migita and Stille in 1977 and 1979, respectively.[7,8] Tin reagents could be perfect owing to wide functional group tolerance and high stability, if the reaction was run in a small scale. Organoboron reagents are in turn more stable and less toxic but yet considered inert for the cross-coupling reaction until 1979 when Miyaura and Suzuki revealed organoboranes underwent through the palladium-catalyzed cross-coupling in the presence of a base as an activator.[9] Because the Suzuki–Miyaura reaction shows excellent chemoselectivity and organoboron reagents are easily accessible and air stable, such reactions became widely applied in various fields

regarding organic chemistry. In recognition of the contribution for palladium-catalyzed cross-couplings in organic synthesis, the Nobel Prize in chemistry was awarded to Suzuki, Negishi, and Heck in 2010. In contrast, silicon is an earth-abundant element and organosilicon reagents are superior in terms of chemoselectivity and easy-handling based on their high stability, good solubility, and non-toxicity. In addition, a variety of silicon reagents are readily accessible by both stoichiometric and catalytic procedures. Accordingly, the silicon-based cross-coupling reaction has a potential of the best choice. In spite of such advantages, the desired coupling of silicon remained took a long time before invention, because organosilanes are too stable. In 1988, Hiyama and Hatanaka unveiled that vinyl(trimethyl)silane coupled smoothly with aryl iodides in the presence of a palladium catalyst with the aid of a fluoride ion as an activator.[10] After their discovery, silicon-based cross-coupling chemistry has been evolved to date. The author describes its history including technical advancements and future problems of the silicon-based cross-coupling reaction in the following sections, along with methods for preparation of organosilicon reagents.

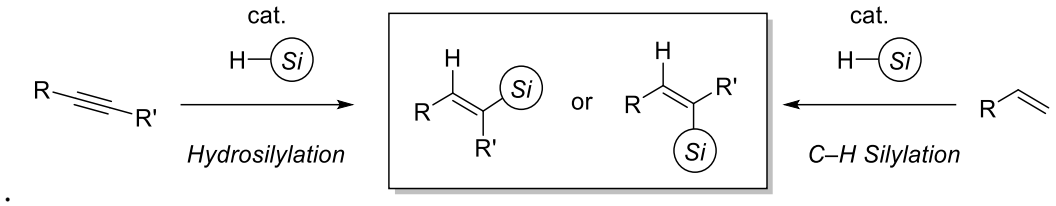
1-2. Preparation of Organosilicon Reagents

An array of organosilicon reagents including alkenyl-, aryl, alkyl-, and alkynylsilanes are synthesized generally by the reaction of organolithium or -magnesium reagents with electrophilic silanes like chlorosilanes. The procedure is common and representative to access to organosilicon reagents. However, the corresponding organolithium and -magnesium reagents are in general so reactive that they suffer from functional group selectivity.[11] To overcome the problem, alternative routes are possible which use transition-metal catalysis as shown bellow.

1-2-1. Preparation of Alkenylsilanes with Catalysts

The most practical and direct method to synthesize alkenylsilanes is hydrosilylation of alkynes with hydrosilanes where Si–H bonds are added to C–C triple bonds cis-specifically with the assistance of transition-metal catalysts (Scheme 1, left).[12] Noble metal catalysts such as platinum, rhodium, and palladium show high catalytic activity to give selectively *β-E*-alkenylsilanes. Recent hydrosilylation chemistry shows that base metal catalysts like iron and cobalt work equally well.[13] Although hydrosilylation generally takes place *β*-cis-selectively, ruthenium and rhodium catalysts sometimes produce *β-Z*-alkenylsilanes[14] or α-alkenylsilanes exclusively.[15] What is more, catalytic C–H silylation of terminal alkenes has appeared as an attractive method to

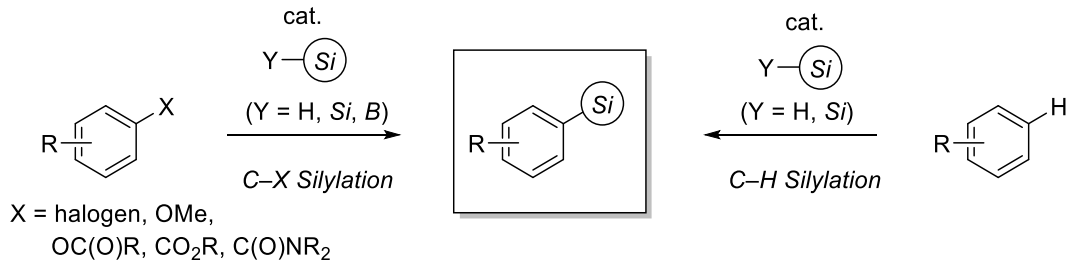
prepare alkenylsilanes (Scheme 1, right).[16] In addition to these reactions, there are a number of synthetic methods of alkenylsilanes which involve silyl-Heck reaction,[17] addition reaction of silicon–carbon or silicon–heteroatom bonds to alkynes,[18] and formal olefin metathesis between alkenes and vinylsilanes.[19]



Scheme 1-1. Representative Route for Preparation of Alkenylsilanes

1-2-2. Preparation of Arylsilanes with Catalysts

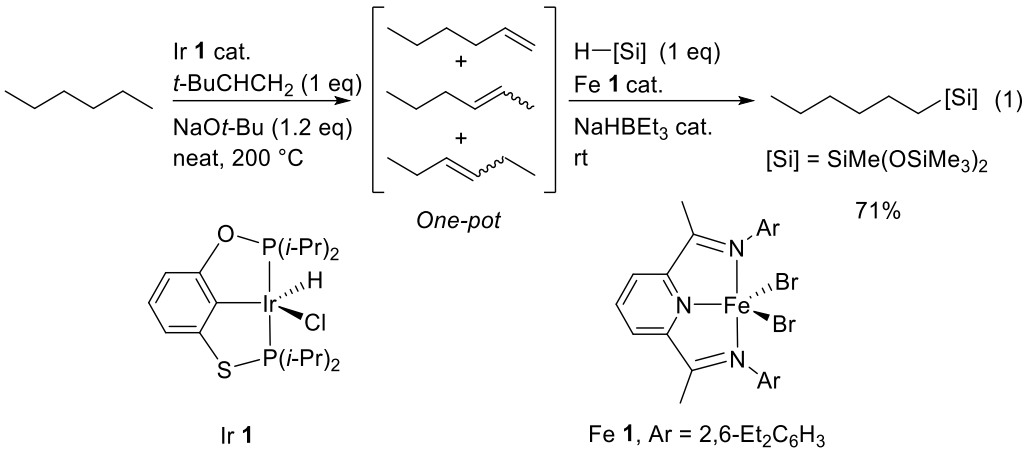
Transition-metal-catalyzed silylation of aryl halides with hydrosilanes[20] or disilanes[21] is a modern entry to obtain functionalized arylsilanes (Scheme 2, left). This sort of reaction is generally run with a palladium, platinum, or rhodium catalyst.[20,21] Recent progress in stable-bond-activation chemistry has made it possible to transform anisole, aryl ester, benzoate, and benzamide derivatives[22–25] into arylsilanes with silylboranes as silylating agents through aryl–OMe or aryl–carbonyl bond cleavage (Scheme 2, left). It is worthy to note that arylsilanes can be obtained directly from simple aromatic hydrocarbons via catalytic C–H silylation under transition-metal catalysis (Scheme 2, right).[26] The regioselectivity depends on catalysts; silylation occurs preferably at the least hindered C–H bond, the most electron-rich, or the most electron-deficient position. In addition, some chemists have unveiled that similar reactions occur remarkably under metal-free conditions upon use of KO*t*-Bu,[27] $B(C_6F_5)_3$,[28] or $H(OEt_2)(BAr_4)$ (Brookhart's acid)[29] as the catalyst.



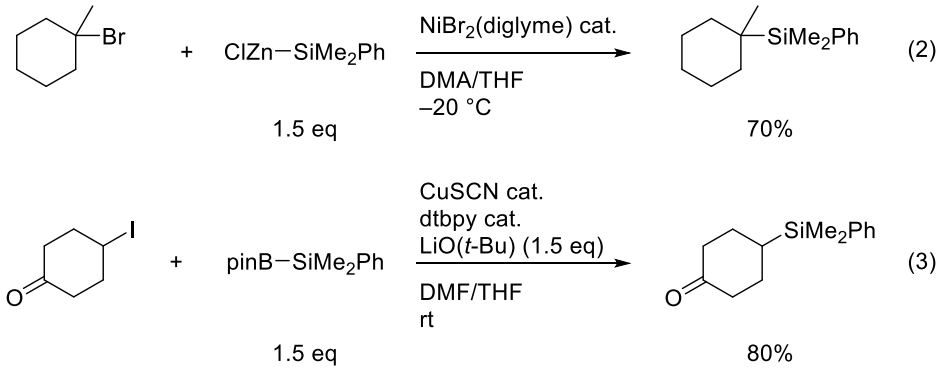
Scheme 1-2. Representative Route for Preparation of Alkenylsilanes

1-2-3. Preparation of Alkylsilanes with Catalysts

As with alkenylsilanes, alkylsilanes are prepared by hydrosilylation of alkenes.[30] Using an appropriate optically active catalyst, enantioselective hydrosilylation proceeds successfully.[31] Compared with alkenyl- and arylsilanes, non-directed C–H silylation of alkanes are quite limited except for intramolecular reaction.[32] In 2015, Huang established formal C–H silylation of simple linear alkanes (Eq. 1).[33] Indeed, a one-pot reaction based on dehydrogenation of alkanes by **Ir1** catalyst and chain-walking-type hydrosilylation by iron catalyst **Fe1** bearing an (N-N-N)-pincer ligand allows for conversion of a terminal aliphatic C–H bond into a C–Si bond.

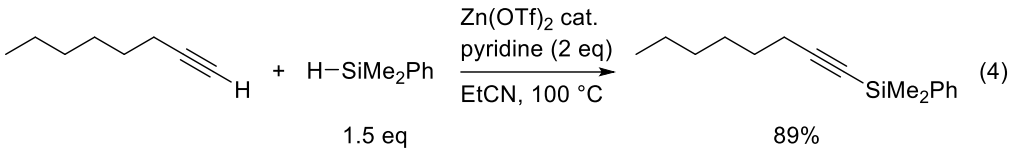


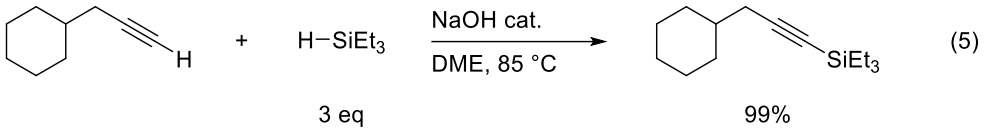
Generally, *secondary* and *tertiary* alkylsilanes are difficult to prepare even by stoichiometric reaction.[34a] In 2016, Fu and Oestreich independently overcome the problem. Fu found *secondary* and *tertiary* alkyl halides react with silylzinc reagents in the presence of a nickel catalyst to give the corresponding alkylsilanes.[34b] Oestreich reported similar halides are silylated by silylboranes in the presence of a copper catalyst.[34c] Although the mechanisms of these reactions remain yet to be clarified, both of them are considered to proceed via a hemolytic cleavage of alkyl halides.



1-2-4. Preparation of Alkynylsilanes with Catalysts

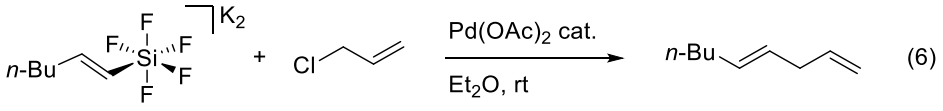
Dehydrogenative silylation of terminal alkynes with hydrosilanes is a promising strategy to prepare alkylnylsilanes directly.[35] For example, Tsuchimoto demonstrated terminal alkynes were silylated with hydrosilanes easily in the presence of a zinc catalyst (Eq. 4).[35h] Furthermore, alkali metal hydroxides and alkoxides were demonstrated to effect the reaction (Eq. 5).[35j]

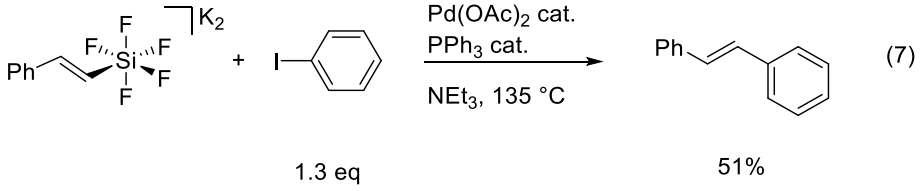




1-3. Silicon-based Cross-coupling Reaction

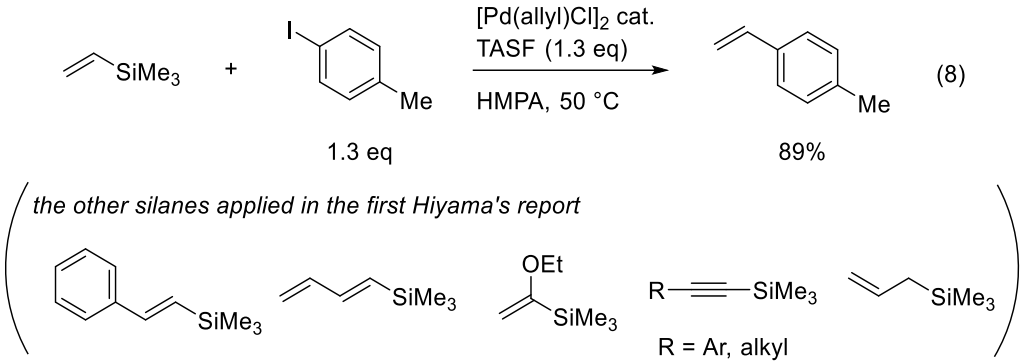
Summarized here are historical background and recent progress in the silicon-based cross-coupling reaction. In 1978, Tamao and Kumada achieved the first transition-metal-catalyzed carbon–carbon bond-forming reactions using organosilicon reagents. They showed organo(pentafluoro)silicates coupled with allyl chloride in the presence of a palladium catalyst (Eq. 6).[36a] Subsequently they reported the cross-coupling reaction of such silicates with aryl and alkenyl halides (Eq. 7).[36b] These contributions have unveiled that highly coordinated silicates are presumably responsible to transmetalation with organopalladium complexes.





In 1988, silicon-based cross-coupling reaction was evolved to synthetically practical level by Hiyama and Hatanaka, who found that Pd-catalyzed cross-coupling of electron-neutral tetra-coordinated organosilicon reagents like vinyl-, alkynyl-, and allyl(trimethyl)silanes with aryl iodides took place with the aid of $[F_2SiMe_3][S(NMe_2)_3]$

(TASF) as an activator (Eq. 8).[37] They suggested that organosilanes upon activation with fluorides generated hypervalent silicates, which were true active species toward transmetalation. The most important point of the report is readily accessible tetrahedral silicon reagents readily become cross-coupling-active by a fluoride ion. In fact, catalytic transformations using various organosilicon reagents have appeared so far since the seminal report.



The well-accepted reaction mechanism of the silicon-based cross-coupling reaction consists following steps: (1) oxidative addition of organic halides (R^2–X) to a palladium(0) with generation of X–Pd–R^2, (2) transmetalation of hypervalent silicon species, generated in situ from R^1SiY_3 and a fluoride ion, with X–Pd–R^2 to give R^1–Pd–R^2, (3) reductive elimination of the palladium(II) complex yielding the coupled product (R^1–R^2) with regeneration of the palladium(0) complex.[38] Some experimental results show the transition state in the transmetallation step is based on palladium(II) complexes and silicates (Figure 1-1, TS-A). In contrast, recent theoretical and experimental study suggests that its transition state comprises palladium fluorides and tetra-coordinated organosilanes directly (Figure 1-1, TS-B).[39] In any possible pathways, the Lewis acidity of the silicon center is essential for successful transmetalation.

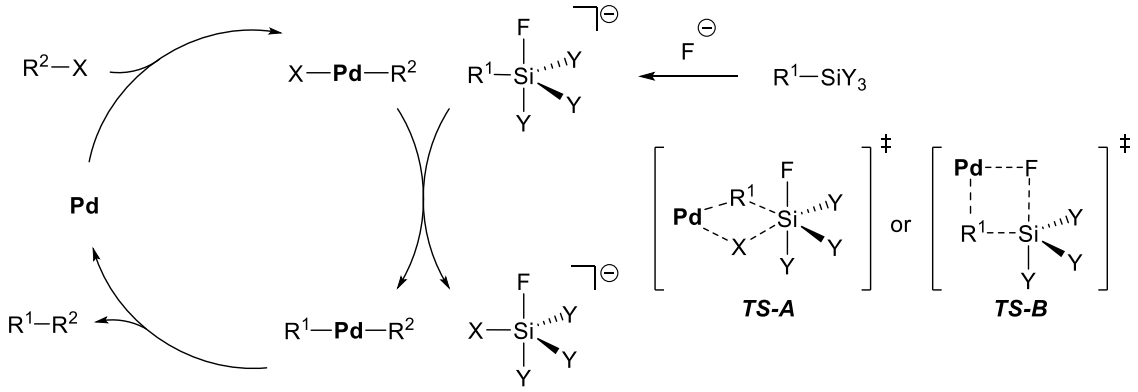
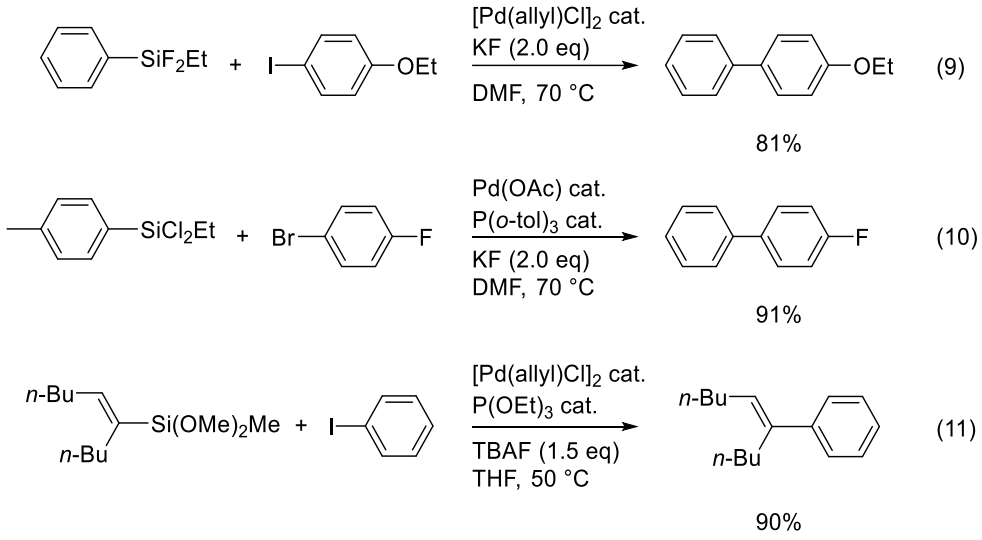


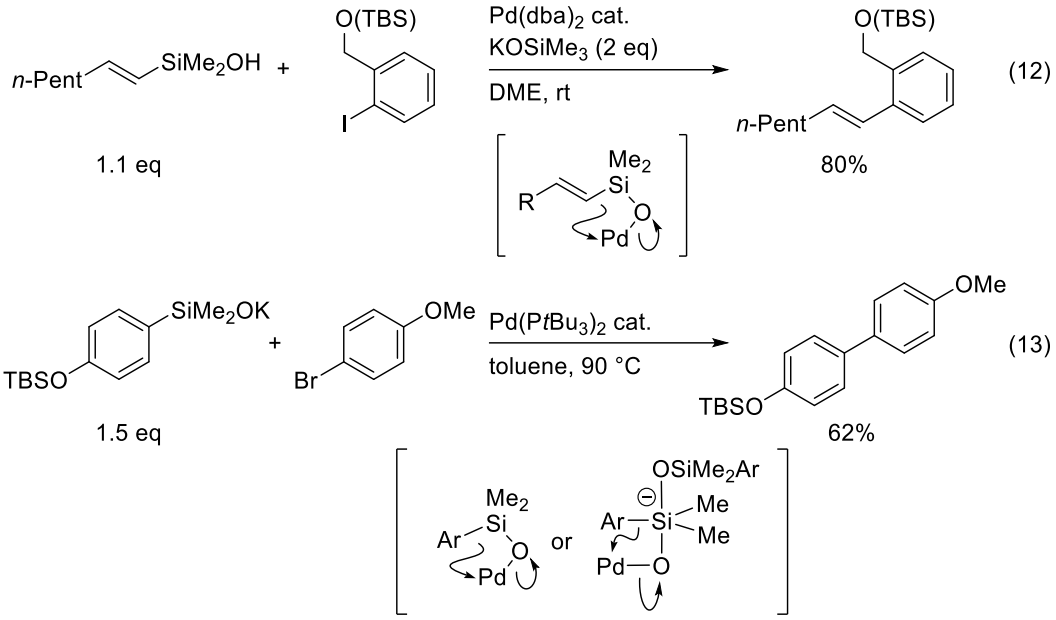
Figure 1-1. Plausible Mechanism of Pd-catalyzed Cross-coupling of Silicon reagents

1-3-1. Cross-coupling of Halosilanes, Alkoxysilanes, and Silanols

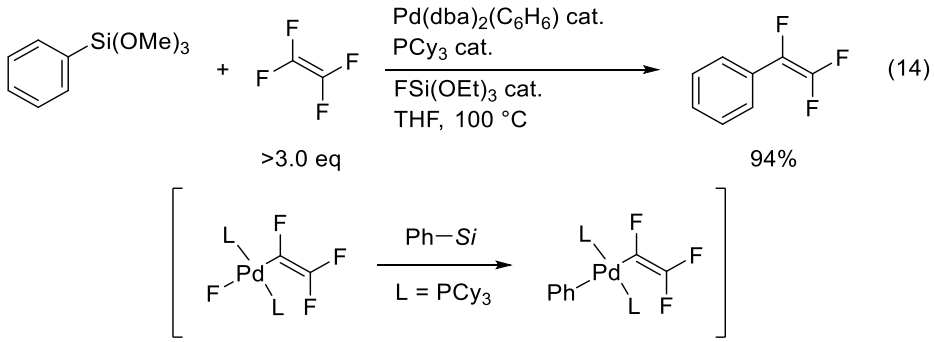
Since the pioneer works were announced, a quite large number of silicon-based cross-coupling reactions have been reported.[40] Although a few organo(trimethyl)silanes were applied in the first Hiyama's report, most of tetraorganosilanes were found to be inapplicable for the coupling due to their low electrophilicity. Thus, chemists including Hiyama modified silicon reagents and found out that organofluoro-,[41] chrolo-,[42] and alkoxysilanes[43] have enough reactivity for the cross-coupling reaction (Eq. 9–11). These electron-negative heteroatoms on silicon are considered to enhance their Lewis acidity to embrace a fluoride ion. Hydroxy ions were disclosed to behave as a good activator of the cross-coupling as well.[42b] Such silanes cross-couple with various aryl and alkenyl halides including iodides, bromides, and less-reactive chlorides[44] along with such phenol-based electrophiles as triflates,[45] tosylates,[46] and mesylates.[47] Recent progress in stable-bond-activation chemistry allows to utilize arylsilanes as arylating agents toward carboxylic acids,[47] aryl carbamates,[49] and hydrocarbons[50] directly at sp^2- or sp^3-hybridized C–H bonds.



Silanols also cross-couple with various (pseudo)haloarenes.[40c] Hiyama and Denmark independently reported Ag_2O or tetrabutylammonium fluoride (TBAF) were suitable for Pd-catalyzed cross-coupling of aryl- and alkenylsilanol.[51,52] After a while, Denmark improved silanol-based cross-coupling, which took place in the presence of a $KOSiMe_3$ base (Eq. 12).[52b] The silanol moiety tolerates these conditions to effect the cross-coupling of potassium organosilanolates as nucleophiles (Eq 13).[53] In this case, the silanolates play roles as a nucleophilic activator and delivery of organic coupling partner. The reaction mechanism is regarded at first to involve an intramolecular transmetalation through siloxypalladium complexes.[54]

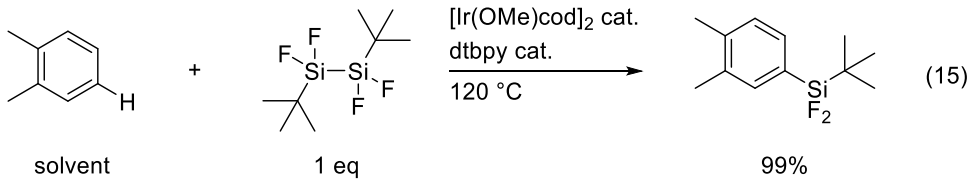


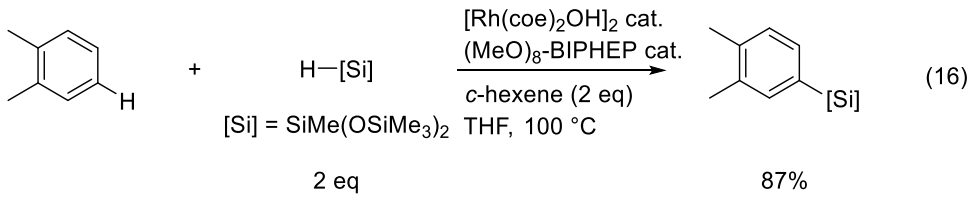
In addition to the silanolate cross-coupling, there are a few reports on the activator-free cross-coupling reactions. Ogoshi demonstrated aryl(trimethoxy)silanes cross-coupled with tetrafluoroethene without any base through C–F bond cleavage.[55] He used at first the stoichiometric palladium complexes and revealed that the reaction took place via oxidative addition of the C–F bond to palladium(0) followed by direct transmetalation between arylsilanes and palladium fluorides possibly through TS-B in Figure 1. Similar reaction was discussed some years ago by Hiyama using allylic and benzylic carbonates.[56]

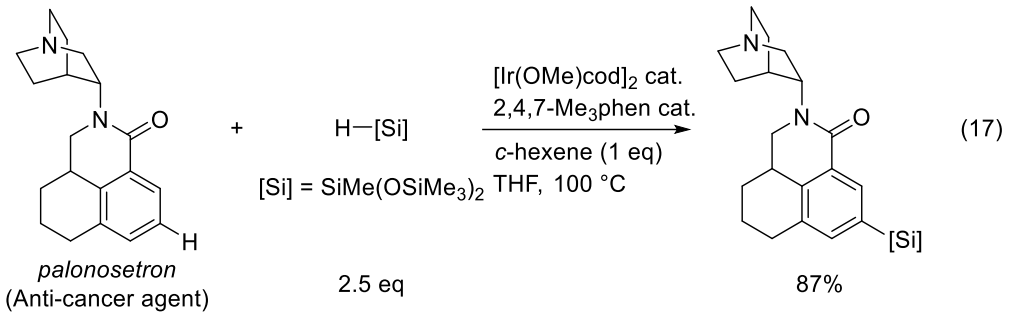


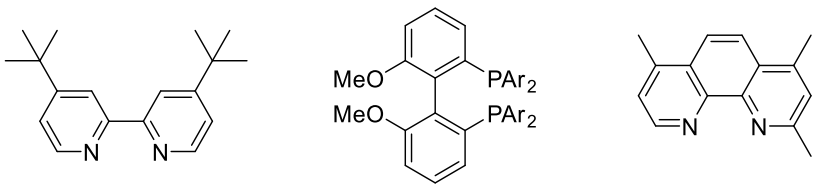
Combinations of aryl C–H silylation[26] and cross-coupling are attractive strategy for rapid synthesis of biaryls showcased by Ishiyama and Miyaura, who used di-*t*-Bu-tetrafluorodisilane as the excellent silylating agent for aromatic hydrocarbon in excess in the presence of a $[Ir(OMe)cod]_2$/dtbpy catalyst.[57] The resulting arylsilanes were applied to sequential cross-coupling reaction. Whereas the intermolecular aryl C–H silylation without directing groups mostly require the substrates in excess, very recently, Cheng and Hartwig solved the stoichiometric problem and established rhodium- and iridium-

catalyzed C–H silylation of arenes as a limiting reactant with H–SiMe(OSiMe$_3$)$_2$[26b] to form cross-coupling-active arylsilanes.[26f,g]

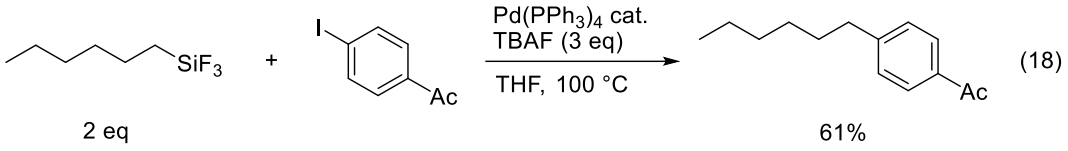


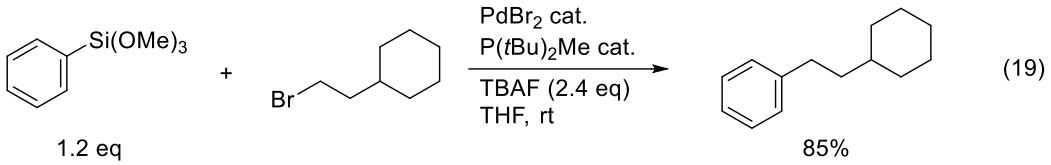




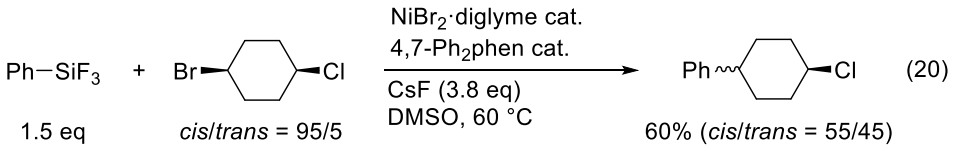


Although a large number of reports on Pd-catalyzed silicon-based C(sp^2)–C(sp^2) and C(sp)–C(sp^2) bond-forming reactions are available, cross-coupling using alkyl halides or alkylsilanes to construct C(sp^3)–C(sp^2) bonds is hardly achieved, possibly because transmetalation of an alkyl group from Si to Pd is disfavored and a quite fast β-hydride elimination on palladium follows. In 1994, Hiyama reported the cross-coupling of alkyl(trifluoro)silanes with aryl bromides to give alkylarenes in moderate to good yields (Eq. 18).[58] Later, Fu disclosed that cross-coupling of alkyl bromides with aryl(trimethoxy)silanes successfully took place with a bulky electron-donating phosphine which prevents β-hydride elimination (Eq 19).[59]

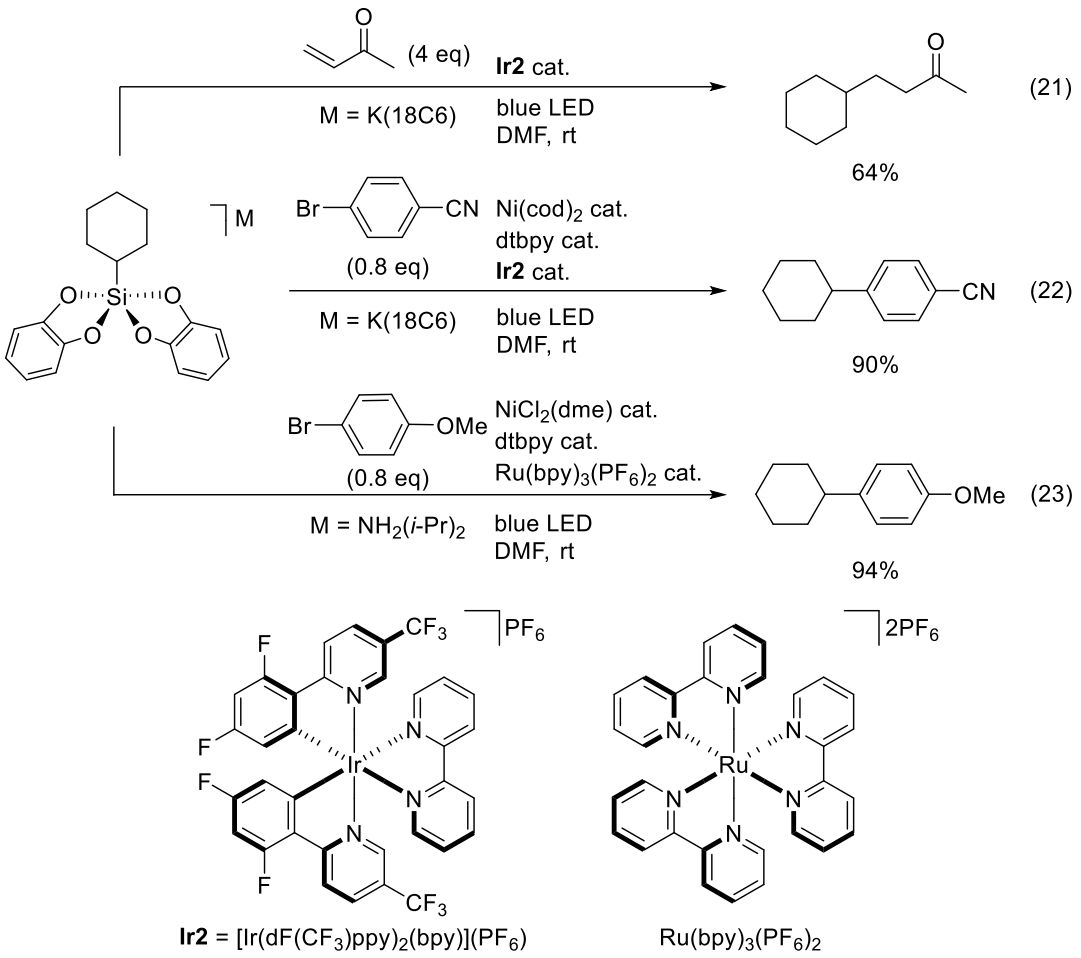




Nickel catalyst is also effective for the cross-coupling of organosilicon reagents showing a reactivity different from palladium, because nickel metal complexes can participate in a single-electron-transfer process (SET). In 2004, Fu first accomplished that Ni-catalyzed cross-coupling of arylsilanes with primary and secondary alkyl halides (Eq. 20).[60] The stereochemical outcome from *cis*-1,4-dihalocyclohexane indicates that alkyl–Br bond is homolytically cleaved.



Recent progress in photo-redox catalysis has inspired chemists to invent cross-coupling of alkyl radical generated from alkylsilicates.[61,62] In 2015, Goddard, Ollivier, and Fensterbank reported that alkyl(bis-catecholato)silicates generates an alkyl radical mediated by a photo-redox catalyst, Ir[(dF(CF_3)ppy)$_2$(bpy)]PF_6 (**Ir2**), under irradiation with blue LED.[61] The resulting alkyl radical reacts with activated olefins like enones to give Michel adducts (Eq. 21). The photo-redox strategy evolved Ni/Ir dual catalysts which made it possible to alkylate aryl bromides using alkylsilicates as an alkylating agent (Eq. 22). Subsequently, Molander demonstrated that aryl bromides cross-coupled with similar alkyl(bis-catecholato)silicates with Ni/Ru catalytic combination mediated by blue LED irradiation (Eq. 23).[62] Based on a similar photo-induced cross-coupling, a plausible catalytic cycle is suggested, which consists of the following steps (Figure 1-2).[63] First, blue LED excites Ir(III) to Ir*(III), which oxidizes an alkylsilicate to generate alkyl radical via SET. This alkyl radical couples with Ni(0) to form an alkyl–Ni(I) complex followed by oxidative addition of an aryl bromide to furnish an alkyl(aryl)Ni(III)–Br complex. Subsequently, reductive elimination produces the coupled product and Ni(I)–Br. Finally, single electron transfer between Ni(I) and Ir(II) reproduce Ni(0) and Ir(III).



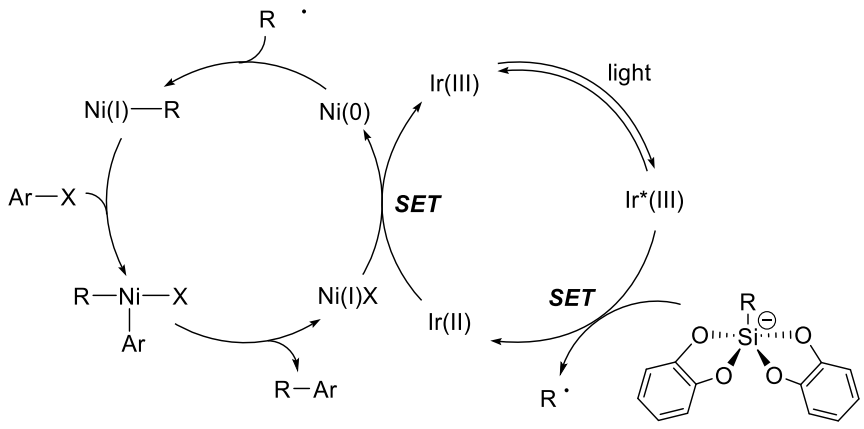
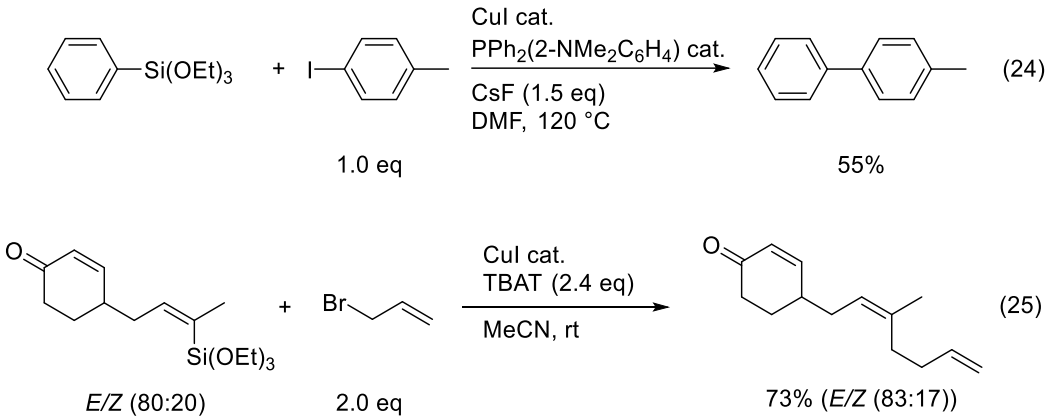


Figure 1-2. Plausible Mechanism of Ni/Ir-catalyzed Cross-couplings

Copper salts also have a potential to catalyze cross-coupling of silicon.[64] For example, Giri reported biaryls are produced from aryl(triethoxy)silanes and aryl iodides

in the presence of a catalytic amount of CuI and $PPh_2(2\text{-}NMe_2C_6H_4)$, where the reaction proceeds possibly through an oxidative addition of aryl iodides to arylcopper(I) species followed by a reductive elimination (Eq. 24).[64c] Thereafter, alkenyl(triethoxy)silanes were also found to react with allyl bromide in the presence of CuI catalyst to give allylated alkenes with retention of the configuration (Eq. 25).[64f] This reaction occurs in preference to 1,4-addition toward its enone moiety.



1-3-2. Cross-coupling of Triorganosilyl-type Reagents

As discussed above, a wide verity of halosilanes or alkoxysilanes are applicable to the cross-coupling reaction. However, these silanes are not easy to handle because of instability against moisture as well as basic and/or acidic reagents. On the other hand, tetraorganosilanes are ideal types of reagents in view of cost, accessibility, toxicity, stability, and solubility, though they are generally inert for the cross-coupling due to their robustness aside from some exceptions.[65] Cross-coupling active alkenyl(triorgano)silanes reported to date and their corresponding activators are summarized in Figure 1-3. Applied to the cross-coupling with aryl iodides in the presence of TASF were vinyl-, α-ethoxyvinyl-, 1,4-butadienyl, and *β*-stylyl(trimethyl)silane as well as alkynylsilanes and allylsilanes.[37] Recently, Omote and Ando added *β*-CF_3-vinyl(trimethyl)silane to the list.[66] More than a decade later, 1-alkenyl-1- methylsilacyclobutanes were found to be activated by TBAF to couple with organic halides at room temperature.[67] Hereby, these silanes were assumed to undergo the reaction after ring-opening reaction of four-membered ring by hydrated TBAF to form fluorosilanes or silanols, which were considered to be true active species.[67b] Similarly, 2-pyridyl-,[68] 2-thienyl-,[69] benzyl-,[70] 3,5-bis(trifluoromethyl)phenyl-,[71] phenyl-,[72] allyl,[73] and perfluorophenyl[74]-substituted alkenylsilanes act as precursors of fluorosilanes and/or silanols in situ.

Intramolecular activation strategy is an alternative to develop active silicon

reagents. Shindo reported that (*Z*)-$SiMe_3$-acrylic acid undergoes the reaction upon activation by Cs_2CO_3 through intramolecular activation by a proximal carboxylate moiety,[75] whereas Nakao and Hiyama invented alkenyl-[2-(***H***ydr***O***xy***M***ethyl)phenyl]-dimethyl***Si***lanes (alkenyl-HOMSi), which were demonstrated to undergo the cross-coupling reaction even in the presence of a weak base like K_2CO_3.[76] The details of HOMSi are described in a later section of this Chapter.

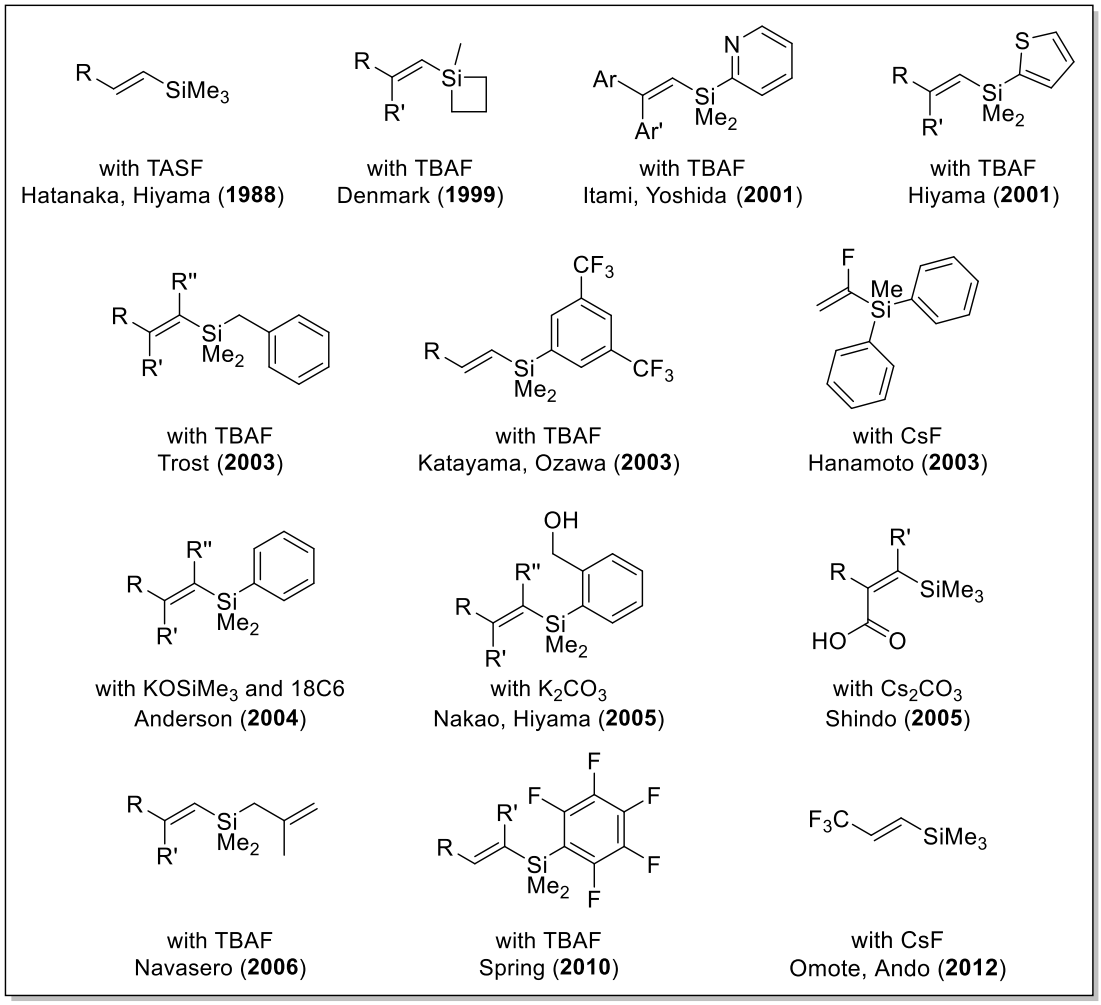


Figure 1-3. Cross-coupling-active Alkenyl(triorgano)silanes and their Activators

In comparison with alkenylsilanes, cross-coupling-active aryl(triorgano)silanes is limited and most of them have a narrow scope of substrates. Active type of arylsilanes are summarized in Figure 4. Those which show a range of substrate generality are limited to aryl(*triallyl*)silanes,[77] Ar–*HOMSi*,[76] and aryl(*2-hydroxyprop-2-yl*)cyclohexylsilanes.[78] In contrast, the most popular trimethylsilyl group is applicable only when 2-pyridyl[79] or benzofuran-2-yl[80] group is introduced as a coupling nucleophilic partner. The type of aryl(trimethyl)silanes needs in general an additional Ag_2O, KF, or hydroxide mediators

in a stoichiometric amount. Some types of aryl(triorgano)silanes were applied to the coupling by Itami/Yoshidia,[81] Murata,[82] Kita,[83] Gevorgyan,[84] and Murai/Takai.[85]

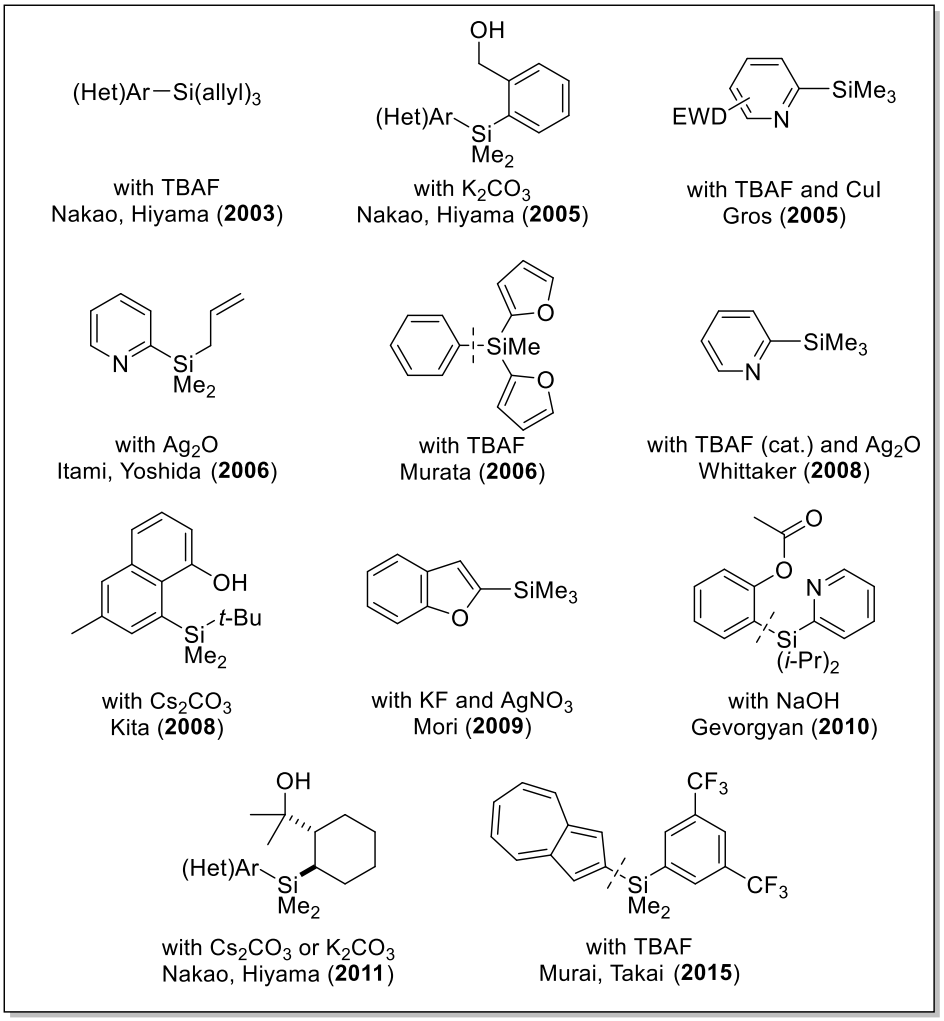
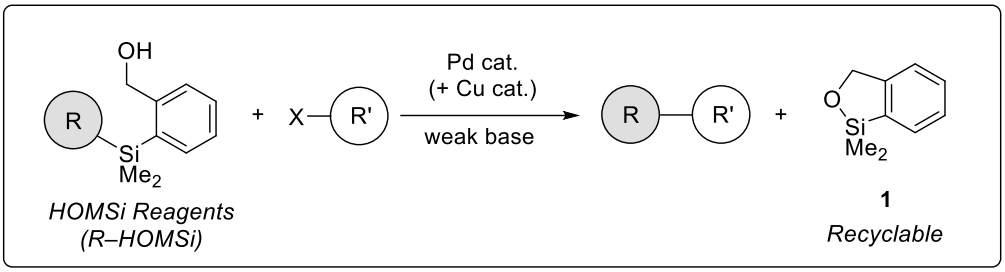


Figure 1-4. Cross-coupling-active Aryl(triorgano)silanes and their Activators

As described above, HOMSi reagents are one of the silicon-based cutting-edge reagents for the cross-coupling in view of a wide substrate scope as well as stability and easy-handling (Scheme 1-3). There are many types of HOMSi reagents for not only arylation and alkenylation but also primary and secondary alkylation,[87] and polymerization (Figure 1-5).[88] These reagents are stable but reactive enough to participate the cross-coupling reaction upon activation by a weak base like potassium carbonate. In addition, the silicon residue, cyclic silyl ether **1**, is recyclable to the starting R–HOMSi by treatment with R–Li or R–MgX reagents or by a sequential hydride reduction/protection followed by a hydrosilylation of alkynes.[76]



Scheme 1-3. Typical Preparative Methods for HOMSi Reagents

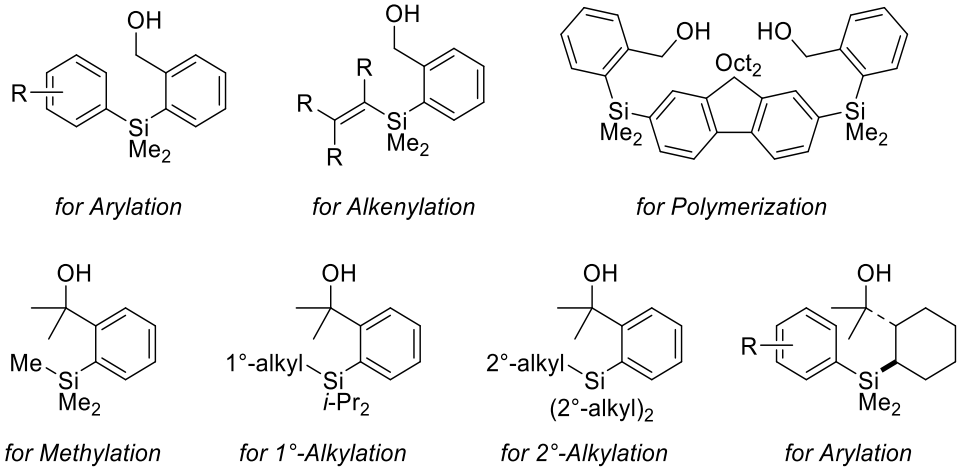
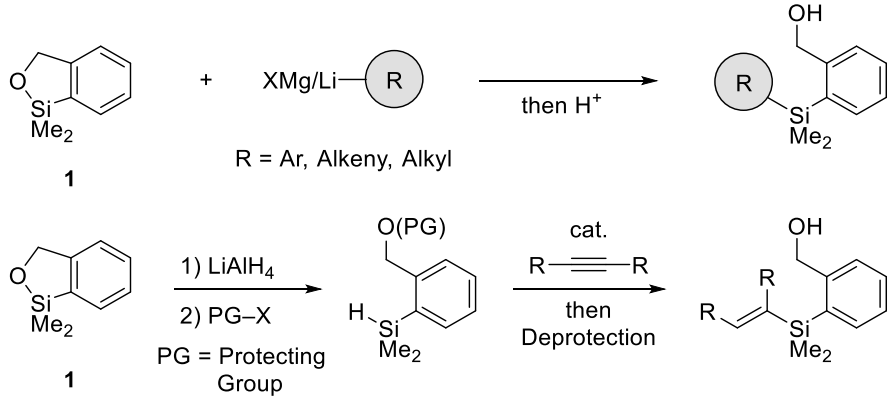


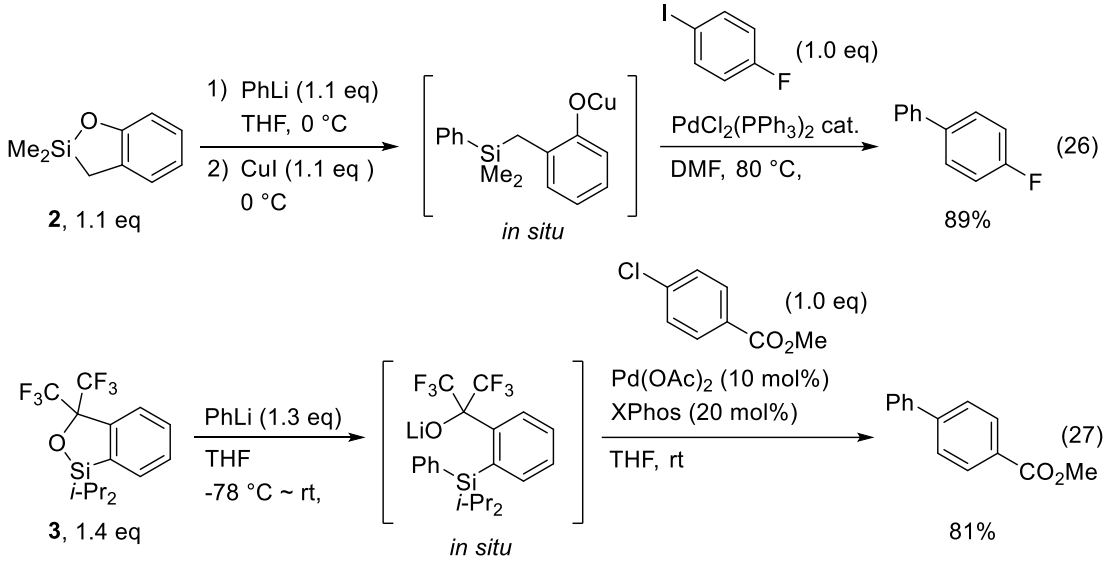
Figure 1-5. A Variety of HOMSi Reagents



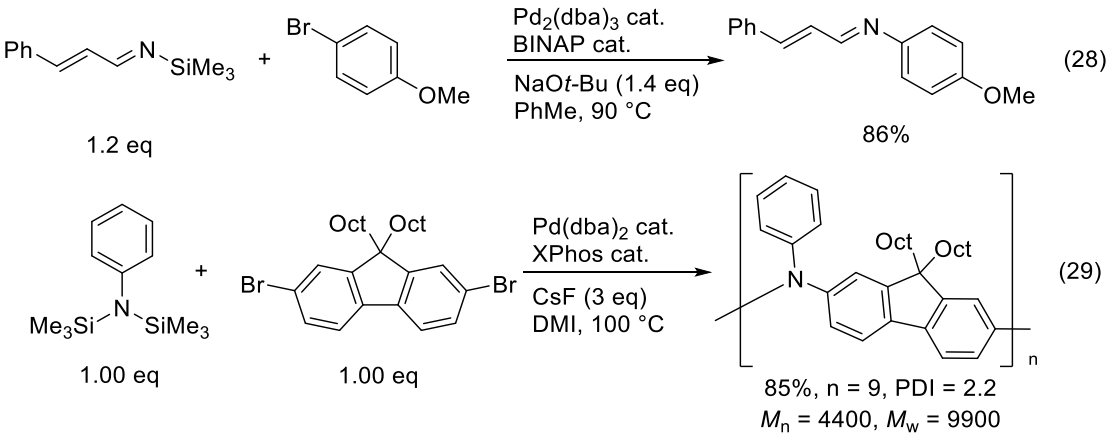
Scheme 1-4. Conventional Preparative Methods for HOMSi Reagents

Intramolecular activation strategy was also studied independently by Tamao, who found tri(organo)silyl-type reagents in situ generated from silyl ether **2** along with aryllithium and copper iodide coupled with iodoarenes in the presence of a palladium catalyst (Eq. 26).[89] Cyclic silyl ethers were similarly employed by Smith III as a surrogate for reactive silicon reagents.[90] For example, **3** undergoes the Pd-catalyzed cross-coupling

of phenyllithium with an aryl chloride smoothly to give a biaryl in a good yield (Eq. 27).[90f]



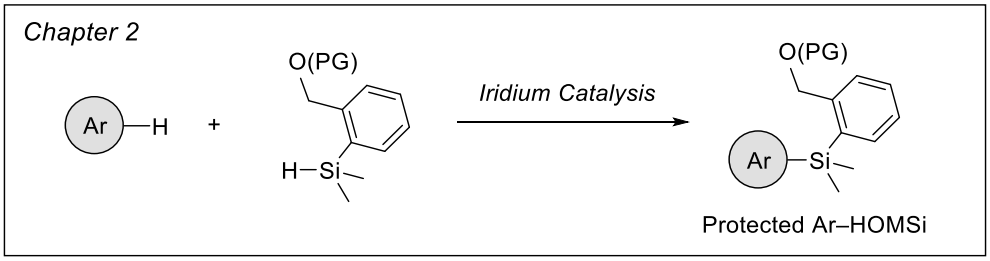
Miscellaneous types of cross-coupling are possible using tri(alkyl)silyl-type reagents. Silicon reagents $Me_3Si–NR_2$,[91] $Me_2(t\text{-}Bu)Si–OR$,[92] $Me_3Si–SiMe_3$,[22] $Me_3Si–SAr$,[93] $R_3Si–CF_3$,[94] $Me_3Si–CH_2NR_2$,[95] $Me_3Si–C(=O)R$,[96] and $Me_3Si–CF_2C(=O)NR_2$[97] have enough reactivity for the carbon–carbon or carbon–heteroatom bond forming reaction in the presence of a fluoride or other base. For example, *N*-$SiMe_3$-imines couple with aryl bromides under the Pd catalysis (Eq. 28). In addition, *N*,*N*-bis($SiMe_3$)aniline undergoes the Pd-catalyzed cross-coupling polymerization to give polyarylamines, an important class of materials in organic electronics (Eq. 29).



1-4. Outline of the Dissertation

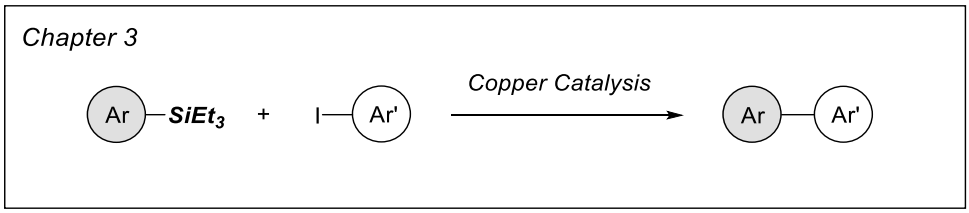
Tri(organo)silyl-type reagents are promising reagents in view of easy-handling and ready accessibility coupled with high stability, solubility, and non-toxicity as discussed above. However, most of cross-coupling-active tetraorganosilanes disclosed so far lack practicality because of sophisticatedly functionalized silicon reagents which need multiple-step and/or tedious procedures for preparation. Accordingly silicon-based cross-coupling reaction was expected to become a more popular tool for organic synthesis, if the following features are endowed: (1) straightforward synthesis of reactive silicon reagents, (2) reactions which allow to use readily accessible trialkylsilyl-type reagents and common catalysts. Thus, the author has studied the cross-coupling reaction focusing on tri(organo)silyl-, *inter alia*, trialkylsilyl-type reagents to provide a definitive cross-coupling reaction. Results on his studies are described in the dissertation which consists of six chapters including this one.

In Chapter 2, a rapid synthesis of Ar–HOMSi is described. The synthesis was done via aryl C–H silylation using an iridium catalyst. Previously Ar–HOMSis were prepared starting with the corresponding organic halides. The present method allows us to obtain the reagents from aromatic hydrocarbons directly. Various heteroaryl- and alkenyl-HOMSi accessible by the procedure. This Chapter will be closed by rapid construction of an oligoarylene-bisHOMSi to give an organic solar cell material through sequential C–H silylation/cross-coupling sequence.



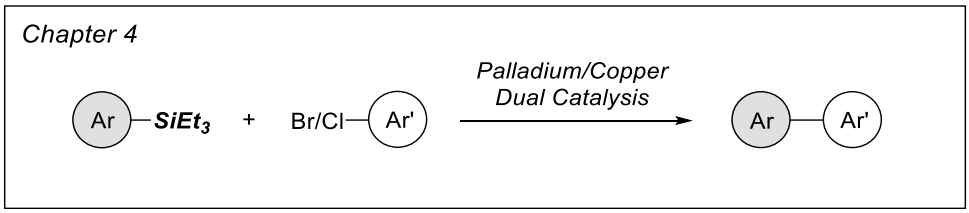
Scheme 1-5. Rapid Synthesis of HOMSi Reagents via Ir-catalyzed C–H Silylation

In Chapter 3, the first cross-coupling reaction using aryl(triethyl)silanes will be discussed. Although recent advances in aromatic dehydrogenative silylation led to an easy access to aryl(triethyl)silanes, the cross-coupling of the resulting silanes remained to be developed. The author found the desired reaction of aryl(triethyl)silanes with iodoarenes occurred in the presence of a catalytic amount of cupric bromide and applied the present reaction to polyarylene synthesis.



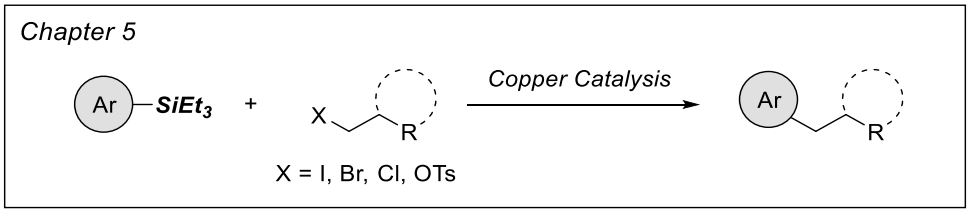
Scheme 1-6. The First Cross-coupling of Aryl(triethyl)silanes Enabled by Copper Catalysis

In Chapter 4, palladium(0)/copper(I) dual catalytic system will be shown effective for the cross-coupling of aryl(triethyl)silanes with aryl bromides and chlorides. As aryl iodides are expensive, sometimes hard to prepare, and need harsh conditions, the present catalyst system is effective against such problems and allow us to use more general electrophilic coupling partner, aryl bromides and chlorides, under milder conditions.



Scheme 1-7. Palladium/Copper Catalysis for Cross-coupling of Aryl(triethyl)silanes with Aryl Bromides or Chlorides

In Chapter 5, aryl–alkyl bond-forming coupling between aryl(triethyl)silanes and alkyl halides will be discussed. Because the silicon-based cross-coupling reaction with alkyl halides as electrophilic partner remained unexplored, the author extended the scope of electrophiles in the cross-coupling of aryl(triethyl)silanes to alkyl halides and found that a combination of copper(I) iodide and phenanthroline is a solution for the reaction.



Scheme 1-8. Copper-catalyzed Aryl–Alkyl Coupling of Aryl(triethyl)silanes with Alkyl Halides

In the final Chapter, the author concludes the dissertation with comments about future perspective of silicon-based cross-coupling chemistry.

1-5. References and Notes

1. (a) *Metal-Catalyzed Cross-Coupling Reactions*, Diederich, F., Stang, P. J., Eds.; Wiley-VCH, Weinheim, 1998. (b) Metal-Catalyzed Cross-Coupling Reactions, 2nd ed., Meijere, A. d.; Diederich, F., Eds.; Wiley-VCH, Weinheim, 2004. (c) *Metal-Catalyzed Cross-Coupling Reactions and More*, Meijere, A. d., Bräse, S., Oestreich M., Eds.; Wiley-VCH, Weinheim, 2014.
2. Tamura, M.; Kochi, J. K. *J. Am. Chem. Soc.* **1971**, *93*, 1487.
3. Tamao, K.; Sumitani, K.; Kumada, M. *J. Am. Chem. Soc*. **1972**, *94*, 4374.
4. Corriu, R. J. P.; Massse, J. P. *J. Chem. Soc., Chem. Commun*. **1972**, 144.
5. Yamamura, M.; Moritani, I.; Murahashi, S.-I. *J. Organomet. Chem*. **1975**, *91*, C39.
6. (a) King, A. O.; Okukado, N.; Negishi, E. *J. Chem. Soc. Chem. Commun*. **1977**, 683. (b) Negishi, E; King, A. O.; Okukado, N. *J. Org. Chem.* **1977**, *42*, 1821.
7. Kosugi, M.; Sasazawa, K.; Shimizu, Y.; Migita, T. *Chem. Lett.* **1977**, *6*, 301.
8. Milstein, D.; Stille, J. K. *J. Am. Chem. Soc*. **1978**, *100*, 3636.
9. Miyaura, N.; Yamada, K.; Suzuki, A. *Tetrahedron* L*ett*. **1979**, *20*, 3437.
10. Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 918.
11. Kochel reported that *i*-PrMgCl/LiCl complex (Turbo Grignard reagent) underwent magnesium–halogen exchange with aryl halides without damaging electrophilic functionality, which gives functionalized aryl Grignard reagents. (a) Krasovskiy, A.; Knochel, P. *Angew. Chem. Int. Ed*. **2004**, *43*, 3333. (b) R. L.-Y. Bao, R. Zhao, L. Shi, *Chem. Commun.* **2015**, *51*, 6884. However, to the best of his knowledge, there is solo example of synthesis of functionalized arylsilanes utilizing Turbo Grignard reagent. See: (c) Wang, M.; Gan, D.; Wooley, K. L. *Macromolecules* **2001**, *34*, 3215.
12. *Hydrosilylation: A Comprehensive Review on Recent Advances*, Bogdanm M., Ed.; Springer, Berlin, 2009.
13. (a) Bartik, T.; Nagy, G.; Kvintovics, P.; Happ, B. *J. Organomet. Chem.* **1993**, *453*, 29. (b) Tillack, A.; Pulst, S.; Baumann, W.; Baudisch, H.; Kortus, K.; Rosenthal, U. *J. Organomet. Chem.* **1997**, *532*, 117. (c) Isobe, M.; Nishizawa, R.; Nishikawa, T.; Yoza, K. *Tetrahedron Lett.* **1999**, *40*, 6927. (d) Bart, S. C.; Lobkovsky, E.; Chirik, P. J. *J. Am. Chem. Soc*. **2004**, *126*, 13794. (e) Yong, L.; Kirleis, K.; Butenschön, H. *Adv. Synth. Catal.* **2006**, *348*, 833. (f) Belger, C.; Plietker, B. *Chem. Commun.* **2012**, *48*, 5419. (g) Konno, T.; Taku, K.; Yamada, S.; Moriyasu, K.; Ishihara, T. *Org. Biomol. Chem.* **2009**, *7*, 1167.(h) Zhenbo Mo, Jie Xiao, Yafei Gao, and Liang Deng *J. Am. Chem. Soc.* **2014**, *136*, 17414. (i) Huang, K.-H.; Isobe, M. Eur. *J. Org. Chem.* **2014**, 4733.

14. Trost, B. M.; Ball, Z. T.; Jöge, T. *J. Am. Chem. Soc*. **2002**, *124*, 7922 (b) Trost, B. M.; Ball, Z. T. *J. Am. Chem. Soc*. **2003**, *125*, 30 (c) Trost, B. M.; Ball, Z. T. *J. Am. Chem. Soc*. **2005**, *127*, 17644.
15. Trost, B. M.; Ball, Z. T. *J. Am. Chem. Soc.* **2001**, *123*, 12726.
16. For a sumary, see: Marciniec, B. *Coord. Chem. Rev.* **2005**, *249*, 2374.
17. (a) Yamashita, H.; Kobayashi, T.; Hayashi, T.; Tanaka, M. *Chem. Lett.* **1991**, *20*, 761. (b) McAtee, J. R.; Martin, S. E. S.; Ahneman, D. T.; Johnson, K. A.; Watson, D. A. *Angew. Chem., Int. Ed.* **2012**, *51*, 3663. (c) Martin, S. E. S.; Watson, D. A. *J. Am. Chem. Soc*. **2013**, *135*, 13330. (d) McAtee, J. R.; Yap, . P. A.; Watson, D. A. *J. Am. Chem. Soc*. **2014**, *136*, 10166. (e) McAtee, J. R.; Krause, S. B.; Watson, D. A. *Adv. Synth. Catal.* **2015**, *357*, 2317.
18. For selected examples, see: (a) Ansell, B. M.; Navarro, C.; Spencer, J. *Coord. Chem. Rev.* **2017**, *336*, 54. (b) Fopp, C.; Romain, E.; Isaac, K.; Chemla, F.; Ferreira, F.; Jackowski, O.; Oestreich, M.; Perez-Luna, A. *Org. Lett.* **2016**, *18*, 2054. (c) Shintani, R.; Kurata, H.; Nozaki, K. *J. Org. Chem*. **2016**, *81*, 3065. Ohmura T.; Suginome, M. *Bull. Chem. Soc. Jpn*. 2009. *82*, 29. (d) Fleming, I.; Roessler, F. *J.C.S. Chem. Comm.* **1980**, 276.
19. For a review, see: (a) Marciniec, B. *Acc. Chem. Res.* **2007**, *40*, 943. For examples using ruthenium catalysts, see: (c) Marciniec, B.; Pietraszuk, C.; Foltynowicz, Z. *J. Mol. Catal*. **1992**, *76*, 307. (d) Yi, C. S.; He, Z.; Lee, D. W.; Rheingold, A. L.; Lam, K.-C. *Organometallics* **2000**, *19*, 2036. (e) Itami, Y.; Marciniec, B.; Majchrzak, M.; Kubicki, M. *Organometallics* **2003**, *22*, 1835. (f) Pawluc, P.; Szudkowska, J.; Hreczycho, G.; Marciniec, B. *J. Org. Chem.* 2011, *76*, 6438. (g) Szudkowska-Frątczak, J.; Marciniec, B.; Hreczycho, G.; Kubicki, M.; Pawluc, P. *Org. Lett.* **2015**, 17, 2366. For examples using rhodium catalysts, see: (h) Marciniec, B.; Walczuk-Gusciora, E.; Pietraszuk, C. *Organometallics* **2001**, *20*, 3423. (i) Marciniec, B.; Kownacki, I.; Franczyk, A.; Kubicki, M. *Dalton Trans.* **2011**, *40*, 5073.
20. For recent examples, see: (a) Iranpoor, N.; Firouzabadi, H.; Azadi, R. *J. Organomet. Chem.* **2010**, *695*, 887. (b) Lesbani, A.; Kondo, H.; Sato, J.; Yamanoi, Y.; Nishihara, H. *Chem. Commun*. **2010**, *46*, 7784. (c) Lesbani, A.; Kondo, H.; Yabusaki, Y.; Nakai, M.; Yamanoi, Y.; Nishihara, H. *Chem. Eur. J.* **2010**, *16*, 13519. (d) Huang, C.; Chernyak, N.; Dudnik, A. S.; Gevorgyan, V. *Adv. Synth. Catal*. **2011**, *353*, 1285. (e) Kurihara, Y.; Nishikawa, M.; Yamanoi, Y.; Nishihara, H. *Chem. Commun.* **2012**, *48*, 11564. (f) Inubushi, H.; Kondo, H.; Lesbani, A.; Miyachi, M.; Yamanoi, Y.; Nishihara, H. *Chem. Commun.* **2013**, *49*, 134.
21. For recent examples, see: (a) Gooßen, L. J.; Ferwanah, A.-R. S. *Synlett* **2000**, 1801.

(b) Shirakawa, E.; Kurahashi, T.; Yoshida, H.; Hiyama, T. *Chem. Commun.* **2000**, 1895. (c) Denmark, S. E.; Kallemeyn, J. M. *Org. Lett.* **2003**, *5*, 3483. (d) Iwasawa, T.; Komano, T.; Tajima, A.; Tokunaga, M.; Obora, Y.; Fujihara, T.; Tsuji, Y. *Organometallics* **2006**, *25*, 4665. (e) Kashiwabara, T.; Tanaka, M. *Organometallics* **2006**, *25*, 4648. (f) McNeill, E.; Barder, T. E.; Buchwald, S. L. *Org. Lett.* **2007**, *9*, 3785. (g) Yamamoto, Y.; Matsubara, H.; Murakami, K.; Yorimitsu, H.; Osuka, A. *Chem. Asian J.* **2015**, *10*, 219

22. Zarate, C.; Nakajima, M.; Martin, R. *J. Am. Chem. Soc*. **2017**, *139*, 1191.
23. Zarate, C.; Martin, R. *J. Am. Chem. Soc*. **2014**, *136*, 2236.
24. (a) Guo, L.; Chatupheeraphat, A.; Rueping, M. *Angew. Chem. Int. Ed*. **2016**, *55*, 11810. (b) Pu, X.; Hu, J.; Zhao, Y.; Shi, Z. *ACS Catal.* **2016**, *6*, 6692.
25. Leea, S.-C.; Guoa, L.; Yuea, H.; Liaoa, H.-H.; Rueping, M. *Synlett* **2017**, *28*, 2594.
26. For recent reviews, see: (a) Cheng, C.; Hartwig, J. F. *Chem. Rev*. **2015**, *115*, 8946. (b) Bähr, S.; Oestreich, M. *Angew. Chem. Int. Ed*. **2017**, *56*, 52. For selected examples of transition-metal-catalyzed intermolecular dehydrogenative silylation of arenes without directing groups, see: (a) Tsukada, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 5022. (b) Murata, M.; Fukuyama, N.; Wada, J.; Watanabe, S.; Masuda, Y. *Chem. Lett.* **2007**, *36*, 910. (c) Lu, B.; Falck, J. R. *Angew. Chem. Int. Ed.* **2008**, *47*, 7508. (d) Ishiyama, T.; Saiki, T.; Kishida, E.; Sasaki, I.; Ito, H.; Miyaura, N. *Org. Biomol. Chem*. **2013**, *11*, 8162. (e) Klare, H. F. T.; Oestreich, M.; Ito, J.-i.; Nishiyama, H.; Ohki, Y.; Tatsumi, K. *J. Am. Chem. Soc*. **2011**, *133*, 3312. (f) Cheng, C.; Hartwig, J. F. Science **2014**, 343, 853. (g) Cheng, C.; Hartwig, J. F. *J. Am. Chem. Soc*. **2015**, *137*, 592. (h) Murai, M.; Takami, K.; Takeshima, H.; Takai, K. *Org. Lett.* **2015**, *17*, 1798. (i) Murai, M.; Takami, K.; Takai, K. *Chem. Eur. J.* **2015**, *21*, 4566. (j) Yin, Q.; Klare, H. F. T.; Oestreich, M. *Angew. Chem. Int. Ed.* **2016**, *55*, 3204. (k) Lee, K.-S.; Katsoulis, D.; Choi, J. *ACS Catal.* **2016**, *6*, 1493. (l) Fang, H.; Guo, L.; Zhang, Y.; Yao, W.; Huang, Z. *Org. Lett*. **2016**, *18*, 5624.
27. (a) Toutov, A. A.; Liu, W.-B.; Betz, K. N.; Fedorov, A.; Stoltz, B. M.; Grubbs, R. H. *Nature* **2015**, *518*, 80. Liu, W.-B.; Schuman, D. P.; Yang, Y.-F.; Toutov, A. A.; Liang, Y.; Klare, H. F. T.; Nesnas, N.; Oestreich, M.; Blackmond, D. G.; Virgil, S. C.; Banerjee, S.; Zare, R. N.; Grubbs, R. H.; Houk, K. N.; Stoltz, B. M. *J. Am. Chem. Soc*. **2017**, *139*, 6867. (c) Banerjee, S.; Yang, Y.-F.; Jenkins, I. D.; Liang, Y.; Toutov, A. A.; Liu, W.-B.; Schuman, D. P.; Grubbs, R. H.; Stoltz, B. M.; Krenske, E. H.; Houk, K. N.; Zare, R. N. *J. Am. Chem. Soc.* **2017**, *139*, 6880.
28. Ma, Y.; Wang, B.; Zhang, L.; Hou, Z. *J. Am. Chem. Soc*. **2016**, *138*, 3663.
29. Chen, Q.-A.; Klare, H. F. T.; Oestreich, M. *J. Am. Chem. Soc.* **2016**, *138*, 7868.

30. For recent reviews, see: (a) Obligacion, J. V.; Chirik, P. J. *Nat. Rev. Chem*. **2018**, *2*, 15. (b) Du, X.; Huang, Z. *ACS Catal.*, **2017**, *7*, 1227 (c) Nakajima, Y.; Shimada, S. *RSC Adv*. **2015**, *5*, 20603.
31. For a review, see: Gibson, S. E.; Rudd, M. *Adv. Synth. Catal.* **2007**, *349*, 781.
32. (a) Simmons, E. M.; Hartwig, J. F. *J. Am. Chem. Soc*. **2010**, *132*, 17092. (b) Simmons, E. M.; Hartwig, J. F. *Nature* **2012**, *483*, 70. (c) Li, B.; Driess, M.; Hartwig, J. F. *J. Am. Chem. Soc*. **2014**, *136*, 6586. (d) Ghavtadze, N.; Melkonyan, F. S.; Gulevich, A. V.; Huang, C.; Gevorgyan, V. *Nat. Chem.* **2014**, *6*, 122. (e) Lee, T.; Wilson, T. W.; Berg, R.; Ryberg, P.; Hartwig, J. F. *J. Am. Chem. Soc*. **2015**, *137*, 6742. (f) Lee, T.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2016**, *55*, 8723. (g) Su, B.; Zhou, T. G.; Li, X. W.; Shao, X. R.; Xu, P. L.; Wu, W. L.; Hartwig, J. F.; Shi, Z. J. *Angew. Chem., Int. Ed*. **2017**, *56*, 1092. (h) Bunescu, A.; Butcher, T. W.; Hartwig, J. F. *J. Am. Chem. Soc*. **2018**, *140*, 1502. (i) Karmel, C.; Li, B.; Hartwig, J. F. *J. Am. Chem. Soc.* **2018**, *140*, 1460.
33. Jia, X.; Huang, Z. *Nat. Chem*. **2016**, *8*, 157.
34. (a) Bähr, S.; Xue, W.; Oestreich, M. *ACS Catal*. **2019**, *9*, 16. (b) Chu, C. K.; Liang, Y.; Fu, G. C. *J. Am. Chem. Soc*. **2016**, *138*, 6404. (c) Xue, X.; Qu, Z.-W.; Grimme, S.; Oestreich, M. *J. Am. Chem. Soc.* **2016**, *138*, 14222
35. (a) Calas, R.; Bourgeois, P. C. R. *Acad. Sc. Paris* **1969**, *268*, 72. (b) Voronkov, M. G.; Ushakova, N. I.; Tsykhanskaya, I. I.;Pukhnarevich, V. B. *J. Organomet. Chem.* **1984**, *264*, 39. (c) Ishikawa, J.-i.; Inoue, K.; Itoh, M. *J. Organomet. Chem.* **1998**, *552*, 303. (d) Baba, T.; Kato, A.;Yuasa, H.; Toriyama, F.; Handa, H.; Ono, Y. *Catal. Today* **1998**, *44*, 271. (e) Ishikawa, J.-i.; Itoh, M. *J. Catal.* **1999**, *185*, 454. (f) Rahaim, R. J.; Shaw, J. T. *J. Org. Chem*. **2008**, *73*, 2912. (g)Yamaguchi, K.; Wang, Y.; Oishi, T.;Kuroda, Y.; Mizuno, N. *Angew. Chem., Int. Ed*. **2013**, *52*, 5627. (h) Tsuchimoto, T.; Fujii, M.; Iketani, Y.; Sekine, M. *Adv. Synth. Catal*.**2012**, *354*, 2959. (i) Kownacki, I.; Orwat, B.; Marciniec, B.; Kownacka, A. *Tetrahedron Lett.* **2014**, *55*, 548. (j) Toutov, A. A.; Betz, K. N.; Schuman, D. P.; Liu, W.-B.; Fedorov, A.; Stoltz, B. M.; Grubbs, R. H. *J. Am. Chem. Soc.* **2017**, *139*, 1668.
36. Yoshida, J.; Tamao, K.; Takahashi, M.; Kumada, M. *Tetrahedron Lett.* **1978**, *19*, 2161. (b) Yoshida, J.; Tamao, K.; Yamamoto, H.; Kakui, T.; Uchida, T.; Kumada, M. *Organometallics* **1982**, *1*, 542.
37. Hatanaka, Y.; Hiyama, T. *J. Org. Chem*. **1988**, *53*, 918.
38. (a) Hatanaka, Y.; Hiyama, T. *Synlett* **1991**, 845. (b) Hiyama, T. *J. Organomet. Chem.* **2002**, *653*, 58.
39. (a) Sugiyama, A.; Ohnishi, Y.; Nakaoka, M.; Nakao, Y.; Sato, H.; Sakaki, S.; Nakao,

Y.; Hiyama, T. *J. Am. Chem. Soc.* **2008**, *130*, 12975. (b) Amatore, C.; Grimaud, L.; Le Duc, G.; Jutand, A. *Angew. Chem. Int. Ed*. **2014**, *53*, 6982.

40. For recent reviews, see: (a) Nakao, Y.; Hiyama, T. *Chem. Soc. Rev*. **2011**, *40*, 4893. (b) Sore, H. F.; Galloway, W. R. J. D.; Spring, D. R. *Chem. Soc. Rev.* **2012**, *41*, 1845. (c) Denmark, S. E.; Ambrosi, A. *Org. Process Res. Dev*. **2015**, *19*, 982. (d) Foubelo, F.; Nájera, C.; Yus, M.; *Chem. Rec.* **2016**, *16*, 2521. (e) Komiyama, T.; Minami, Y.; Hiyama, T. *ACS Catal.* **2017**, *7*, 631.
41. For pioneer works, see: (a) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1989**, *54*, 268. (b) Hatanaka, Y.; Fukushima, S.; Hiyama, T. *Chem. Lett.* **1989**, *18*, 1711.
42. For pioneer works, see: (a) Hatanaka, Y.; Gouda, K.-i.; Okahara, Y.; Hiyama, T. *Tetrahedron*, **1994**, *50*, 8301. (b) Hagiwara, E.; Gouda, K.-i.; Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett*. **1997**, *38*, 439.
43. For pioneer works, see: (a) Tamao, K.; Kobayashi, K.; Ito, Y. *Tetrahedron Lett.* **1989**, *30*, 6051. (b) Shibata, K.; Miyazawa, K.; Goto, Y. *Chem. Commun.* **1997**, 1309. (c) Mowery, M. E.; DeShong, P. *J. Org. Chem*. **1999**, *64*, 1684.
44. (a) Gouda, K.-i.; Hagiwara, E.; Hatanaka, Y.; Hiyama, T. *J. Org. Chem*. **1996**, *61*, 7232. (b) Mowery, M. E.; DeShong, P. *Org. Lett.* **1999**, *1*, 2137. (c) Molander, G. A.; lannazzo, L. *J. Org. Chem.* **2011**, *76*, 9182.
45. Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett*. **1990**, *31*, 2719.
46. Zhang, L.; Qing, J.; Yang, P.; Wu, J. *Org. Lett.* **2008**, *10*, 4971.
47. Zhang, L.; Wu, J. *J. Am. Chem. Soc*. **2008**, *130*, 12250.
48. (a) T. Mino, E. Yoshizawa, K. Watanabe, T. Abe, K. Hirai, M. Sakamoto, *Tetrahedron Lett*. **2014**, *55*, 3184. (b) Katayev, D.; Exner, B.; Gooßen, L. J. *ChemCatChem* **2015**, *7*, 2028.
49. Shi, W. J.; Zhao, H. W.; Wang, Y.; Cao, Z. C.; Zhang, L. S.; Yu, D. G.; Shi, Z. J. *Adv. Synth. Catal.* **2016**, *358*, 2410.
50. For a recent brief summary on C–H activation chemistry, see: Crabtree, R. H.; Lei, A. *Chem. Rev*. **2017**, *117*, 8481. For selected examples on C–H activation using organosilicon reagents, see: (b) Yang, S.; Li, B.; Wan, X.; Shi, Z. *J. Am. Chem. Soc*. **2007**, *129*, 6066. (c) Zhou, H.; Xu, Y.-H.; Chung, W.-J.; Loh, T.-P. *Angew. Chem. Int. Ed*. **2009**, *48*, 5355. (d)He, J.; Takise, R.; Fu, H.; Yu, J.-Q. *J Am. Chem. Soc*. **2015**, *137*, 4618. (e) Liang, Z.; Yao, B.; Zhang, Y. *Org. Lett.* **2010**, *12*, 3185. (f) Bi, L.; Georg, G. I. *Org. Lett.* **2011**, *13*, 5413.
51. Hirabayashi, K.; Kawashima, J.; Nishihara, Y.; Mori, A.; Hiyama, T. *Org. Lett*. **1999**, *1*, 299.
52. (a) Denmark, S. E.; Wehrli, D. *Org. Lett.* **2000**, *2*, 565. (b) Denmark, S. E.; Sweis,

R. F. *J. Am. Chem. Soc*. **2001**, *123*, 6439.

53. Denmark, S. E.; Smith, R. C.; Chang, W.-T. T.; Muhuhi, J. M. *J. Am. Chem. Soc.* **2009**, *131*, 3104.
54. (a) Tymonko, S. A.; Smith, R. C.; Ambrosi, A.; Denmark, S. E. *J. Am. Chem. Soc*. 2015, *137*, 6192. (b) Tymonko, S. A.; Smith, R. C.; Ambrosi, A.; Ober, M. H.; Wang, H.; Denmark, S. E. *J. Am. Chem. Soc.* 2015, *137*, 6200.
55. Saijo, H.; Sakaguchi, H.; Ohashi, M.; Ogoshi, S. *Organometallics* **2014**, *33*, 3669.
56. (a) Matsuhashi, H.; Hatanaka, Y.; Kuroboshi, M.; Hiyama, T. *Tetrahedron Lett.* **1995**, *36*, 1539. (b) Matsuhashi, H.; Asai, S.; Hirabayashi, K.; Hatanaka, Y.; Mori, A.; Hiyama, T. *Bull. Chem. Soc. Jpn*. **1997**, *70*, 1943.
57. Ishiyama, T.; Sato, K.; Nishio, Y.; Miyaura N. *Angew. Chem. Int. Ed.* **2003**, *42*, 5346.
58. (a) Matsuhashi, H.; Kuroboshi, M.; Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* **1994**, *35*, 6507. (b) Matsuhashi, H.; Asai, S.; Hirabayashi, K.; Hatanaka, Y.; Mori, A.; Hiyama, T. *Bull. Chem. Soc. Jpn*. **1997**, *70*, 437.
59. Lee, J.-Y.; Fu, G. C. *J. Am. Chem. Soc*. **2003**, *125*, 5616.
60. (a) Powell, D. A.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 7788. b) N. A. Strotman, S. Sommer, G. C. Fu, *Angew. Chem., Int. Ed.* **2007**, *46*, 3556. c) Dai, X.; Strotman, N. A.; Fu, G. C *J. Am. Chem. Soc.* **2008**, *130*, 3302. d) Y. Wu, H.-R. Zhang, Y.-X. Cao, Q. Lan, X.-S. Wang, *Org. Lett*. **2016**, *18*, 5564. (e) C. Lévêque, V. Corcé, L. Chenneberg, C. Ollivier, L. Fensterbank, Eur. *J. Org. Chem.* **2017**, 2118.
61. Corce, V.; Chamoreau, L.-M.; Derat, E.; Goddard, J.-P.; Ollivier, C.; Fensterbank, L. *Angew. Chem., Int. Ed.* **2015**, *54*, 11414.
62. (a) Jouffroy, M.; Primer, D. N.; Molander, G. A. *J. Am. Chem. Soc*. **2016**, *138*, 475. (b) Patel, N. R.; Kelly, C. B.; Jouffroy, M.; Molander, G. A. *Org. Lett*. **2016**, *18*, 764.
63. (a) Lloyd-Jones, G. C.; Ball, L. T. *Science* **2014**, *345*, 381. (b) Gutierrez, O.; Tellis, J. C.; Primer, D. N.; Molander, G. A.; Kozlowski, M. C. *J. Am. Chem. Soc*. **2015**, *137*, 4896.
64. (a) Gurung, S. K.; Thapa, S.; Shrestha, B.; Giri, R. *Synthesis* 2014, *46*, 1933. (b) M. Suginome, H. Kinugasa, Y. Ito, *Tetrahedron Lett*. **1994**, *35*, 8635. (c) H. Ito, H. Sensui, K. Arimoto, K. Miura, A. Hosomi, *Chem. Lett*. **1997**, *639*. (d) S. K. Gurung, S. Thapa, A. S. Vangala, R. Giri, *Org. Lett.* **2013**, *15*, 5378. (e) L. Cornelissen, S. Vercruysse, A. Sanhadji, O. Riant, *Eur. J. Org. Chem*. **2014**, 35. (f) L. Cornelissen, V. Cirriez, S. Vercruysse, O. Riant, *Chem. Commun*. **2014**, *50*, 8018. (g) L. Cornelissen, M. Lefrancq, O. Riant, *Org. Lett.* **2014**, *16*, 3024. (h) L. Cornelissen, A. Nagy, T. Leyssens, O. Riant, *Synlett* **2017**, *28*, 2465.
65. For the author's summary, see: Komiyama, T.; Minami, Y.; Hiyama, T. *Synlett* **2017**,

28, 1873.

66. Omote, M.; Tanaka, M.; Ikeda, A.; Nomura, S.; Tarui, A.; Sato, K.; Ando, A. *Org. Lett*. **2012**, *14*, 2286.
67. (a) Denmark, S. E.; Choi, Y. *J. Am. Chem. Soc*. **1999**, *121*, 5821. (b) Denmark, S. E.; Wehrli, D.; Choi, Y. *Org. Lett*. **2000**, *2*, 2491.
68. (a) Itami, K.; Nokami, T.; Ishimura, Y.; Mitsudo, K.; Kamei, T.; Yoshida, J. *J. Am. Chem. Soc*. **2001**, *123*, 11577. (b) Itami, K.; Kamei, T.; Yoshida, J. *J. Am. Chem. Soc.* **2003**, *125*, 14670.
69. Hosoi, K.; Nozaki, K.; Hiyama, T. *Chem. Lett.* **2002**, *31*, 138.
70. Trost, B. M.; Machacek, M. R.; Ball, Z. T. *Org. Lett.* **2003**, *5*, 1895.
71. Katayama, H.; Nagao, M.; Moriguchi, R.; Ozawa, F. *J. Organomet. Chem.* **2003**, *676*, 49.
72. Hanamoto, T.; Kobayashi, T. *J. Org. Chem*. **2003**, *68*, 6354.
73. Anderson, J. C.; Munday, R. H. *J. Org. Chem.* **2004**, *69*, 8971. (b) Anderson, J. C.; Anguille, S.; Bailey, R. *Chem. Commun*. **2002**, *18*, 2018.
74. Li, L.; Navasero, N. *Org. Lett.* **2006**, *8*, 3733.
75. Sore, H. F.; Blackwell, D. T.; MacDonald, S. J. F.; Spring, D. R. *Org. Lett*. **2010**, *12*, 2806.
76. Shindo, M.; Matsumoto, K.; Shishido, K. *Synlett* **2005**, *16*, 176.
77. (a) Nakao, Y.; Imanaka, H.; Sahoo, A. K.; Yada, A.; Hiyama, T. *J. Am. Chem. Soc.* **2005**, *127*, 6952. (b) Nakao, Y.; Sahoo, A. K.; Yada, A.; Chen, J.; Hiyama, T. *Sci. Technol. Adv. Mater.* **2006**, *7*, 536. (c) Nakao, Y.; Imanaka, H.; Chen, J.; Yada, A.; Hiyama, T. *J. Organomet. Chem*. **2007**, *692*, 585. (d) Nakao, Y.; Ebata, S.; Chen, J.; Imanaka, H.; Hiyama, T. *Chem. Lett.* **2007**, *36*, 606. (e) Nakao, Y.; Chen, J.; Tanada, M.; Hiyama, T. *J. Am. Chem. Soc.* **2007**, *129*, 11694. (f) Chen, J.; Tanaka, M.; Sahoo, A. K.; Takeda, M.; Yada, A.; Nakao, Y.; Hiyama, T. *Bull. Chem. Soc. Jpn.* **2010**, *83*, 554.
78. (a) Nakao, Y.; Oda, T.; Sahoo, A. K.; Hiyama, T. *J. Organomet. Chem.* **2003**, 687, 570. (b) Sahoo, A. K.; Nakao, Y.; Hiyama, T. *Chem. Lett*. **2004**, *33*, 632. (c) Hiyama, T.; Sahoo, A. K.; Oda, T.; Nakao, Y. *Adv. Synth. Catal*. **2004**, *346*, 1715.
79. (a) Tang, S.; Takeda, M.; Nakao, Y.; Hiyama, T. *Chem. Commun*. **2011**, *47*, 307. (b) Ohgi, A.; Semba, K.; Hiyama, T.; Nakao, Y. *Chem. Lett*. **2016**, *45*, 973.
80. (a) Pierrat, P.; Gros, P.; Fort, Y. *Org. Lett*. **2005**, *7*, 697. (b) Napier, S.; Marcuccio, S. M.; Tye, H.; Whittaker, M. *Tetrahedron Lett*. **2008**, *49*, 6314.
81. Matsuda, S.; Takahashi, M.; Monguchi, D.; Mori, A. *Synlett* **2009**, 1941.
82. Nokami, T.; Tomida, Y.; Kamei, T.; Itami, K.; Yoshida, J. *Org. Lett*. **2006**, *8*, 729.

83. Murata, M.; Ohara, H.; Oiwa, R.; Watanabe, S.; Matsuda, Y. *Synthesis* **2006**, 1771.
84. Akai, S.; Ikawa, T.; Takayanagi, S.; Morikawa, Y.; Mohri, S.; Tsubakiyama, M.; Egi, M.; Wada, Y.; Kita, Y. *Angew. Chem. Int. Ed*. **2008**, *47*, 7673.
85. Chernyak, N.; Dudnik, A. S.; Huang, C.; Gevorgyan, V. *J. Am. Chem. Soc*. **2010**, *132*, 8270.
86. Murai, M.; Takami, K.; Takeshima, H.; Takai, K. *Org. Lett.* **2015**, *17*, 1798.
87. Nakao, Y.; Takeda, M.; Matsumoto, T.; Hiyama, T. *Angew. Chem. Int. Ed.* **2010**, *49*, 4447.
88. Shimizu, K.; Minami, Y.; Nakao, Y.; Ohya, K.; Ikehira, H.; Hiyama, T. *Chem. Lett.* **2013**, *42*, 45.
89. Son, E. C.; Tsuji, H.; Saeki, T.; Tamao, K. *Bull. Chem. Soc. Jpn.* **2006**, *79*, 492.
90. (a) Smith, A. B. III.; Hoye, A. T.; Martinez-Solorio, D.; Kim, Q.-S.; Tong, R. *J. Am. Chem. Soc.* **2012**, *134*, 4533. (b) Martinez-Solorio, D.; Hoye, A. T.; Nguyen, M. H.; Smith, A. B. III Org. Lett. **2013**, 15, 2454. (c) Nguyen, M. H.; Smith, A. B. III *Org. Lett.* **2013**, *15*, 4258. (d) Nguyen, M. H.; Smith, A. B. III *Org. Lett*. 2013, *15*, 4872. (e) Nguyen, M. H.; Smith, A. B. III *Org. Lett*. **2014**, *16*, 2070. (f) Martinez-Solorio, D.; Melillo, B.; Sanchez, L.; Liang, Y.; Lam, E.; Houk, K. N.; Smith, A. B. III *J. Am. Chem. Soc.* **2016**, *138*, 1836.
91. (a) Barluenga, J.; Aznar, F.; Valadés, C. *Angew. Chem. Int. Ed*. **2004**, *43*, 343. (b) Smith, C. J.; Early, T. R.; Holmes, A. B.; Shute, R. E. *Chem. Commun.* **2004**, 1976. (c) Smith, C. J.; Tsang, M. W. S.; Holmes, A. B.; Danheiser, R. L.; Tester, J. W. *Org. Biomol. Chem*. **2005**, 3, 3767. (d) Shimizu, K.; Minami, Y.; Goto, O.; Ikehira, H.; Hiyama, T. *Chem. Lett.* **2014**, *43*, 438. (e) Minami, Y.; Komiyama, T.; Shimizu, K.; Hiyama, T.; Goto, O.; Ikehira, H. *Bull. Chem. Soc. Jpn*. **2015**, *88*, 1437. (f) Minami, Y.; Komiyama, T.; Shimizu, K.; Uno, S.-i.; Hiyama, T.; Goto, O.; Ikehira, H. *Synlett* **2017**; *28*, 2407.
92. Cui, S. L.; Jiang, Z.-Y.; Wang, Y. G. *Synlett* **2004**, 1829.
93. F.-Rodríguez, M. A.; Shen, Q.; Hartwig, J. F. *J. Am. Chem. Soc.* **2006**, *128*, 2180.
94. (a) Oishi, M.; Kondo, H.; Amii, H. *Chem. Commun.* 2009, 1909. (b) Cho, E. J.; Senecal, T. D.; Kinzel, T.; Zhang, Y.; Watson, D. A.; Buchwald, S. L. *Science* 2010, *328*, 1679.
95. Ogiwara, Y.; Maegawa, Y.; Sakino, D.; Sakai, N. *Chem. Lett.* **2016**, *45*, 790.
96. Remeur, C.; Kelly, C. B.; Patel, N. R.; Molander, G. A. *ACS Catal.*, **2017**, *7*, 6065.
97. Ge, S.; Arlow, S. I.; Mormino, M. G.; Hartwig, J. F. *J. Am. Chem. Soc.* **2014**, *136*, 14401.

Chapter 2

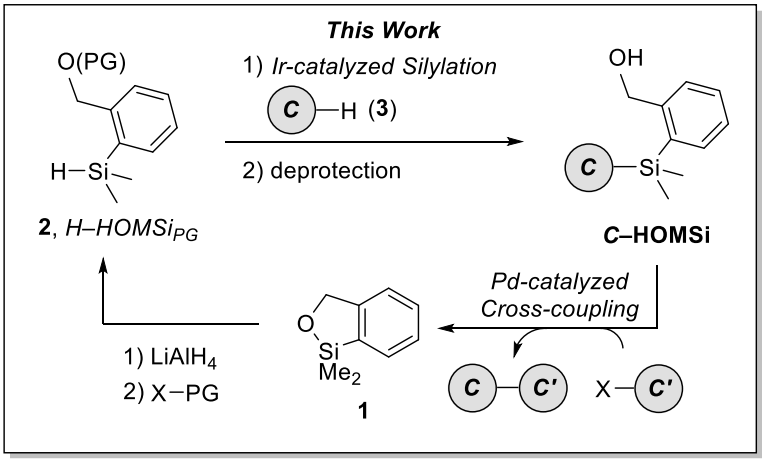
Rapid Synthesis of HOMSi Reagents via Iridium-catalyzed C–H Silylation

Iridium-catalyzed C–H silylation of heteroaromatics and terminal alkenes was found to be effective for synthesis of HOMSi reagents straightforwardly. Single and double C–H silylation of such arenes proceeds smoothly under the present conditions. The resulting single or double silicon reagents could be applied to the cross-coupling reaction to give bi- and teraryls including a monomer for materials of organic electronics.

2-1. Introduction

The silicon-based cross-coupling reaction has advantageous in view of stability, solubility, easy handling, and accessibility as described in the first chapter. In particular, R–[2-(***H***ydr***O***xy***M***ethyl)phenyl]dimethyl***Si***lanes (R–HOMSi or HOMSi reagents) are considered as state-of-the-art silicon-based coupling reagents because they are stable yet enough reactive to undergo the cross-coupling reaction upon activation even with weak base such as potassium carbonate or potassium phosphate.[1]

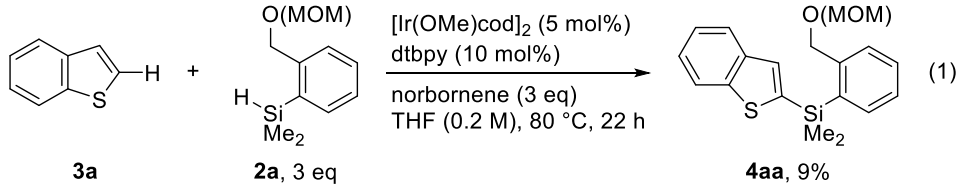
In the early days, HOMSi reagents were prepared by nucleophilic addition of organolithium or magnesium to 1-sila-2-oxaindane **1**. After that, transition-metal-catalyzed silylation of aryl halides with hydrosilanes[2] or disilanes[3] were developed to get the reagents bearing reactive functional groups. Kondo reported that Pd-catalyzed silylation of aryl iodides using HOMSi-type hydrosilanes, H–[2-(THPoxymethyl)pheny]dimethylsilanes (H–HOMSi$_{THP}$, **2$_{THP}$**) gave protected Ar–HOMSi containing Ac and CN groups.[2] Hiyama and Minami also reported Pd/Cu-catalyzed silylation of aryl bromides with protected HOMSi-type disilanes to yield Ar–HOMSi$_{PG}$ having many kinds of functional groups such as CHO, CN, and NHBoc group.[3] However, both methods require aryl halides as starting materials. On the other hand, catalytic C–H silylation of aromatic hydrocarbons is attractive in view of green chemistry.[4] Because HOMSi-type hydrosilanes, H–HOMSi$_{PG}$ **2** are accessible by hydride reduction of cyclic silyl ether **1** followed by protection of the OH group, and straightforward synthesis of Ar–HOMSi via a dehydrogenative silylation can realize HOMSi-based silicon-sustainable cross-coupling protocol (Scheme 2-1). Thus, the author decided to develop the straightforward synthesis of Ar-HOMSi.



Scheme 2-1. Silicon Cycle through HOMSi-based Cross-coupling

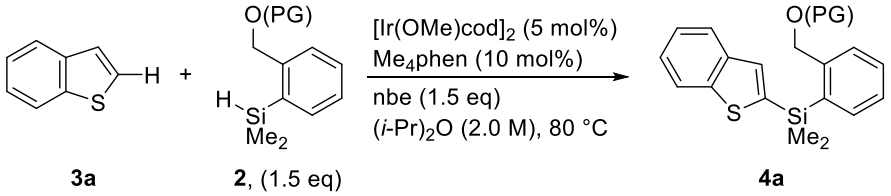
2-2. Result and Discussion

Prior studies revealed such late-transition-metal catalysts as ruthenium, platinum, rhodium, and iridium are effective for dehydrogenative C–H silylation of aromatic hydrocarbons without directing groups as of 2014.[4] The author tested an array of transition-metal catalysts based on the pioneer's works and found that the Falck's conditions showed a potential to obtain Ar–HOMSi; the reaction of benzothiophene (**3a**) with MOM-protected hydrosilanes **2a** using [Ir(OMe)cod]$_2$/4,7-di-*tert*-butyl-2,2'-bypyridyl (dtbpy) catalytic system gave desired product **4aa** albeit in < 10% yield (Eq. 1 and Table S2-1, Run 1).



Optimization of the conditions resulted in isolate MOM-protected benzothienyl-HOSMi **4aa** in 75% yield in the presence of [Ir(OMe)cod]$_2$ (5 mol%), 3,4,7,8-tetramethylphenanthroline (Me$_4$phen, 10 mol%), norbornene (nbe, 1.5 eq) in (*i*-Pr)$_2$O (2 M) at 80 °C (Table 2-1, Run 1). Replacing the MOM group by other protecting groups like THP and SEM to resist basic conditions, corresponding HOMSis **4ab** and **4ac** were produced in good to excellent yields (Runs 2 and 3). Acetyl- or pivaroyl-protected benzothienyl–HOMSis **4ad** and **4ae** were similarly yielded by the same reactions (Runs 4 and 5).

Table 2-1. Scope of the Protecting Groups[a]



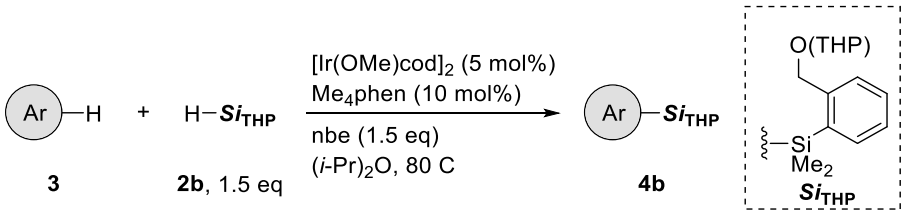
Run	PG in **2**	Time /h	Product, Yield /%[b]
1	**2a**, MOM	48	**4aa**, 75
2	**2b**, THP	3	**4ab**, 89
3	**2c**, SEM	40	**4ac**, 52
4	**2d**, Ac	11	**4ad**, 54

5	**2e**, Piv	15	**4ae,** 38

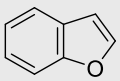
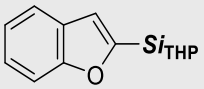
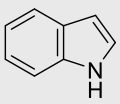
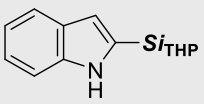
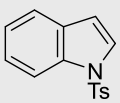
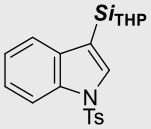
[a] Unless otherwise noted, a mixture of **3a** (1 eq), **2** (1.5 eq), $[Ir(OMe)(cod)]_2$ (5 mol%), Me_4phen (10 mol%), and norbornene (1.5 eq) in $(i\text{-Pr})_2O$ was heated at 80 °C. [b] Isolated yield.

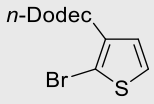
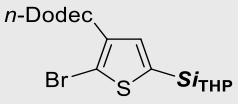
The results of the mono silylation of other heteroaromatics **3** with **2b** was summarized in Table 2-2. Benzofuran (**3b**) underwent the reaction at its C2 position to give THP-protected benzofuryl–HOMSi (**4bb**) in 93% yield (Run 1). Though the yield was moderate, non-protected indole (**3c**) was silylated similarly to afford **4cd**. When *N*-tosyl-indole (**3d**) was used, C2-silylation did not take place at all (Run 3). Instead, silylation of **3d** at the C3 position occurred to produce **4bd** in 29% yield using dtbpy and *t*-Bu-CH=CH_2 as a hydrogen acceptor.[5] These phenomena are consistent with the prior study by Falck. 2-Bromo-5-dodecylthienyl-HOMSi (**4eb**) was also produced in excellent yield (Run 4). At that time, the bromine atom on the thiophene ring did not interfere with this silylation. Unfortunately, other arenes like pyridine, benzene, 1,3-bis(trifluoromethyl)benzene, and anisole were inapplicable to the reaction.

Table 2-2. Synthesis of THP-protected Aryl-HOMSi 4b[a]



3 **2b**, 1.5 eq **4b**

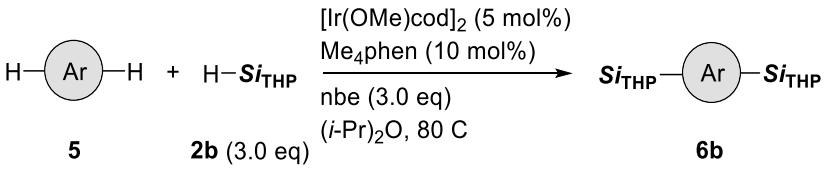
Run	Arene **3**	Time /h	Product, Yield /%[b]
1	 **3b**	9	 **4bb**, 93
2	 **3c**	3	 **4cd**, 44
3[c]	 **3d**	37	 **4db**, 29

4		5		
	3e		**4eb**, 93	

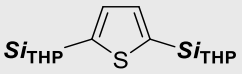
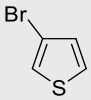
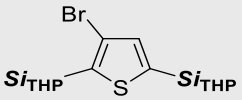
[a] Unless otherwise noted, a mixture of **3** (1 eq), **2b** (1.5 eq), $[Ir(OMe)(cod)]_2$ (5 mol%), Me_4phen (10 mol%), and norbornene (1.5 eq) in $(i\text{-Pr})_2O$ was heated at 80 °C. [b] Isolated yield. [c] Instead of Me_4phen, norbornene, and $(i\text{-Pr})_2O$, dtbpy, *t*-BuCH=CH_2 , and toluene were used.

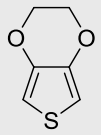
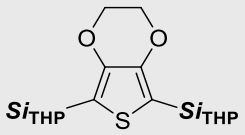
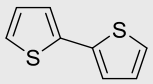
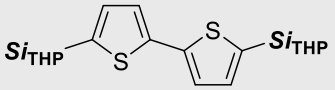
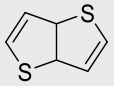
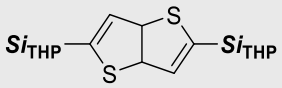
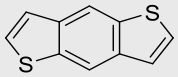
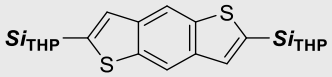
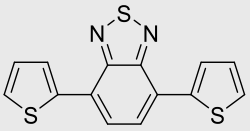
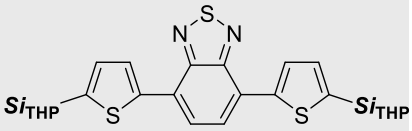
Similarly, an array of heteroaromatics **5** served as good substrates for double C–H silylation using three equivalent of **2b** (Table 2-3). The author first tested the reaction of thiophene (**5a**) and desired doubly silylated product **6ab** was formed in 47% accompanied with *o*-tolyldimethylsilylthiophene **6ab'** and **6ab"** were observed in 17% and 5%, respectively via a benzyl C–O bond cleavage (Run 1).[6,7] To improve the efficiency of the reaction, he screened ligands and H_2 acceptors and found that a combination of dtbpy and *t*-BuCH=CH_2 slightly increased the yield of **6ab** to 60% and decrease the yields of **6ab'** and **6ab"** to 9% and <1% (Run 3). Other thiophene derivatives **5b**–**5g** were found to undergo the silylation to give arylene-bisHOMSi **5bb**–**5gb** in good to excellent yields (Runs 3–8).

Table 2-3. Synthesis of Aryl-$(HOMSi)_2$

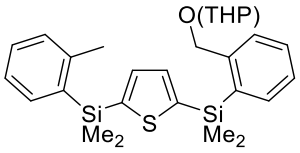


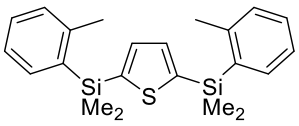
5 **2b** (3.0 eq) **6b**

Run	Arylsilane	time /h	Product, Yield /%[b]
			
1	**5a**	6	**6ab**, 47%
2[c]	**5a**	92	**6ab**, 60%
3		5	
	5b		**6bb**, 88%

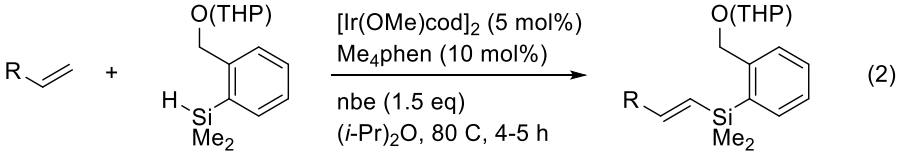
4	 **5c**	5	 **6cb**, 98%
5	 **5d**	2	 **6db**, 94%
6	 **5e**	4	 **6eb**, 50%
7[d]	 **5f**	40	 **6fb**, 86%
8[c]	 **5g**	86	 **6gb**, 86%

[a] Unless otherwise noted, a mixture of **6** (1 eq), **2a** (3 eq), $[Ir(OMe)(cod)]_2$ (5 mol%), Me_4phen (10 mol%), and norbornene (3 eq) in $(i\text{-Pr})_2O$ was heated at 80 °C. [b] Isolated yield. [c] Instead of Me_4phen and norbornene, dtbpy and t-BuCHCH$_2$ were used. [d] Run with 3 mmol scale at 100 °C and 1.76 gram of **6fb** was isolated.


6ab'


6ab"

His method was applicable not only to aryl C–H silylation but also to alkenyl C–H silylation.[8] The author briefly demonstrated such reactions using styrene (**7a**) and *i*-butyl vinyl ether (**7b**), and then corresponding (*E*)-alkenyl–HOMSis **8a** and **8b** were isolated in 98% and 77%, respectively (Eq. 2).



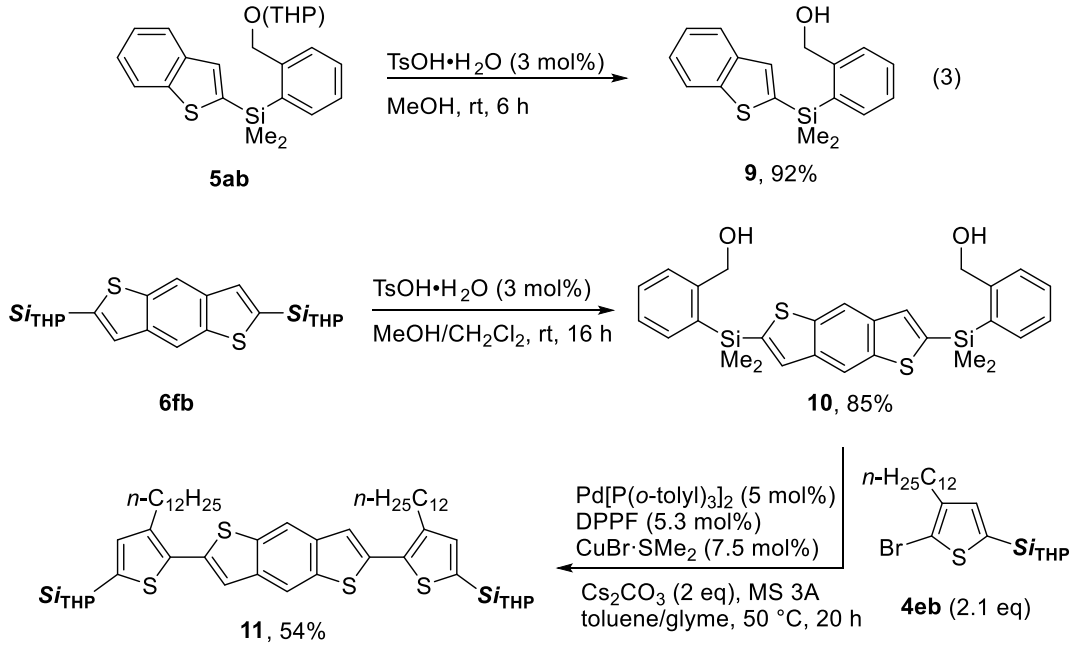
(2)

7a (R = Ph)
7b (R = O(*i*-Bu))

2b, 1.5 eq

8a, 98% (*E*/*Z* = >20:1)
8b, 77% (*E*/*Z* = 16:1)

Cross-coupling-active aryl-HOMSi reagents were obtained by deprotection of synthesized protected aryl-HOMSis reagents. For example, THP group in **4ab** was successfully removed under acidic conditions and corresponding coupling-active HOMSi **9** was obtained in excellent yields (Eq. 3). At last, he showed the synthesis of silicon-based oligoarylene monomer for a organic solar cell[9] by a sequential C–H silylation/cross-coupling protocol. Indeed, double cross-coupling reaction of **10** with **3eb** withstanding steric hindrance of dodecyl group led to produce oligothienylene-bisHOMSi **11** in moderate yield (Scheme 2-2).



Scheme 2-2. Rapid Synthesis a Monomer for Organic Solar Cell

2-3. Conclusion

In conclusion, the author has shown the straightworward protocol for the synthesis of protected heteroaryl- and alkenyl–HOMSi reagents via the dehydrogenative silylation achieved by iridium/Me4phen catalysis. The resulting silylated reagents are readily transformed into the corresponding cross-coupling-active HOMSi reagents. At last, he demonstrated the rapid construction of a silicon-based oligoarylene monomer for organic electronics thorugh the present method and the cross-coupling reaction.

2-4. Experimental Section and Additional Information

The following general aspects along with apparatus and chemicals apply to Chapters 2 to 5 unless otherwise stated.

General: All manipulations of oxygen- and moisture-sensitive materials were conducted with a standard Schlenk technique or in a dry box under an argon atmosphere. Flash column chromatography was performed using Kanto Chemical silica gel (spherical, 50 μm), silica gel neutral (spherical, 50 μm) or Merck aluminium oxide 90 active neutral. Analytical TLC was performed on Merck Kieselgel 60 F254 (0.25 mm) plates. Preparative TLC was carried out using Wakogel B-5F silica gel. Visualization was accomplished with UV light (254 nm).

Apparatus: ^{1}H and ^{13}C NMR spectra in $CDCl_3$ solution were recorded with Varian Mercury 400 spectrometer. The chemical shifts in the ^{1}H NMR spectra were recorded relative to Me_4Si as an internal standard, and the chemical shifts in the ^{13}C NMR spectra were recorded relative to $CHCl_3$ (δ 77.16). ^{1}H NMR data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, sext = sextet, sept = septet, br = broad, m = multiplet), coupling constants (Hz), and integration. The IR spectra were measured by JASCO FT/IR-4200. GCMS were measured on Agilent 6890N/5975B. High-resolution mass spectra (HRMS) were measured by JEOL JMS-T100LC AccuTOF. Melting points were measured by a MPA100 Optimelt Automated Melting Point System.

Chemicals: All the reaction was carried out under an argon atmosphere. Unless otherwise noted, commercially available reagents were used without further purification. Anhydrous THF was purchased from Kanto Chemical and further purified by passing through activated alumina under positive argon pressure as described by Grubbs et al. Other anhydrous solvents such as diisopropylether were also purchased from Kanto Chemical. 2-(Tetrahydropyranyloxymethyl)phenyl bromide was prepared by the reaction of the corresponding alcohol with 3,4-dihydro-2*H*-pyran.

Preparation of MOM-protected H-HOMSi 2a. 2-Methoxymethyl-1-bromobenzene (5.8 g, 25 mmol) was dissolved in the THF (90 mL) and cooled to –78 °C. After the addition of a solution of *n*-BuLi in hexane (2.7 M, 10 mL, 27 mmol) over 5 minutes, the resultant solution was stirred at –78 °C for 3 h. Chlorodimethylsilane (2.8 mL, 25 mmol)

was added dropwise over 5 min, and the mixture was stirred at room temperature overnight. After the addition of water, the reaction mixture was extracted with Et_2O, washed with brine, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chlomatography using hexane and ethyl acetate (20:1) as an eluentto give 2-[(methoxymethoxy)methyl]phenyldimethylsilane (**2a,** 4.2 g, 20 mmol, 80% yield) as Colorless oil, R_f 0.26 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.36 (d, *J* = 3.6 Hz, 6H), 3.43 (s, 3H), 4.54 (sep, *J* = 3.6 Hz, 1H), 4.69 (s, 2H), 4.72 (s, 2H), 7.30 (ddd, *J* = 2.0, 7.2, 7.2 Hz, 1H), 7.38 (ddd, 1.2, 7.2, 7.6 Hz, 1H), 7.40-7.43 (m, 1H), 7.55 (dd, *J* = 0.8, 7.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -2.95, 55.6, 69.4, 95.8, 127.3, 128.5, 129.5, 135.0, 136.7, 143.3. IR (neat) 2951, 2930, 2881, 2120, 1439, 1379, 1250, 1207, 1150, 1128, 1101, 1080, 1038, 984, 953, 939, 881, 837, 773, 750, 716, 689, 637, 569, 449, 432, 401 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 210 (M^+, 0.3), 179 (11), 165 (23), 163 (24), 150 (22), 149 (100), 135 (18), 133 (18), 121 (12), 119 (10), 105 (16), 91 (13), 89 (15), 59 (10); HRMS (ESI) calcd for $C_{11}H_{18}KO_2Si$ (M + K) 249.0713, found 249.9723.

Preparation of THP-protected H-HOMSi 2b. Tetrahydropyran-2-yloxymethyl-1-bromobenzene (9.7 g, 35 mmol) was dissolved in the Et_2O (250 mL) and cooled to –78 °C. After the addition of a solution of BuLi in hexane (2.7 M, 15 mL, 40 mmol) over 5 min, the resulting solution was stirred at –78 °C for 2 h. Chlorodimethylsilane (6.0 mL, 46 mmol) was added dropwise over 5 min, and the mixture was stirred at room temperature overnight. The reaction was quenched with water, and the whole mixture was extracted several times with hexane. The combined organic phase was washed with brine, dried over $MgSO_4$, and concentrated *in vacuo* to give a resiude, which was purified by distillation under vacuum (bp 120 °C under 2.3 hPa) to give 2-[(tetrahydropyran-2-yloxy)- methyl]phenyldimethylsilane (**2b**, 6.7 g, 27 mmol, 77% yield) as Colorless oil, registry number: 853955-58-5. R_f 0.33 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.36 (d, *J* = 1.6 Hz, 3H), 0.37 (d, *J* = 1.6 Hz, 3H), 1.48-1.78 (m, 5H), 1.82-1.93 (m, 1H), 3.50 (m, 1H), 3.94 (ddd, *J* = 3.2, 6.4, 11.6 Hz, 1H), 4.54 (sep, *J* = 3.6 Hz, 1H), 4.59 (d, *J* = 11.6 Hz, 1H), 4.73 (t, *J* = 3.2 Hz, 1H), 4.86 (d, *J* = 11.6 Hz, 1H), 7.29 (ddd, *J* = 1.2, 7.2, 7.2 Hz, 1H), 7.38 (ddd, *J* = 1.2, 7.2, 7.2 Hz, 1H), 7.44 (dd, *J* = 0.8, 7.6 Hz, 1H), 7.54 (dd, *J* = 0.8, 7.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -2.98, -2.88, 19.4, 25.6, 30.7, 62.1, 69.2, 98.1, 127.1, 128.4, 129.5, 134.8, 136.6, 143.7. IR (neat) 2943, 2870, 2120, 1591, 1439, 1384, 1350, 1250, 1120, 1182, 1153, 1117, 1078, 1055, 1022, 964, 878, 835, 812, 773, 750, 685, 644, 552, 532, 517, 432 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 249 (M^+ - H, 0.1), 163 (13), 150 (21), 149 (100), 133 (9), 105 (10), 91 (12), 85 (42), 67 (10), 57 (9), 55 (9); HRMS (ESI) calcd for $C_{14}H_{22}NaO_2Si$ (M + Na) 273.1287, found 273.1279.

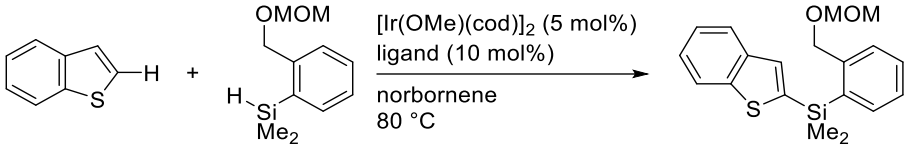
2-[(2-Trimethylsilylethoxy)methoxy]methyl]phenyl-dimethylsilane (2c). Colorless oil, R_f 0.40 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.06 (s, 9H), 0.38 (d, *J* = 4.0 Hz, 6H), 0.98-1.02 (m, 2H), 3.68-3.72 (m, 2H), 4.57 (sep, *J* = 4.0 Hz, 1H), 4.73 (s, 2H), 4.79 (s, 2H), 7.31 (ddd, *J* = 1.6, 7.2, 7.2 Hz, 1H), 7.37-7.44 (m, 2H), 7.57 (dd, *J* = 1.2, 7.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -2.89, -1.27, 18.2, 65.5, 69.6, 94.3, 127.3, 128.5, 129.6, 135.0, 136.7, 143.5. IR (neat) 2953, 2922, 2893, 1591, 1435, 1408, 1377, 1285, 1248, 1202, 1192 1177, 1155, 1130, 1103, 1082, 935, 920, 856, 831, 785, 748, 692, 665, 642, 611, 571, 561, 532, 501, 463, 430, 405 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 265 (M^+ - H - 2Me), 0.1), 223 (14), 207 (13), 175 (8), 163 (18), (149 (100), 135 (19), 121 (26), 105 (15), 89 (18), 73 (99), 59 (21); HRMS (ESI) calcd for $C_{15}H_{28}NaO_2Si_2$ (M + Na) 319.1526, found 319.1525.

Preparation of Ac-protected H-HOMSi 2d. 1,1-Dimethyl-2-oxa-1-silaindane (**1**, 1.6 g, 10 mmol) was added dropwise to a suspention of $LiAlH_4$ (380 mg, 10 mmol) in Et_2O (30 mL) at 0 °C, and the mixture was stirred at –0 °C for 100 min. Acetyl chloride (7.5 mL, 105 mmol) was added dropwise over 5 min and the resultant mixture was stirred at room temperature overnight. The reaction mixture was filtered through a Florisil pad and concentrated *in vacuo*. The residule was purified by column chlomatography using hexane and ethyl acetate (20:1) as an eluent gave (2-acetoxymethyl)phenyl(dimethyl)silane (**1d**, 1.1 g, 5.3 mmol, 53% yield). Registry number: 853955-59-6. Colorless oil, R_f 0.25 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.37 (d, *J* = 4.0 Hz, 6H), 2.09 (s, 3H), 4.55 (q, *J* = 3.6 Hz, 1H) 5.20 (s, 2H), 7.31-7.39 (m, 3H), 7.56 (dd, *J* = 0.8, 7.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -3.02, 21.1, 67.0, 127.9, 129.2, 129.7, 135.1, 137.3, 141.0, 170.8. IR (neat) 3057, 2959, 2903, 2124, 1736, 1591, 1466, 1437, 1379, 1362, 1221, 1163, 1130, 1080, 1024, 964, 880, 835, 772, 750, 685, 637, 606, 588, 552, 519, 494, 465, 430, 403 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 208 (M^+, 0.3), 207 (19), 193 (14), 165 (30), 163 (13), 151 (93), 149 (100), 147 (19), 145 (10), 135 (19), 133 (42), 123 (14), 121 (12), 119 (10), 117 (22), 105 (17), 91 (25), 89 (7), 77 (7), 75 (31).

According to the similar procedure, 2-(2-pivaloxymethyl)phenyldimethylsilane (**2e**) was prepared**.** Colorless oil, R_f 0.39 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.38 (d, *J* = 4.0 Hz, 6H), 1.23 (s, 9H), 4.57 (sep, *J* = 3.8 Hz, 1H), 5.20 (s, 2H), 7.30–7.34 (m, 1H), 7.38–7.40 (m, 2H), 7.55 (ddd, *J* = 1.2, 1.2, 7.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ –3.02, 27.4, 38.9, 66.2, 127.6, 128.6, 129.8, 134.9, 136.9, 141.5,

178.5. IR (neat) 2961, 2905, 2872, 2122, 1726, 1591, 1479, 1460, 1396, 1364, 1279, 1250, 1207, 1142, 1080, 1032, 964, 941, 881, 837, 804, 754, 710, 685, 646, 633, 608, 581, 542, 486, 449, 426, 412 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 250 (M^+, 4), 249 (19), 235 (41), 163 (17), 159 (56), 149 (100), 144 (14), 133 (31), 121 (34), 105 (12), 91 (17), 75 (13), 57 (92); HRMS (ESI) calcd for $C_{14}H_{22}NaO_2Si$ (M + Na) 273.1287, found 273.1298.

Table 2-4. Optimization of the conditions for the reaction of 3a with 2a[a]



3a **2a** **4aa**

Run	**1a** (eq)	**L**	nbe /eq	solvent /M	time /h	yield of **4aa** /%[b]
1	3	**L1**	3	THF (0.2)	16	9
2	3	**L2**	3	THF (0.2)	22	10
3	3	**L3**	3	THF (0.2)	22	10
4	3	**L4**	3	THF (0.2)	22	17
5	3	**L4**	3	THF (1)	24	62
6	1	**L4**	1.2	THF (1)	18	60
7	1	**L4**	1.2	THF (2)	24	77
8	1	**L4**	1.2	*i*Pr2O (2)	38	80
9	1	**L4**	1.2	1,4-dioxane (2)	38	73
10	1	**L4**	1.2	CPME (2)	38	64
11[c]	1.5	**L4**	1.5	*i*Pr2O (2)	48	75[c]

[a] Unless otherwise noted, a mixture of **1** (1–3 eq), **2a** (1 eq), $[Ir(OMe)(cod)]_2$ (5 mol%), ligand (10 mol%), and norbornene (1.2–3 eq) in solvent was heated at 80 °C. [b] NMR yield. [c] Isolated yield. **L1** = 4,4′-di-*tert*-bulyl-2,2′-bipyridyl, **L2** = 2,2′-bipyridyl, **L3** = 1,10-phenanthroline, **L4** = 3,4,7,8-tetramethyl-1,10-phenanthroline.

This table shows the details of the optimization of the reaction conditions.

Silylation of benzothiophene (3a) using 2b to give 4-benzothienyl(tetrahydropyran-2-yloxy)methylphenyldimethylsilane (3b)—*General procedure for single silylation of heteroaromatics and alkenes*— Benzothiophene (**3a**, 66 mg, 0.49 mmol), **2b** (188 mg, 0.75 mmol), and 2-norbornene (72 mg, 0.77 mmol) were added sequentially to a solution of $[Ir(OMe)(cod)]_2$ (16 mg, 25 μmol) and 3,4,7,8-tetramethyl-1,10-phenanthroline (Me_4phen, **L4**, 13 mg, 51 μmol) in *i*Pr_2O (0.25 mL) prepared in a 3 mL-vial in a dry box.

The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 80 °C for 3 h. The reaction mixture was filtered through s Celite pad, and the filtrate was concentrated *in vacuo*. The residue was purified by preparative TLC to give (2-benzothienyl)[(tetrahydropyran-2-yloxy- methyl)phenyl]dimethylsilane (**4ab**, 167 mg, 0.44 mmol, 89% yield) as Colorless oil, R_f 0.15 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.71 (s, 6H), 1.39-1.64 (m, 5H), 1.75-1.78 (m, 1H), 3.33-3.39 (m, 1H), 3.73 (ddd, *J* = 3.2, 8.8, 11.6 Hz, 1H), 4.49-4.52 (m, 2H), 4.66 (d, *J* = 12.0 Hz, 1H), 7.27-7.35 (m, 3H), 7.43 (ddd, *J* = 1.6, 7.2, 7.6 Hz, 1H), 7.47 (s, 1H), 7.51 (d, *J* = 7.6 Hz, 1H), 7.58 (dd, J = 1.6, 7.6 Hz, 1H), 7.77-7.79 (m, 1H), 7.85-7.87 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.00, 0.07, 19.5, 25.5, 30.6, 62.2, 68.9, 98.0, 122.3, 123.7, 124.1, 124.4, 127.1, 129.0, 130.2, 132.4, 135.4, 135.5; 140.9, 141.2, 144.0, 144.3. IR (neat) 2941, 2868, 1589, 1493, 1452, 1437, 1418, 1404, 1384, 1348, 1321, 1290, 1250, 1200, 1182, 1155, 1117, 1076, 1055, 1022, 968, 905, 868, 831, 808, 777, 746, 727, 689, 667, 650, 611, 563, 552, 532, 505, 461, 432 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 382 (M^+, 0.5), 283 (15), 281 (14), 265 (22), 221 (9), 191 (13), 163 (68), 149 (36), 134 (29), 115 (8), 85 (100) 67 (10), 57 (10), 55 (13); HRMS (ESI) calcd for $C_{22}H_{26}NaO_2SSi$ (M + Na) 405.1321, found 405.1335

(2-Benzothienyl)[2-(methoxymethoxymethyl)phenyl]dimethylsilane (4aa). Colorless oil, R_f 0.15 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.71 (s, 6H), 3.27 (s, 3H), 4.56 (s, 2H), 4.60 (s, 2H), 7.29-7.36 (m, 3H), 7.44 (ddd, *J* = 1.6, 7.2, 7.6 Hz, 1H), 7.47-7.49 (m, 2H), 7.59 (dd, *J* = 1.2, 7.6 Hz, 1H), 7.78-7.80 (m, 1H), 7.85-7.87 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.04, 55.5, 69.3, 95.8, 122.3, 123.7, 124.2, 124.4, 127.3, 128.9, 130.2, 132.3, 135.4, 135.7, 140.9, 141.1, 143.8, 143.9. IR (neat) 3055, 2949, 2928, 2882, 1589, 1558, 1490, 1454, 1437, 1418, 1364, 1290, 1250, 1182, 1148, 1126, 1101, 1078, 1038, 1018, 968, 939, 920, 831, 808, 777, 746, 727, 691, 667, 652, 615, 563, 503 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 342 (M^+, 0.2), 281 (6), 265 (12), 221 (7), 191 (6), 163 (48), 149 (30), 147 (100); HRMS (ESI) calcd for $C_{19}H_{22}NaO_2SSi$ (M + Na) 365.1008, found 365.1008.

(2-Benzothienyl)[2-(2-trimethylsilylethoxymethoxymethyl)phenyl]dimethylsilane (4ac). Colorless oil, R_f 0.25 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ -0.02 (s, 9H), 0.71 (s, 6H), 0.85-0.89 (m, 2H), 3.55-3.59 (m, 2H), 4.609 (s, 2H), 4.614 (s, 2H), 7.27-7.35 (m, 3H), 7.43 (ddd, *J* = 1.6, 7.2, 7.6 Hz, 1H), 7.45-7.48 (m, 2H), 7.57-7.59 (m, 1H), 7.77-7.80 (m, 1H), 7.85-7.87 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -1.28, 0.08, 18.1, 65.4, 69.5, 94.3, 122.3, 123.7, 124.2, 124.4, 127.2, 128.9, 130.2, 132.3, 135.4, 135.7, 140.9, 141.1, 143.96, 144.03. IR (neat) 3055, 2951, 2880, 1591,

1493, 1454, 1435, 1416, 1375, 1290, 1248, 1204, 1186, 1155, 1126, 1103, 1076, 1053, 1034, 968, 935, 90, 854, 831, 808, 777, 746, 728, 692, 667, 652, 611, 563, 503, 459, 433 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 428 (M^+, 0.1), 335 (43), 339 (9), 281 (24), 265 (64), 221 (14), 191 (27), 163 (73), 147 (49), 133 (11), 115 (11), 103 (15), 91 (19), 73 (100), 59 (9); HRMS (ESI) calcd for $C_{23}H_{32}NaO_2SSi_2$ (M + Na) 451.1559, found 451.1565.

(2-Benzothienyl)[2-(acetoxymethyl)phenyl]dimethylsilane (4ad). Colorless oil, R_f 0.16 (hexane–ethyl acetate = 20:1). ^1H NMR (400 MHz, $CDCl_3$) δ 0.72 (s, 6H), 1.88 (s, 3H), 5.09 (s, 2H), 7.24-7.37 (m, 3H), 7.40-7.44 (m, 2H), 7.47 (m, 1H), 7.62 (d, *J* = 7.2 Hz, 1H), 7.78-7.80 (m, 1H), 7.84-7.87 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.04, 20.9, 66.7, 122.3, 123.7, 124.2, 124.5, 128.0, 129.9 (d, *J* = 1.5 Hz), 130.4, 132.5, 135.8, 136.5, 140.4, 141.1, 141.4, 144.0, 170.8. IR (neat) 3057, 2957, 2916, 2849, 1734, 1591, 1493, 1454, 1436, 1417, 1377, 1360, 1290, 1223, 1184, 1157, 1128, 1078, 1065, 1018, 968, 922, 908, 833, 808, 779, 746, 727, 691, 667, 652, 606, 588, 563, 505, 468 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 340 (M^+, 0.3), 325 (22), 267 (12), 266 (24), 265 (100), 249 (8), 221 (11), 191 (8), 165 (15), 163 (59), 149 (12), 115 (6); HRMS (ESI) calcd for $C_{19}H_{20}NaO_2SSi$ (M + Na) 363.0851, found 363.0862.

(2-Benzothienyl)[2-(pivaloxymethyl)phenyl]dimethylsilane (4ae). Colorless oil, R_f 0.22 (hexane–ethyl acetate = 20:1). ^1H NMR (400 MHz, $CDCl_3$) δ 0.74 (s, 6H), 1.17 (s, 9H), 5.14 (s, 2H), 7.27-7.37 (m, 3H), 7.44-7.47 (m, 2H), 7.49 (d, *J* = 0.8 Hz, 1H), 7.61 (dd, *J* = 0.8, 7.6 Hz, 1H), 7.80-7.82 (m, 1H), 7.86-7.89 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.02, 27.3, 38.8, 66.1, 122.3, 123.8, 124.2, 124.5, 127.6, 129.0, 130.3, 132.5, 135.5, 135.8, 140.3, 141.1, 142.1, 144.0, 178.3. IR (neat) 2960, 1724, 1591, 1493, 1477, 1454, 1441, 1415, 1397, 1364, 1279, 1251, 1206, 1142, 1076, 1032, 1018, 968, 939, 918, 833, 808, 779, 745, 727, 691, 667, 650, 606, 563, 540, 505, 490, 434 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 382 (M^+, 0.3), 367 (24), 281 (8), 280 (8), 266 (23), 265 (100), 249 (9), 221 (11), 191 (17), 163 (77), 115 (11), 85 (11), 57 (98); HRMS (ESI) calcd for $C_{22}H_{26}NaO_2SSi$ (M + Na) 405.1321, found 405.1315.

(2-Benzofuryl)[(tetrahydropyran-2-yloxymethyl)phenyl]dimethylsilane (4bb). A yellow oil, R_f 0.18 (hexane–ethyl acetate = 20:1). ^1H NMR (400 MHz, $CDCl_3$) δ 0.68 (s, 3H), 0.69 (s, 3H), 1.41-1.59 (m, 4H), 1.61-1.68 (m, 1H), 1.75-1.81 (m, 1H), 3.39-3.45 (m, 1H), 3.80 (ddd, *J* = 3.2, 9.6, 10.8 Hz, 1H), 4.55 (d, *J* = 11.6 Hz, 1H), 4.56 (t, *J* = 4.0 Hz, 1H), 4.81 (d, *J* = 12.0 Hz, 1H), 7.02 (d, *J* = 0.8 Hz, 1H), 7.19 (ddd, *J* = 0.8, 7.6, 7.6 Hz, 1H), 7.24-7.30 (m, 2H), 7.41 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 1H), 7.48-7.51 (m,

2H), 7.54-7.57 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -1.55, -1.44, 19.5, 25.5, 30.6, 62.2, 68.9, 98.0, 111.5, 117.7, 121.2, 122.5, 124.6, 127.2, 128.1, 128.9, 130.1, 134.6, 135.5, 144.2, 158.3, 162.0. IR (neat) 2941, 2870, 2849, 1589, 1526, 1470, 1441, 1385, 1344, 1296, 1285, 1252, 1221, 1200, 1182, 1157, 1113, 1078, 1055, 1024, 974, 955, 920, 907, 870, 835, 814, 781, 752, 741, 691, 654, 631, 613, 578 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 351 (M^+ - CH_3, 0.1), 267 (10), 265 (10), 250 (7), 249 (29), 191 (9), 163 (45), 150 (10), 149 (73), 133 (7), 118 (31), 105 (8), 89 (13), 85 (100), 67 (10), 63 (10), 57 (11), 55 (22); HRMS (ESI) calcd for $C_{22}H_{26}NaO_3Si$ (M + Na) 389.1549, found 389.1542.

(2-Indolyl)[(tetrahydropyran-2-yloxymethyl)phenyl]dimethylsilane (4cd). A yellow oil, R_f 0.09 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 3H), 0.70 (s, 3H), 1.47-1.61 (m, 4H), 1.64-1.71 (m, 1H), 1.78-1.87 (m, 1H), 3.44-3.49 (m, 1H), 3.83 (ddd, *J* = 3.2, 7.6, 11.2 Hz, 1H), 4.53 (d, *J* = 11.6 Hz, 1H), 4.57 (t, *J* = 4.0 Hz, 1H), 4.83 (d, *J* = 11.6 Hz, 1H), 6.81 (d, *J* = 0.8 Hz, 1H), 7.06 (ddd, *J* = 0.8, 7.2, 7.2 Hz, 1H), 7.14 (ddd, *J* = 0.8, 7.2, 7.2 Hz, 1H), 7.29-7.33 (m, 2H), 7.41 (ddd, *J* = 1.2, 7.2, 7.2 Hz, 1H), 7.46 (d, *J* = 7.6 Hz, 1H), 7.59 (d, *J* = 7.2 Hz, 1H), 7.62 (d, *J* = 7.6 Hz, 1H), 8.75 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.72, -0.45, 19.8, 25.5, 30.6, 62.7, 69.5, 98.5, 111.0, 112.1, 119.6, 120.7, 122.4, 127.6, 128.8, 129.9, 130.1, 135.7, 136.0, 136.8, 139.0, 143.7. IR (neat) 3406, 3316, 2943, 2899, 2868, 2850, 1589, 1439, 1387, 1342, 1302, 1279, 1250, 1231, 1200, 1182, 1150, 1117, 1076, 1055, 1022, 1013, 974, 947, 905, 868, 835, 814, 777, 748, 737, 689, 654, 610, 581, 552, 534, 498, 467, 432, 405 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 365 (M^+, 6), 266 (8), 265 (25), 264 (43), 263 (55), 262 (8), 250 (10), 249 (9), 248 (34), 232 (9), 204 (10), 184 (7), 165 (8), 164 (27), 163 (100), 150 (11), 149 (73), 148 (10), 133 (9), 118 (14), 117 (38), 105 (9), 90 (12), 89 (13), 85 (63), 67 (11), 57 (11), 55 (14); HRMS (ESI) calcd for $C_{22}H_{27}NNaO_2Si$ (M + Na) 388.1709, found 388.1701.

[3-(*N*-Tosylindolyl)][(tetrahydropyran-2-yloxymethyl)phenyl]dimethylsilane (4db). Colorless solid, R_f 0.17 (hexane–ethyl acetate = 10:1), mp 124-125 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.647 (s. 3H), 0.653 (s, 3H), 1.42-1.63 (m, 5H), 1.73-1.80 (m, 1H), 2.36 (s, 3H), 3.36-3.41 (m, 1H), 3.76 (ddd, *J* = 3.2, 10.0, 11.2 Hz, 1H), 4.42 (d, *J* = 12.0 Hz, 1H), 4.44 (t, *J* = 3.6 Hz, 1H), 4.68 (d, *J* = 12.0 Hz, 1H), 7.08 (ddd, *J* = 1.2, 1.2, 7.6 Hz, 1H), 7.23-7.28 (m, 5H), 7.40 (ddd, *J* = 0.8, 8.0, 8.0 Hz, 1H), 7.47 (dd, *J* = 0.8, 7.6 Hz, 1H), 7.51 (dd, *J* = 0.8, 7.2 Hz, 1H), 7.59 (s, 1H), 7.78 (ddd, *J* = 2.0, 2.0,

8.0 Hz, 2H), 7.93 (ddd, *J* = 0.8, 0.8, 8.4 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.56, -0.53, 19.5, 21.7, 25.5, 30.6, 62.2, 68.7, 98.0, 113.5, 117.2, 122.6, 123.2, 124.4, 127.0, 127.2, 128.9, 130.0, 130.1, 132.6, 134.6, 135.4, 135.5, 135.7, 136.0, 144.3, 145.1. IR (neat) 2940, 2920, 2878, 1595, 1447, 1362, 1173, 1128, 1111, 1078, 1022, 1013, 974, 941, 907, 839, 816, 779, 760, 739, 708, 700, 664, 648, 586, 569, 536, 503, 459 cm^{-1}. HRMS (ESI) calcd for $C_{29}H_{33}NNaO_4SSi$ (M + Na) 542.1797, found 542.1800.

[5-(2-Bromo-3-dodecylthienyl)][2-(tetrahydropyranyloxymethyl)phenyl]-dimethylsilane (3i). Colorless oil, R_f 0.31 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.61 (s, 6H), 0.88 (t, *J* = 6.8 Hz, 3H), 1.26-1.30 (m, 18H), 1.48-1.61 (m, 4H), 1.64-1.71 (m, 1H), 1.78-1.84 (m, 1H), 2.52 (t, *J* = 7.6 Hz, 2H), 3.45-3.50 (m, 1H), 3.82 (ddd, *J* = 3.2, 8.8, 11.6 Hz, 1H), 4.47, (d, *J* = 12.0 Hz, 1H), 4.56 (t, *J* = 3.6 Hz, 1H), 4.74 (d, *J* = 12.0 Hz, 1H), 6.90 (s, 1H), 7.28 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 1H), 7.42 (ddd, *J* = 1.2, 7.6, 7.6 Hz), 7.48-7.52 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.04, 0.15, 14.3, 19.5, 22.8, 25.6, 29.45, 29.49, 29.51, 29.54, 29.7, 29.79, 29.80, 29.82, 30.0, 30.7, 32.1, 62.2, 68.8, 98.0, 114.4, 127.1, 128.9, 130.1, 135.4, 135.5, 136.4, 139.3, 143.5, 144.2. IR (neat) 2922, 2851, 1589, 1464, 1454, 1439, 1404, 1350, 1250, 1200, 1182, 1153, 1117, 1078, 1055, 1024, 982, 953, 907, 970, 835, 810, 777, 752, 733, 689, 648, 517 cm^{-1}. HRMS (ESI) calcd for $C_{30}H_{47}BrNaO_2SSi$ (M + Na) 601.2147 found 601.2136.

Double silylation of 3-bromothiophene (5b) using 2b. —*General procedure of double silylation of Arenes*— 3-Bromothiophene (81 mg, 0.49 mmol), **1b** (378 mg, 1.5 mmol) and 2-norbornene (143 mg, 1.5 mmol) were added sequentially to a solution of $[Ir(OMe)(cod)]_2$ (17 mg, 26 μmol), 3,4,7,8-Me_4-phen (12 mg, 50 μmol) in $(i\text{-}Pr)_2O$ (0.25 mL) prepared in a 3 mL-vial in a dry box. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 80 °C for 5 h. The resultant mixture was filtered through Celite, and the filtrate was evaporated and concentrated *in vacuo*. The residule was purified by preparative TLC to give 2,5- bis{2-[(tetrahydropyran-2-yloxy)methyl]phenyldimethylsilyl}-3-bromothiophene (**6ba**, 281 mg, 0.43 mmol, 88% yield) as a yellow oil, R_f 0.31 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.63 (s, 6H), 0.70 (s, 6H), 1.44-1.70 (m, 10H), 1.77-1.85 (m, 2H), 3.42-3.50 (m, 2H), 3.78-3.85 (m, 2H), 4.44 (d, *J* = 11.6 Hz, 1H), 4.47 (d, *J* = 11.2 Hz, 1H), 4.53 (t, *J* = 3.6 Hz, 1H), 4.56 (t, *J* = 3.6 Hz, 1H), 4.71 (d, *J* = 12.0 Hz, 1H), 4.75 (d, *J* = 12.0 Hz, 1H), 7.17 (s, 1H), 7.25-7.31 (m, 2H), 7.39-7.43 (m, 2H), 7.47-7.54 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.35, -0.34, 0.14, 0.26, 19.47, 19.51, 25.6, 30.6, 62.2, 62.3,

68.87, 68.89, 97.9, 98.0, 119.1, 127.0, 127.2, 128.7, 129.0, 130.0, 130.2, 134.9, 135.2, 135.5, 135.6, 139.5, 140.2, 144.08, 144.13, 146.0. IR (neat) 2941, 2899, 2868, 2848, 1471, 1439, 1396, 1385, 1348, 1250, 1200, 1182, 1153, 1117, 1076, 1055, 1022, 1001, 974, 954, 905, 870, 835, 806, 777, 750, 689, 652, 642, 608, 552, 525, 488, 461, 428, 402 cm^{-1}. HRMS (ESI) calcd for $C_{32}H_{43}BrNaO_4SSi_2$ (M + Na) 681.1502, found 681.1534.

2,5-Bis{2-[(tetrahydropyran-2-yloxy)methyl]phenyl-dimethylsilyl}thiophene (6ab). A yellow oil, R_f 0.29 (hexane–ethyl acetate = 10:1). ^1H NMR (400 MHz, $CDCl_3$) δ 0.64 (s, 12H), 1.44-1.68 (m, 10H), 1.76-1.85 (m, 2H), 3.42-3.48 (m, 2H), 3.81 (ddd, *J* = 2.4, 8.8, 11.2 Hz, 2H), 4.48 (d, *J* = 12.0 Hz, 2H), 4.54 (t, *J* = 3.6 Hz, 2H), 4.75 (d, *J* = 12.0 Hz, 2H), 7.26 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 2H), 7.29 (s, 2H), 7.40 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 2H), 7.48-7.52 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.41, 0.52, 19.5, 25.6, 30.7, 62.2, 68.9, 97.9, 127.0, 128.7, 129.9, 135.4, 136.1, 136.6, 144.2, 144.9. IR (neat) 2941, 2899, 2870, 2849, 1589, 1466, 1439, 1250, 1200, 1182, 1153, 1117, 1076, 1055, 1022, 1003, 974, 905, 891, 870, 833, 802, 775, 750, 689, 652, 637, 611, 552, 519, 498, 471, 430, 403 cm^{-1}. HRMS (ESI) calcd for $C_{32}H_{44}NaO_4SSi_2$ (M + Na) 603.2397, found 603.2411.

2,5-Bis{2-[(tetrahydropyran-2-yloxy)methyl]phenyldimethylsilyl}-3,4-ethylenedioxythiophene (6cb). A yellow oil, R_f 0.20 (hexane–ethyl acetate = 10:1). ^1H NMR (400 MHz, $CDCl_3$) δ 0.595 (s, 6H), 0.599 (s, 6H), 1.46-1.73 (m, 10H), 1.79-1.88 (m, 2H), 3.44-3.49 (m, 2H), 3.86 (ddd, *J* = 3.2, 8.8, 11.6 Hz, 2H), 4.10 (s, 4H), 4.57 (d, *J* = 12.4 Hz, 2H), 4.61 (t, *J* = 3.2 Hz, 2H), 4.80 (d, *J* = 12.4 Hz, 2H), 7.25 (ddd, *J* = 1.6, 7.2, 7.6 Hz, 2H), 7.38 (ddd, *J* = 1.6, 7.6, 7.6 Hz, 2H), 7.48-7.51 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.53, -0.50, 19.5, 25.6, 30.7, 62.1, 64.4, 68.8, 98.0, 116.4, 126.8, 128.2, 129.7, 135.3, 136.0, 144.2, 148.5. IR (neat) 2940, 2870, 1589, 1543, 1462, 1452, 1433, 1420, 1385, 1352, 1285, 1248, 1120, 1169, 1155, 1117, 1076, 1053, 1022, 968, 927, 907, 870, 837, 808, 775, 748, 687, 650, 610, 567, 544, 450, 469, 432 cm^{-1}. HRMS (ESI) calcd for $C_{34}H_{46}NaO_6SSi_2$ (M + Na) 661.2451, found 661.2443.

5,5'-Bis{2-[(tetrahydropyran-2-yloxy)methyl]phenyldimethylsilyl}bithiophene (6db). A yellow solid, R_f 0.29 (hexane–ethyl acetate = 10:1), mp 69-72 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 0.65 (s, 12H), 1.44-1.70 (m, 10H), 1.76-1.85 (m, 2H), 3.43-3.49 (m, 2H), 3.82 (ddd, *J* = 2.8, 8.4, 11.2 Hz, 2H), 4.51 (d, *J* = 12.0 Hz, 2H), 4.56 (t, *J* = 3.6 Hz, 2H), 4.77 (d, *J* = 12.0 Hz, 2H), 7.12 (d, *J* = 3.6 Hz, 2H), 7.21 (d, *J* = 3.6 Hz,

2H), 7.27 (ddd, *J* = 1.2, 7.2, 7.2 Hz, 2H), 7.41 (ddd, *J* = 1.6, 7.2, 7.6 Hz, 2H), 7.50 (d, *J* = 7.6 Hz, 2H), 7.54 (dd, *J* = 1.6, 7.6 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.16, 0.25, 19.5, 25.6, 30.7, 62.2, 68.9, 98.0, 125.3, 127.1, 128.9, 130.1, 135.5, 135.7, 136.2, 138.3, 143.1, 144.2. IR (neat) 2943, 2870, 1589, 1439, 1422, 1348, 1323, 1250, 1200, 1117, 1076, 1024, 986, 905, 872, 833, 799, 775, 750, 687, 653, 548, 529, 494, 421 cm^{-1}. HRMS (ESI) calcd for $C_{36}H_{46}NaO_4S_2Si_2$ (M + Na) 685.2274, found 685.2308.

5,5'-Bis{2-[(2-tetrahydropyranyloxy)methyl]phenyl-dimethylsilyl}dithiophene (6eb). A yellow solid, R_f 0.19 (hexane–ethyl acetate = 20:1), mp 90-93 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 12H), 1.41-1.67 (m, 10H), 1.74-1.83 (m, 2H), 3.38-3.43 (m, 2H), 3.77 (ddd, *J* = 2.4, 8.0, 11.2 Hz, 2H), 4.49-4.54 (m, 4H), 4.77 (d, *J* = 12.0 Hz, 2H), 7.28 (dd, *J* = 7.2 Hz, 2H), 7.30 (s, 2H), 7.42 (ddd, *J* = 1.2, 7.2, 7.6 Hz, 2H), 7.50 (d, *J* = 7.6 Hz, 2H), 7.55 (d, *J* = 7.2 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.12, 0.20, 19.5, 25.5, 30.6, 62.2, 68.9, 98.1, 126.7, 127.1, 129.0, 130.1, 135.577, 135.584, 143.6, 144.2, 147.1. IR (neat) 2940, 2899, 2868, 2849, 1589, 1564, 1452, 1435, 1385, 1348, 1304, 1250, 1200, 1180, 1153, 1117, 1076, 1053, 1022, 1005, 974, 905, 862, 833, 804, 777, 750, 689, 652, 633, 619, 569, 538, 496, 461, 440, 403 cm^{-1}. HRMS (ESI) calcd for $C_{34}H_{44}NaO_4S_2Si_2$ (M + Na) 659.2117, found 659.2111.

2,6-Bis{2-[(tetrahydropyran-2-yloxy)methyl]phenyldimethylsilyl}benzo[1,2-*b*:4,5-*b′*]dithiophene (6fb). Colorless solid, R_f 0.13 (hexane–ethyl acetate = 10:1), mp 115-117 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.72 (s, 12H), 1.37-1.64 (m, 10H), 1.71-1.80 (m, 2H), 3.35-3.40 (m, 2H), 3.75 (ddd, *J* = 2.8, 8.8, 11.2 Hz, 2H), 4.51-4.54 (m, 4H), 4.79 (d, *J* = 12.0 Hz, 2H), 7.29 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 2H), 7.42 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 2H), 7.47 (d, *J* = 0.8 Hz, 2H), 7.51 (d, *J* = 7.2 Hz, 2H), 7.58 (dd, *J* = 0.8, 7.6 Hz, 2H), 8.21 (d, *J* = 0.8 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.10, -0.02, 19.4, 25.5, 30.6, 62.1, 68.9, 98.0, 116.3, 127.1, 128.9, 130.2, 131.4, 135.3, 135.5, 139.3, 141.1, 142.5, 144.3. IR (neat) 2951, 2868, 1508, 1454, 1453, 1352, 1323, 1287, 1246, 1200, 1119, 1076, 1059, 1020, 957, 907, 874, 833, 802, 781, 750, 729, 683, 644, 552, 519, 471, 434 cm^{-1}. HRMS (ESI) calcd for $C_{38}H_{46}NaO_4S_2Si_2$ (M + Na) 709.2274, found 709.2285.

4,7-Bis{5-[2-(tetrahydropyran-2-yloxymethyl)phenyldimethylsilyl]}-2-thienyl-benzo[1,2,5]thiadiazole (6gb). A red viscous oil, R_f 0.43 (hexane–ethyl acetate = 4:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.72 (s, 12H), 1.42-1.70 (m, 10H), 1.76-1.85 (m, 2H), 3.43-3.48 (m, 2H), 3.82 (ddd, *J* = 3.2, 8.4, 11.2 Hz, 2H), 4.55 (d, *J* = 12.0 Hz, 2H), 4.59

(t, *J* = 3.6 Hz, 2H), 4.81 (d, *J* = 12.0 Hz, 2H), 7.30 (dd, *J* = 7.6, 7.6 Hz, 2H), 7.33 (d, *J* = 3.2 Hz, 2H), 7.43 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 2H), 7.52 (d, *J* = 7.6 Hz, 2H), 7.60 (d, *J* = 7.6 Hz, 2H), 7.84 (s, 2H), 8.17 (d, *J* = 3.6 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.22, 0.32, 19.5, 25.6, 30.7, 62.2, 68.9, 98.0, 126.0, 126.1, 127.1, 128.91, 128.94, 130.1, 135.6, 135.7, 136.5, 140.8, 144.2, 145.2, 152.7. IR (neat) 2940, 2924, 2868, 2849, 1589, 1570, 1518, 1464, 1452, 1435, 1404, 1385, 1344, 1321, 1248, 1200, 1182, 1153, 1117, 1076, 1057, 1022, 982, 905, 868, 833, 804, 775, 750, 689, 650, 615, 521, 500, 467, 430 cm^{-1}. HRMS (ESI) calcd for $C_{42}H_{48}N_2NaO_4S_3Si_2$ (M + Na) 819.2212, found 819.2206.

(*E*)-1-(Tetrahydropyran-2-yloxy)methyl]phenyldimethylsilyl-2-phenylethene (8a). Colorless oil, R_f 0.30 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.49 (s, 6H), 1.45-1.71 (m, 5H), 1.78-1.87 (m, 1H), 3.43-3.48 (m, 1H), 3.87 (ddd, *J* = 3.2, 9.6, 11.2 Hz, 1H), 4.61 (d, *J* = 12.0 Hz, 1H), 4.65 (t, *J* = 3.6 Hz, 1H), 4.86 (d, *J* = 12.0 Hz, 1H), 6.66 (d, *J* = 18.8 Hz, 1H), 6.94 (d, *J* = 18.8 Hz, 1H), 7.22-7.27 (m, 1H), 7.29-7.34 (m, 3H), 7.39 (ddd, *J* = 1.2, 7.6, 7.6 Hz, 1H), 7.42-7.45 (m, 2H), 7.50 (d, *J* = 7.6 Hz, 1H), 7.58 (dd, *J* = 1.2, 7.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -1.14, -1.09, 19.5, 25.6, 30.7, 62.3, 69.0, 98.1, 126.6, 127.0, 128.0, 128.2, 128.6, 128.7, 129.6, 135.2, 136.9, 138.3, 144.1, 145.0. IR (neat) 2941, 2899, 2868, 2848, 1602, 1572, 1495, 1466, 1439, 1385, 1348, 1321, 1285, 1248, 1200, 1182, 1153, 1117, 1076, 1055, 1024, 989, 976, 953, 905, 870, 845, 829, 810, 775, 746, 731, 689, 644, 613, 573, 548, 534, 490, 463, 430, 401 cm^{-1}. HRMS (ESI) calcd for $C_{22}H_{28}NaO_2Si$ (M + Na) 375.1756, found 375.1761

(*E*)-1-(Tetrahydropyran-2-yloxy)methyl]phenyldimethylsilyl-2-isobutyloxy-ethene (8b). The following data of ***E*-8b** were collected from s mixture of ***E*-8b** and ***Z*-8b** (16:1), as ***E*-8b** could not be separated from ***Z*-8b**. A colorles oil, R_f 0.30 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) ***E*-8b** δ 0.39 (s, 6H), 0.94 (d, *J* = 6.4 Hz, 6H), 1.48-1.78 (m, 5H), 1.81-1.91 (m, 1H), 1.94 (sep, *J* = 6.4, 6.4 Hz, 1H), 3.49 (d, *J* = 6.4 Hz, 2H), 3.51-3.57 (m, 1H), 3.93 (ddd, *J* = 3.2, 8.4, 11.2 Hz, 1H), 4.63 (d, *J* = 11.6 Hz, 1H), 4.67 (d, *J* = 15.2 Hz, 1H), 4.70 (t, *J* = 3.6 Hz, 1H), 4.87 (d, *J* = 11.6 Hz, 1H), 6.46 (d, *J* = 15.2 Hz, 1H), 7.26 (dd, *J* = 7.2, 7.6 Hz, 1H), 7.37 (ddd, *J* = 1.6, 7.2, 7.6 Hz, 1H), 7.51 (d, *J* = 7.6 Hz, 1H), 7.55 (dd, *J* = 0.8, 7.6 Hz, 1H). ***Z*-8b** δ 0.44 (s, 6H), 0.85 (d, *J* = 6.8 Hz, 6H), 4.30 (d, *J* = 8.4 Hz, 1H), 4.57-4.60 (m, 1H), 4.84 (t, *J* = 3.2 Hz, 1H), 6.64 (d, *J* = 8.4 Hz, 1H). Other peaks can not be assigned.; ^{13}C NMR (101 MHz, $CDCl_3$) ***E*-8b** δ -0.40, -0.34, 19.4, 19.6, 25.6, 28.2, 30.8, 62.3, 68.9, 74.6, 94.2, 98.0, 126.9, 128.5, 129.5, 135.1, 137.6, 144.0, 157.3. IR (neat) 2951, 2943, 2872, 1614,

1589, 1457, 1454, 1439, 1392, 1348, 1323, 1284, 1247, 1228, 1199, 1182, 1145, 1116, 1076, 1055, 1024, 974, 958, 945, 906, 860, 819, 806, 748, 684, 650, 607, 559, 534, 513, 499, 468, 459, 432, 420, 401 cm^{-1}. HRMS (ESI) calcd for $C_{20}H_{32}NaO_3Si$ (M + Na) 371.2018, found 371.2019.

Deprotection of 4ab. 4-Toluenesulfonic acid monohydroxide (2.5 mg, 0.013 mmol) was added to a solution of 3b (196 mg, 0.51 mmol) in methanol (4.5 mL) at room tempreture. The resultant solution was stirred for 6 h. The reaction mixture was dried in vacuo. 2-Benzothienyl[2-(hydroxymethyl)phenyl]dimethylsilane (**9**) was isolated in 92% yield (140 mg, 0.47 mmol) by column chlomatography using hexane and ethyl acetate (4:1) as eluents. A beige oil, R_f 0.47 (hexane–ethyl acetate = 4:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.71 (s, 6H), 1.58 (brs, 1H), 4.66 (s, 2H), 7.28-7.35 (m, 3H), 7.42-7.47 (m, 2H), 7.48 (s, 1H), 7.61 (d, *J* = 7.2 Hz, 1H), 7.77-7.80 (m, 1H), 7.84-7.86 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.04, 65.4, 122.2, 123.7, 124.3, 124.5, 127.7, 128.2, 130.4, 132.3, 134.9, 135.6, 140.9, 141.1, 143.8, 146.8. IR (neat) 3319, 3055, 2961, 1589, 1493, 1452, 1435, 1416, 1387, 1290, 1258, 1213, 1200, 1182, 1155, 1125, 1076, 1016, 968, 908, 831, 806, 779, 746, 727, 691, 667, 650, 604, 563, 548, 503, 461, 405 cm^{-1}. HRMS (ESI) calcd for $C_{17}H_{18}NaOSSi$ (M + Na) 321.0745, found 321.0754.

Deprotection of 5ab. 4-Toluenesulfonic acid monohydroxide (1.8 mg, μmol) was added to a solution of **5ab** (343 mg, 0.50 mmol) in a mixture of methanol (6.5 mL) and dichloromethane (4.5 mL) at room tempreture. The resultant solution was stirred for 18 h. After the dilution of chloroform, the reaction mixture was washed with brine, dried over $MgSO_4$, and concentrated *in vacuo*. 2,6-Bis[2-(hydroxymethylphenyl)dimethyl-silyl]benzo[1,2-*b*:4,5-*b*′]dithiophene **(10)** was isolated in 85% yield (221 mg, 0.43 mmol) by recrystallization using hot toluene-hexane. Off white plates, R_f 0.20 (hexane–ethyl acetate = 3:1), mp 165-167 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.73 (s, 12H), 1.45 (t, *J* = 7.6 Hz, 2H), 4.68 (d, *J* = 7.6 Hz, 4H), 7.30 (ddd, *J* = 0.8, 7.2, 7.2 Hz, 2H), 7.43 (ddd, 0.8, 7.2, 7.2 Hz, 2H), 7.42-7.48 (m, 6H), 7.61 (d, *J* = 7.6 Hz, 2H), 8.21 (s, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.10, 65.6, 116.5, 127.4, 128.4, 130.5, 131.39, 131.41, 135.1, 135.7, 139.6, 141.3, 143.0, 147.1. IR (neat) 3294, 3200, 2949, 1589, 1506, 1433, 1367, 1250, 1121, 1076, 1022, 953, 868, 829, 808, 779, 746, 687, 652, 605, 519, 490, 411 cm^{-1}. HRMS (ESI) calcd for $C_{28}H_{31}O_2S_2Si_2$ (M + H) 519.1304, found 519.1309.

Double cross-coupling of 4ab with 10.

To a mixture of **4ab** (120 mg, 0.21 mmol), Cs_2CO_3 (67 mg, 0.21 mmol), Pd[P(o-

tolyl)$_3$]$_2$ (3.4 mg, 4.8 μmol), DPPF (2.8 mg, 5.1 μmol), CuBr·SMe$_2$ (8.3 mg, 8.3 μmol), molecular sieves 3A (20 mg), toluene (0.15 mL), and 1,2-dimethoxyethane (0.050 mL) were added a screw vial and bis-HOMSi **10** (50 mg, 0.096 mmol) was added to this mixture. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 50 °C for 20 h. The reaction mixture solution was filtered through a Celite, and the filtrate was evaporated and concentrated *in vacuo*. The resiude was purified by preparative TLC to give 2,6-Bis-2-{3-dodecyl-5-[2- (2-tetrahydro-pyranyloxymethyl)phenyl-dimethylsilyl]thienyl}benzo[1,2-*b*:4,5-*b*′]di- thiophene (**11,** 62 mg, 0.052 mmol, 54% yield) as yellow solid, R_f 0.43 (hexane–ethyl acetate = 10:1), mp 85-86 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.67 (s, 17H), 0.87 (t, *J* = 7.2 Hz, 6H), 1.24-1.72 (m, 50H), 1.77-1.86 (m, 2H), 2.85 (t, *J* = 8.0 Hz, 4H), 3.46-3.51 (m, 2H), 3.84 (ddd, *J* = 3.2, 8.4, 11.2 Hz, 2H), 4.54 (d, *J* = 12.0 Hz, 2H), 4.59 (t, *J* = 3.6 Hz, 2H), 4.80 (d, *J* = 12.0 Hz, 2H), 7.08 (s, 2H), 7.31 (ddd, *J* = 1.2, 7.2, 7.2 Hz, 2H), 7.33 (s, 2H), 7.43 (ddd, *J* = 1.2, 7.2, 7.6 Hz, 2H), 7.52 (d, *J* = 6.8 Hz, 2H), 7.58 (dd, *J* = 1.2, 7.2 Hz, 2H), 8.13 (s, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 0.16, 0.28, 14.3, 19.5, 22.8, 25.6, 29.51, 29.54, 29.6, 29.77, 29.82, 30.7, 31.0, 32.1, 62.3, 68.9, 98.0, 116.1, 120.9, 127.1, 128.9, 130.1, 135.5, 135.7, 136.6, 137.2, 137.5, 137.9, 138.6, 138.8, 142.2, 144.2. Some peaks of sp^3 carbon could not be assigned because peak resolution was not enough. IR (neat) 2914, 2846, 1543, 1467, 1454, 1439, 1332, 1255, 1247, 1153, 1134, 1123, 1076, 1038, 1001, 930, 833, 812, 777, 750cm^{-1}. HRMS (ESI) calcd for $C_{70}H_{98}NaO_4S_4Si_2$ (M + Na) 1209.5784, found 1209.5748.

2-5. References and Note

1. (a) Nakao, Y.; Imanaka, H.; Sahoo, A. K.; Yada, A.; Hiyama, T. *J. Am. Chem. Soc.* **2005**, *127*, 6952. (b) Nakao, Y.; Sahoo, A. K.; Yada, A.; Chen, J.; Hiyama, T. *Sci. Technol. Adv. Mater.* **2006**, *7*, 536. (c) Nakao, Y.; Imanaka, H.; Chen, J.; Yada, A.; Hiyama, T. *J. Organomet. Chem*. **2007**, *692*, 585. (d) Nakao, Y.; Ebata, S.; Chen, J.; Imanaka, H.; Hiyama, T. *Chem. Lett.* **2007**, *36*, 606. (e) Nakao, Y.; Chen, J.; Tanada, M.; Hiyama, T. *J. Am. Chem. Soc.* **2007**, *129*, 11694. (f) Chen, J.; Tanaka, M.; Sahoo, A. K.; Takeda, M.; Yada, A.; Nakao, Y.; Hiyama, T. *Bull. Chem. Soc. Jpn.* **2010**, *83*, 554. (g) Nakao, Y.; Takeda, M.; Matsumoto, T.; Hiyama, T. *Angew. Chem. Int. Ed.* **2010**, *49*, 4447. (h) Tang, S.; Takeda, M.; Nakao, Y.; Hiyama, T. *Chem. Commun*. **2011**, *47*, 307. (i) Shimizu, K.; Minami, Y.; Nakao, Y.; Ohya, K.; Ikehira, H.; Hiyama, T. *Chem. Lett.* **2013**, *42*, 45. (j) Ohgi, A.; Semba, K.; Hiyama, T.; Nakao, Y. *Chem. Lett*. **2016**, *45*, 973.
2. Iizuka, M.; Kondo, Y. *Eur. J. Org. Chem*. **2008**, 1161.
3. Minami, Y.; Shimizu, K.; Tsuruoka, C.; Komiyama, T.; Hiyama, T. *Chem. Lett*. **2014**, *43*, 201.
4. For recent reviews, see: (a) Cheng, C.; Hartwig, J. F. *Chem. Rev*. **2015**, *115*, 8946. (b) Bähr, S.; Oestreich, M. *Angew. Chem. Int. Ed*. **2017**, *56*, 52. For selected examples of transition-metal-catalyzed intermolecular dehydrogenative silylation of arenes without directing groups, see: (a) Tsukada, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 5022. (b) Murata, M.; Fukuyama, N.; Wada, J.; Watanabe, S.; Masuda, Y. *Chem. Lett.* **2007**, *36*, 910. (c) Lu, B.; Falck, J. R. *Angew. Chem. Int. Ed.* **2008**, *47*, 7508. (d) Ishiyama, T.; Saiki, T.; Kishida, E.; Sasaki, I.; Ito, H.; Miyaura, N. *Org. Biomol. Chem*. **2013**, *11*, 8162. (e) Klare, H. F. T.; Oestreich, M.; Ito, J.-i.; Nishiyama, H.; Ohki, Y.; Tatsumi, K. *J. Am. Chem. Soc*. **2011**, *133*, 3312. (f) Cheng, C.; Hartwig, J. F. Science **2014**, 343, 853. (g) Cheng, C.; Hartwig, J. F. *J. Am. Chem. Soc*. **2015**, *137*, 592. (h) Murai, M.; Takami, K.; Takeshima, H.; Takai, K. *Org. Lett.* **2015**, *17*, 1798. (i) Murai, M.; Takami, K.; Takai, K. *Chem. Eur. J.* **2015**, *21*, 4566. (j) Yin, Q.; Klare, H. F. T.; Oestreich, M. *Angew. Chem. Int. Ed.* **2016**, *55*, 3204. (k) Lee, K.-S.; Katsoulis, D.; Choi, J. *ACS Catal.* **2016**, *6*, 1493. (l) Fang, H.; Guo, L.; Zhang, Y.; Yao, W.; Huang, Z. *Org. Lett*. **2016**, *18*, 5624.
5. When Me_4phen, norbornene and $(i\text{-Pr})_2O$ were used instead of dtbpy, *t*-BuCH=CH_2, and toluene, C2-silylation of **3d** did not take place at all and **4db** was observed in 24% yield.
6. For benzylic C–O bond cleavage by iridium complexes, see: (a) Chen, C.; Chan, K.

S. *Organometallics* **2017**, *36*, 3456. For other C–O bond cleaving reactions by iridium complexes, see: (b) Choi, J.; Choliy, Y.; Zhang, X.; Emge, T. J.; Krogh-Jespersen, K.; Goldman, A. S. *J. Am. Chem. Soc.* **2009**, *131*, 15627. (c) Kundu, S.; Choi, J.; Wang, D. Y.; Choliy, Y.; Emge, T. J.; KroghJespersen, K.; Goldman, A. S. *J. Am. Chem. Soc*. **2013**, *135*, 5127. (d) Edouard, G. A.; Kelley, P.; Herbert, D. E.; Agapie, T. *Organometallics* **2015**, *34*, 5254.

7. For hydrosilane-directed benzylic C–H activation with iridium catalysis, see: Cho, S. H.; Hartwig, J. F. *J. Am. Chem. Soc*. **2013**, *135*, 8157.
8. (a) Lu, B.; Falck, J. R. *J. Org. Chem.* **2010**, *75*, 1701. (b) Cheng, C.; Simmons, E. M.; Hartwig, J. F. *Angew. Chem., Int. Ed*. **2013**, *52*, 8984.
9. Wang, N.; Chen, Z.; Wei, W.; Jiang, Z. *J. Am. Chem. Soc*. **2013**, *135*, 17060.

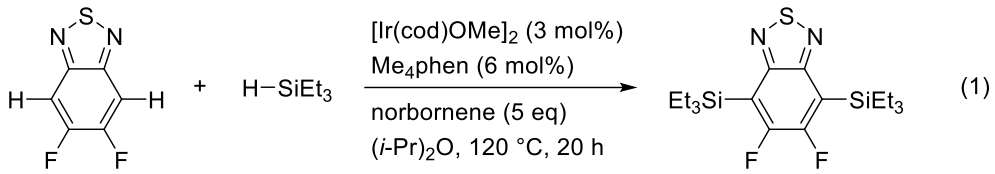
Chapter 3

Aryl(triethyl)silanes for New Entry to Stable and Readily Accessible Cross-coupling Reagents

Discussed herein is the first cross-coupling reaction of aryl(triethyl)silanes, which remained unemployed due to robust nature toward a nucleophilic activation. The author describes aryl(triethyl)silanes cross-couple with aryl iodides in the presence of copper(II) bromide as a crucial catalyst. Various types of coupling along with single coupling, double coupling, and cross-coupling polymerization will be discussed in detail.

3-1. Introduction

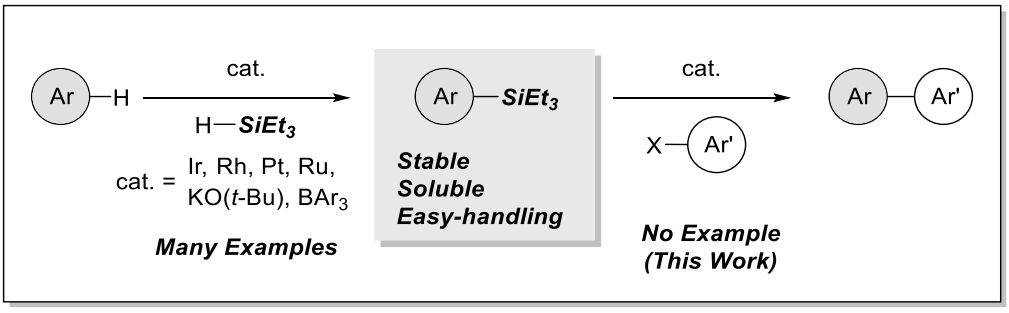
During the study described in Chapter 2, the author has attempted to silylate 5,6-difluoro-2,1,3-benzothiadiazole (**1a**) at 4 and 7 positions to prepare the corresponding bis-HOMSi reagent using hydrosilanes in excess, because the benzothiadiazole core plays a significant role in organic electronics as a π-electron acceptor.[1] All the attempts, however, failed. Nevertheless, he found Ir-catalyzed C–H silylation of **1a** took place to give desired disilylated product **3a** smoothly using triethylsilane (**2**) as the silylating agent (Eq. 1).



(1)

1a **2**, 5 eq **3a**, 94%

Aryl(triethyl)silanes apparently have ideal features in respect to stability, low toxicity, easy handling, and good solubility along with ready accessibility (Scheme 3-1). Indeed, the catalytic aryl C–H silylation with triethylsilane has been carried out by not only transition-metal catalysts including iridium but also by Lewis base, Lewis acid, and strong Brønsted acid.[2] However, cross-coupling reactions of the resulting silanes had no precedents before 2015. Except for some examples of oxidative C–H arylation using Ar–$SiMe_3$,[3] little is known about the general cross-coupling reaction of simple aryl(trialkyl)silanes with organic halides.[4] If this sort of coupling works well, silicon-based cross-coupling evolves to find wider applications. In this Chapter, the author discusses copper(II) bromide enables the fist cross-coupling reaction using Ar–$SiEt_3$ with aryl iodides.

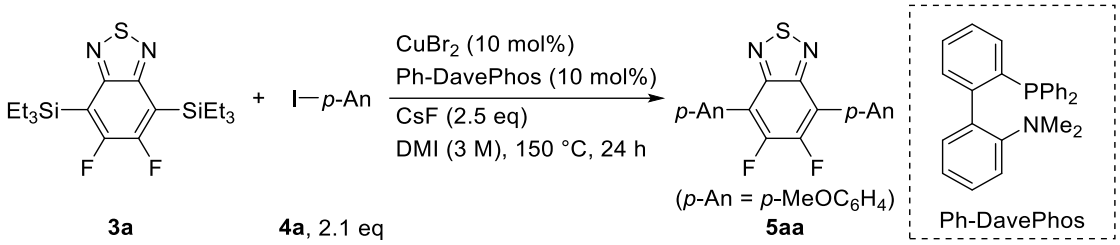


Scheme 3-1. Ideal Silicon-based Cross-coupling using Aryl(triethyl)silanes

3-2. Result and Discussion

After many experimental examinations, some of which are summarized in Table 3-1, the author finally disclosed that bis(triethylsilyl)benzothiadiazole (**3a**) reacted with 2.1 equivalents of *p*-iodoanisole (**4a**) in the presence of $CuBr_2$ (10 mol%), 2-PPh_2-2′-NMe_2-biphenyl (Ph-Davephos, 10 mol%), and CsF (2.5 eq) in 1,3-dimethylimidazolizinone (DMI, 3 M) at 150 °C for 24 h to produce doubly coupled product **5aa** in 94% yield (Table 3-1, Run 1). Although copper dichloride gave the product albeit in a slightly lower yield, such salts as cuprous iodide/bromide and cupric fluoride/acetate did not show any catalytic activity with sharp contrast to the reported Cu(I)-catalyzed silicon-based cross-coupling reactions (Runs 2–6).[5] Palladium dibenzylideneacetone, a typical cross-coupling catalyst, did not catalyze the reaction (Run 7). Effect of ligands was surveyed and various triarylphosphines including PPh_3 showed good performance independent of their electronic property (Runs 8–10). In contrast, trialkylphosphine like PCy_3 strongly inhibited the coupling. The fact that the reaction with $CuBr_2$ in the dark also gave **5aa** in a yield similar to Run 1 shows that light does not affect the present cross-coupling (Run 12). In addition to triethylsilyl, tributylsilyl and trihexylsilyl groups could be utilized for this reaction albeit it took longer reaction times, showing that alkyl chain length on silicon hardly affect the reactivity (Runs 13 and 14). The reaction using Me_2PhSi-substututed benzothiadiazole gave **5aa** in 63% yield with the generation of 4% yield of 4-methoxybiphenyl (Run 15). This fact that an electron-deficient aryl group on silicon reacts with iodoarene faster than electron-rich one contrasts to the reactivity order of normal silicon-based cross-coupling.[6] Use of F_2-benzothiadiazole containing 3,5-bis(trifluoromethyl)phenyldimethylsilyl (Me_2Ar^FSi) group generated an insoluble mixture which did not include **5aa** (Run 16).

Table 3-1. Screening the conditions for the Cross-coupling of 3a



3a **4a**, 2.1 eq **5aa**

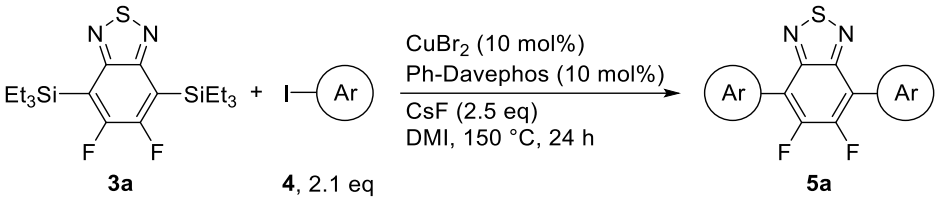
Run	Variation from the standard conditions	Yield of **5aa** /%[b]
1	none	94
2	$CuCl_2$ instead of $CuBr_2$	20[d]
3	CuF_2 instead of $CuBr_2$	3
4	$Cu(OAc)_2$ instead of $CuBr_2$	11
5	CuI instead of $CuBr_2$	<1
6	CuBr instead of $CuBr_2$	5
7	$Pd(dba)_2$ instead of $CuBr_2$	<1
8	PPh_3 instead of Ph-DavePhos	82
9	P(*p*-$MeOC_6H_4)_3$ instead of Ph-DavePhos	85
10	P(*p*-$CF_3C_6H_4)_3$ instead of Ph-DavePhos	88
11	PCy_3 instead of Ph-DavePhos	5
12	in the dark	89
13	Si(*n*-$Bu)_3$ instead of $SiEt_3$	85
14	Si(*n*-$Hex)_3$ instead of $SiEt_3$	84
15	$SiMe_2Ph$ instead of $SiEt_3$	64
16	$SiMe_2Ar^F$ instead of $SiEt_3$	<1

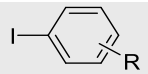
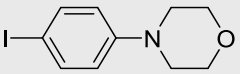
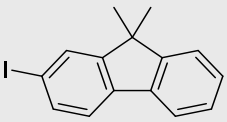
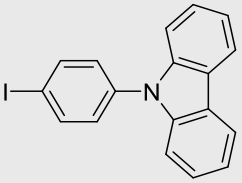
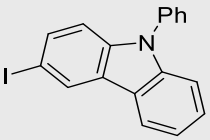
[a] Unless otherwise noted, a mixture of **3a** (1 eq), **4a** (2.1 eq), $CuBr_2$ (5 mol%), Ph-Davephos (10 mol%), and CsF (2.5 eq) in DMI was heated at 150 °C for 24 h. [b] NMR yield. [c] Isolated yield. [d] 4-(*p*-Anisyl)-5,6-F_2-benzothiadiazole was also observed in 34 % yield by ^{1}H NMR analysis. Ar^F = 3,5-$(CF_3)C_6H_3$

Various aryl iodides **4** were surveyed for the double cross-coupling reaction and the results are listed in Table 3-2. Resulting 4,7-diarylbenzothiadiazoles plays an important role as electron acceptor in organic electronics. For instance, *m*-iodoanisole (**4b**) gave **5ab** in an excellent yield (Run 1). Moderate steric hindrance in *o*-iodoanisole (**4c**) did not affect the reaction (Run 2). Selective C–I bond coupling occurred to produce **5ad**–**5af** when iodobenzene having bromine, chlorine, or fluorine at the *para*-position (**4d**–**4f**) was employed (Runs 3–5). Ethoxycarbonyl group tolerates the coupling conditions (Run 6). Triarylamine core as a strong electron donating moiety was successfully introduced to give donor-acceptor-donor type molecule **5ah** in a high yield (Run 7). Although **3a** reacted with 4-morpholino-1-iodobenzene (**4i**) to give **5ai** in a

moderate yield (< 50%). Yield of **5ai** was improved upon use of KF (2.5 eq), 18-crown-6 (2.5 eq), and CPME (Run 8). Under the alternative conditions, π-extended oligoarylenes **5aj**–**5al** were easily prepared (Runs 9–11).

Table 3-2. Scope of Aryl Iodides[a]

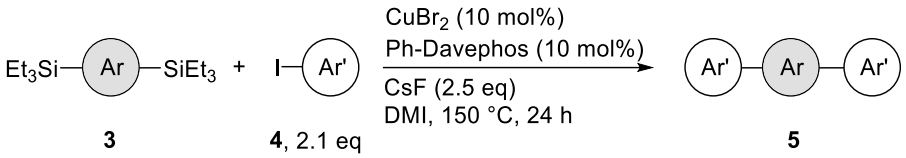


Run	Ar in **4**	Product, Yield /%[b]
		
1	**4b,** R = *m*-OMe	**5ab**, 90
2[c]	**4c,** R = *o*-OMe	**5ac**, 72
3	**4d,** R = *p*-Br	**5ad**, 91
4	**4e,** R = *p*-Cl	**5ae**, 89
5	**4f,** R = *p*-F	**5af**, 85
6	**4g,** R = *p*-CO_2Et	**5ag**, 67
7	**4h,** R = *p*-NPh_2	**5ah**, 77
8[d]	**4i,** 	**5ai**, 92
9[d]	**4j,** 	**5aj**, 92
10[d]	**4k,** 	**5ak**, 57
11[d]	**4l,** 	**5al**, 65

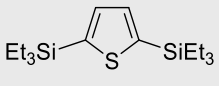
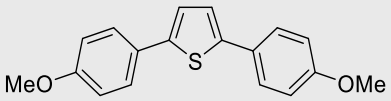
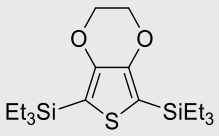
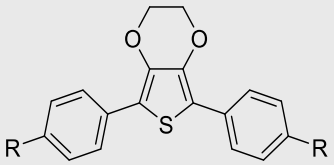
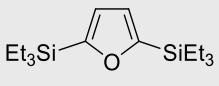
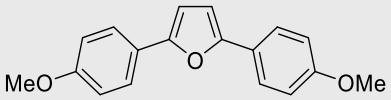
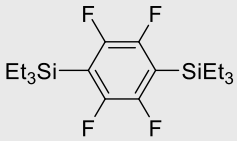
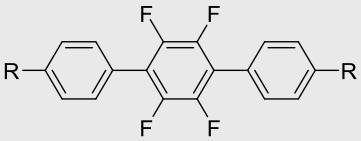
[a] Unless otherwise noted, a mixture of **3a** (1 eq), **4** (2.1 eq), $CuBr_2$ (5 mol%), Ph-DavePhos (10 mol%), and CsF (2.5 eq) in DMI was heated at 150 °C for 24 h. [b] Isolated yield. [c] Run for 2 days. [d] KF, 18-crown-6 ether, and cyclopentyl methyl ether were used instead of CsF and DMI.

Other types of bis(triethyl)silyl aromatics also smoothly coupled with aryl iodides **4** (Table 3-3). The employed disilylarenes **3b**–**3e** are available through catalytic C–H silylation as discussed in Chapter 2. Double cross-coupling reactions of **4a** with 2,5-bis($SiEt_3$)thiophene (**3b**) gave dianisylthiophene **5ba** in good yield (Run 1). Electron-rich disilylthiophene **3c** coupled with phenyl iodide with MeO, CO_2Et, or CN substituent (**4a**, **4g**, **4m**) at the *p*-position (Runs 2–4). Moreover, disilylfuran **3d** also was converted to 2,5-bis(*p*-methoxyphenyl)furan (**5da**) (Run 5). At last, tetrafluoroterpenyls **5ea** and **5eh** were successfully prepared by the reaction of 1,4-$(SiEt_3)_2C_6F_4$ (**3e**) with **4a** and **4h**, respectively (Runs 6 an 7).

Table 3-3. Scope of Bis(triethyl)silylarenes



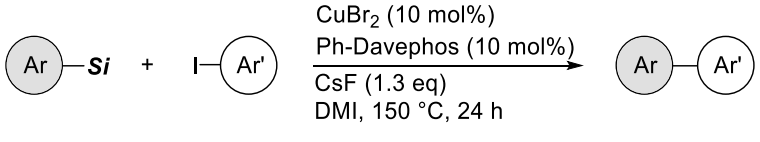
3 **4**, 2.1 eq **5**

Run	Arylsilane **3**	**4**	Product, Yield (%)[b]
1[c]	 **3b**	**4a**	 **5ba**, 70
			
2	**3c**	**4a**	**5ca** (R = OMe), 83
3	**3c**	**4g**	**5cg** (R = CO_2Et), 91
4	**3c**	**4m**	**5cm** (R = CN), 97
5	 **3d**	**4a**	 **5da**, 58
			
6	**3e**	**4a**	**5ea** (R = OMe), 74
7	**3e**	**4h**	**5eh** (R = NPh_2), 57

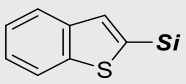
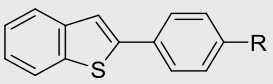
[a] Unless otherwise noted, a mixture of **3** (0.3 mmol), **4** (2.1 eq), $CuBr_2$ (5 mol%), Ph-DavePhos (10 mol%), and CsF (2.5 eq) in DMI was heated at 150 °C for 24 h. [b] Isolated yield. [c] Run at 155 °C in 2 M of DMI.

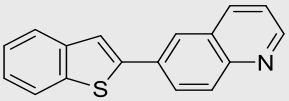
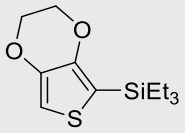
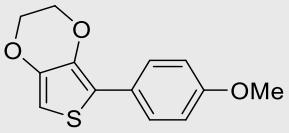
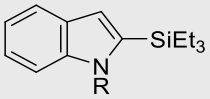
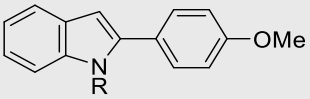
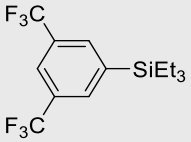
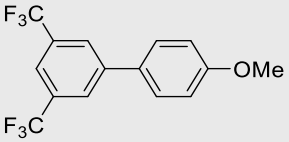
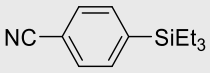
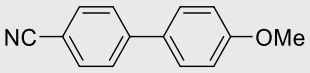
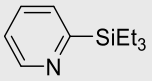
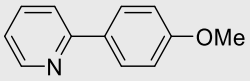
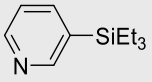
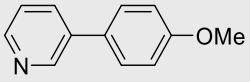
Scope of single coupling of aryl(trialkyl)silanes **6** with aryl iodides **4** was examined and the results are summarized in Table 3-4. The author first examined reactivity of 2-silylbenzothiophene with various trialkylsilyl groups including Me_3Si to $(i\text{-Pr})_3Si$ **6a**–**6a*** toward **4a,** and the desired couling reaction proceeded without any serious problems in all cases (Runs 1–4). Electron-deficient aryl iodides like 4-iodobenzonitrile (**4m**) and 6-iodoquinoline (**4n**) also were applicable to the single coupling (Runs 5 and 6). When monosilylthiophene **6b** was employed, yield of single coupling product **7ba** was only 34%, the major product turned out to be a double coupling product, namely C–H arylated product **5ca** (Run 7). This may be attributed to deprotonation of the acidic C–H bond in the thiophene core (*vide infra*).[7] Similarly, 2-silyl-*N*-methylindole **6c** gave coupled product **7ca**, but non-protected 2-silylindole **6d** produced *N*-anisylsindole **7da** as a sole coupled product via *N*-arylation (Runs 8 and 9). Moreover, 3,5-bis(trifluoromethyl)phenyl-, 4-cyanophenyl-, 2-pyridyl-, and, 3-pyridyl(triethyl)silanes gave biaryls **7ea**–**7ha** in moderate to excellent yields (Runs 10–13). It should be noted that 2-pyridyltriethylsilanes are more stable and easy-handling than 2-pyridylboronic acid or its esters, which often undergo protodeborylation quite rapidly.[8] Finally, the author applied electron-neutral arylsilanes like phenyl(trimethyl)silane and 2-naphthyl(triethyl)silane to the reaction, but no reaction occurred due to their high stability.

Table 3-4. Scope of Aryl(trialkyl)silanes

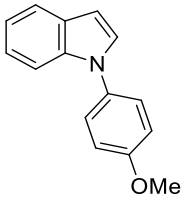


3 **4**, 1.0 eq **5**

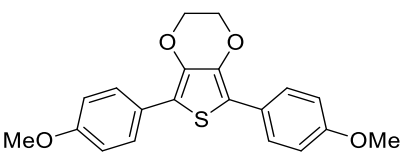
Run	Arylsilane **3**	**4**	Product, Yield (%)[b]
			
1	**6a** (***Si*** = $SiEt_3$)	**4a**	**7aa** (R = OMe), 90
2	**6a'** (***Si*** = $SiMe_3$)	**4a**	**7aa**, 93 [c]
3	**6a"** (***Si*** = $SiMe_2(t\text{-Bu})$)	**4a**	**7aa**, 95 [c]
4	**6a*** (***Si*** = $Si(i\text{-Pr})_3$)	**4a**	**7aa**, 92 [c]

5	**6a** (***Si*** = $SiEt_3$)	**4m**	**7am** (R = CN), 92
6	**6a** (***Si*** = $SiEt_3$)	**4n**	 **7an**, 98%
7	 **6b**	**4a**	 **7ba** 34% [c]
			
8	**6c** (R = Me)	**4a**	**7ca**, 52
9	**6d** (R = H)	**4a**	**7da**, 0
10	 **6e**	**4a**	 **7ea**, 56
11	 **6f**	**4a**	 **7fa**, 28
12	 **6g**	**4a**	 **7ga**, 72
13	 **6h**	**4a**	 **7ha**, 71

[a] Unless otherwise noted, a mixture of **6** (0.3 mmol), **14** (1.0 eq), $CuBr_2$ (5 mol%), Ph-DavePhos (10 mol%), and CsF (2.5 eq) in DMI was heated at 150 °C for 24 h. [b] Isolated yield. [c] NMR Yield.

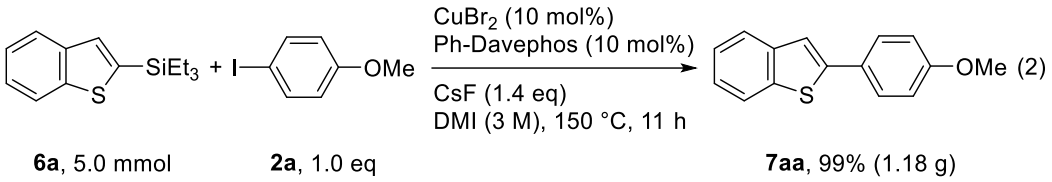


7da, 87%

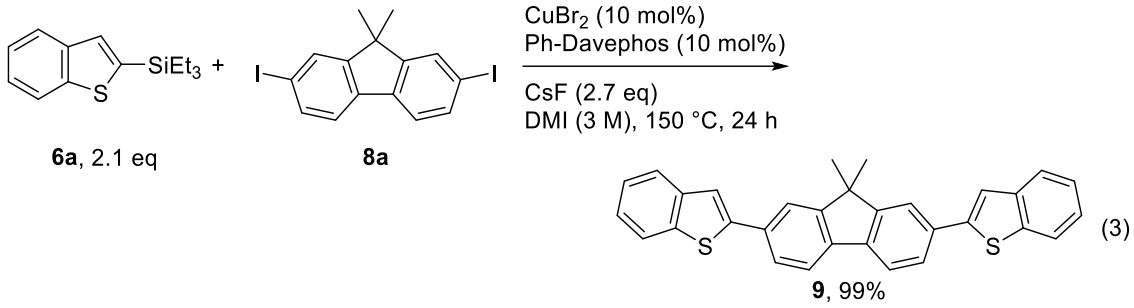


5ca, 64% [c]

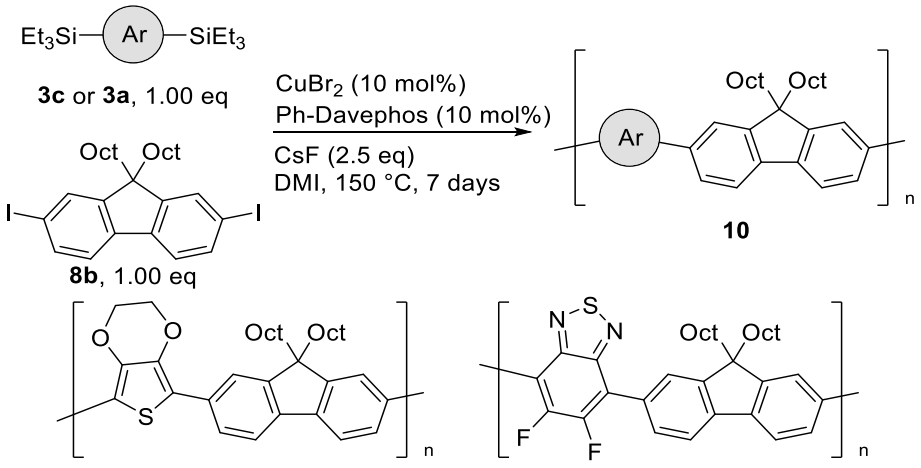
A gram-scale reaction was run without any problem: 5 mmol of **6a** coupled quantitatively with **2a** to give 1.18 g of **7aa** (Eq. 2).



Double coupling reaction using diiodoarenes **8** was next examined, and targeted product **9** was isolated in 99% yield by the reaction between **6a** and 2,7-diiodofluorene **8a** in 99% yield (Eq. 3).



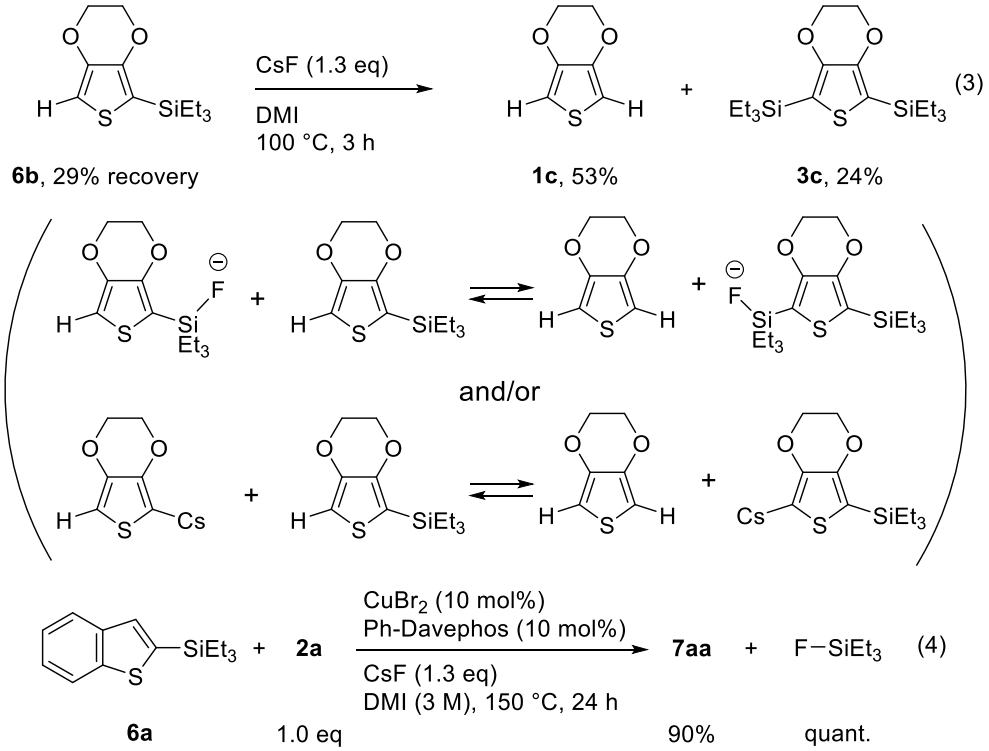
Furthermore, using bis(triethylsilyl)-type reagents **3c** or **3a**, successful cross-coupling copolymerization is achieved (Scheme 3-2). For example, co-polymerization for of dislilylthiophene **3c** and 2,7-diiodo-9,9-dioctylfluorene (**8b**) gave poly(thienylene-fluorenilene)s **11c** with n = 12, Mw = 14072, and PDI = 2.20.[9a,b] In a similar manner, **3a** and **8b** produced copolymer **11a** with n = 11, Mw = 12305, and PDI = 2.44.[9c]



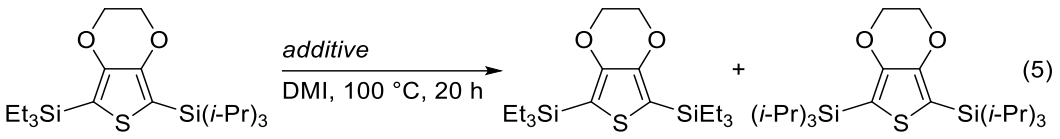
[a]Instead of CsF and DMI, the reacion was run wirh KF, 18C6, and CPME for 4 days.

Scheme 3-2. Cross-coupling Polymerization

To investigate the reaction mechanism of the present cross-coupling reaction, the author first treated monosilylthiophene **6b** with CsF and observed protodesilylated thiophene **1c** and disilylthiophene **3c** were produced (Eq. 3). This observation perhaps comprises the following steps in sequence: formation of silicates from arylsilanes and CsF, deprotonation of intermolecular thienyl C–H bond to give arylcesium and the fluorosilane, and finally nucleophilic addition of aryl cesium to the fluorosilane. He monitored the reaction of **6a** with **2a** by ^{1}H and ^{19}F NMR and detected a quantitative amount of F–$SiEt_3$ (Eq. 4).

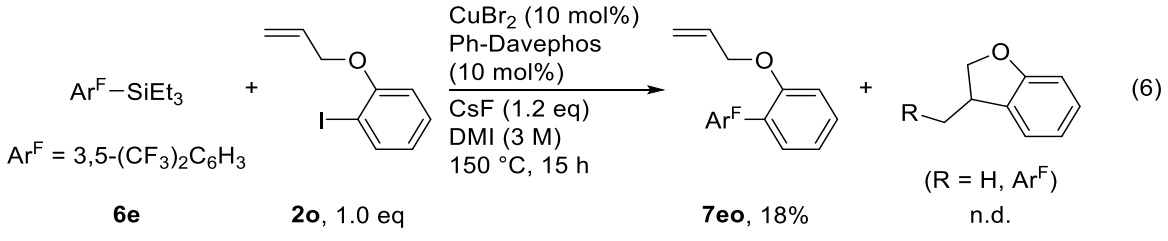


In addition, unsymmetrical disilyl thiophene **11** with CsF made silicon scrambling forming bis(triethyl)thiophene **3c** and bis(tri-*iso*-propyl)thiophene **12** (Eq. 5). This silicon scrambling could be derived from any of the following three pathway: (1) ligand exchange between the aryl(triethyl)fluorosilicate and the aryl(tri-*iso*-propyl)fluorosilicate via the aryl-bridged silicate dimer,[10] (2) ligand exchange between aryl(trialkyl)fluorosilicates and 4-coordinated aryl(trialkyl)silanes,[11] (3) reveasible nucleophilic attack by arylcesium to fluorosilanes. In any cases, arylsilicates were probably formed. Replacing CsF by CuF_2, no reaction occured. This result perhaps means direct transmetallation between arylsilanes and CuF_2 did not take place (Eq. 5).

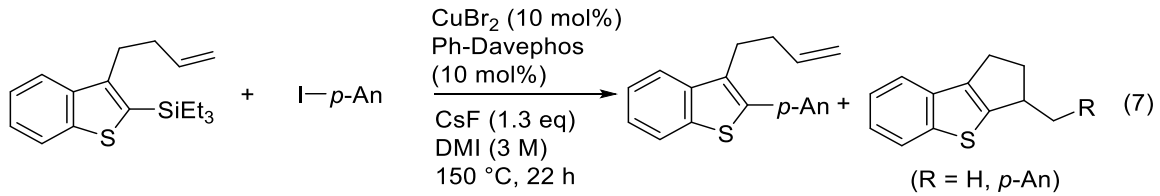


11, 37% recovery (w/ CsF, 1.3 eq) **3c**, 18% **12**, 19%
11, no conversion (w/ CuF_2, 10 mol%) **3c**, 0% **12**, 0%

Because Tamao and Kumada reported Cu(II) can be reduced to Cu(I) through a single electron transfer (SET) with hexa-coordinated silicates accompanying generation of a radical species,[12] he attempted radical clock experiments using 3-homoallyl-2-silyl-benzothiophene (**6i**), which reacted with **4a** to give only normal coupled product **7ia** (66%) without formation of the cyclized products (Eq. 6).[13] Similarly, when reaction of 2-allyloxyiodobenzene (**2o**) was conducted, what he observed is that in only normal coupled product **7eo** was produced in 18% yield (Eq. 7).[14] These facts indicate that free aryl radical intermediates are not generated from both iodoarenes and arylsilanes or the coupling involving a radical intermediate proceeds very quickly. At last, when a catalytic amount of TEMPO, galvinoxyl, or bis-3,5-tert-butyl-4-hydroxytoluene (BHT) was added to the reaction of **6e** with **4a** as a radical quencher, **7ea** was formed in a lower yield with the formation of simply hydrogenated arenes, **13** and **14** (Table 3-5). In particular, BHT mostly interfered with the reaction. Use of 2 equivalents of the quenchers, the coupling was completely suppressed in all cases.

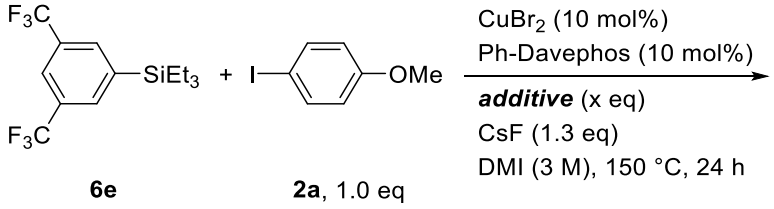


6e **2o**, 1.0 eq **7eo**, 18% n.d.

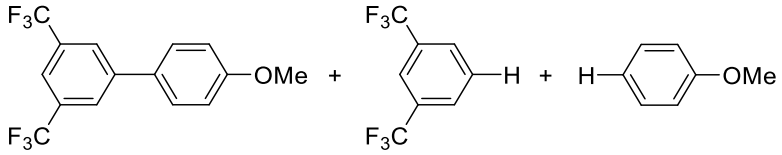


6i **2a**, 1.0 eq **7ia**, 66% n.d.

Table 3-5. Effect of Radical Scavengers [a]



6e **2a**, 1.0 eq



7ea **13** **14**

Run	Additive (eq)	NMR yield /%[b]		
		7ea	**13**	**14**
1	-	56	25	0
2	TEMPO (10 mol%)	20	16	67
3	TEMPO (2 eq)	0	60	65
4	Galvinoxyl (10 mol%)	39	9	38
5	Galvinoxyl (2 eq)	0	16	0
6	BHT (10 mol%)	2	46	77
7	BHT (2 eq)	0	45	21

[a] Unless otherwise noted, a mixture of **6e** (0.3 mmol), **2a** (1.0 eq), $CuBr_2$ (5 mol%), Ph-DavePhos (10 mol%), and CsF (2.5 eq) in DMI was heated at 150 °C for 24 h. [b] NMR Yield.

With the experimental data in hand, the author proposes a mechanism as shown in Figure 3-1. It is not probable to asume a mechanism which includes Cu(I)/Cu(III) cycle because copper(I) salts were all inacive for the reaction. The result of Run 11 in Table 3-1 indicates electron-rich aryl group is more reactive and transmetalated from silicon to palladium than electron-deficient ones. This contrasts sharply to the classical cross-coupling through transmetalation. It seems reasonable to consider that arylsilicates (**I**) is fisrt generated via the reaction of Ar^1–$SiEt_3$ with CsF. Such silicates are reportedly readily oxidized by copper(II) dihalide. Based on these things, he proposes single-electron-transfer (SET) from **I** to CuX_2 forms CuX and pentacoordinate silicate radical (**II**) and/or Ar^1 radical **III**. Oxidative addition of aryl iodides to CuX gives Ar^2–CuX_2, which couple with **II** or **III** to form coupled product Ar^1–Ar^2 and regenerate CuX_2.

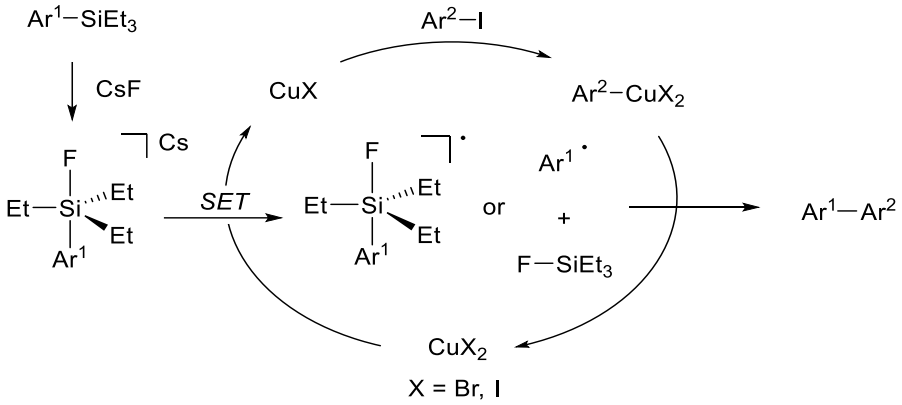


Figure 3-1. Proposed Catalytic Cycle

3-3. Conclusion

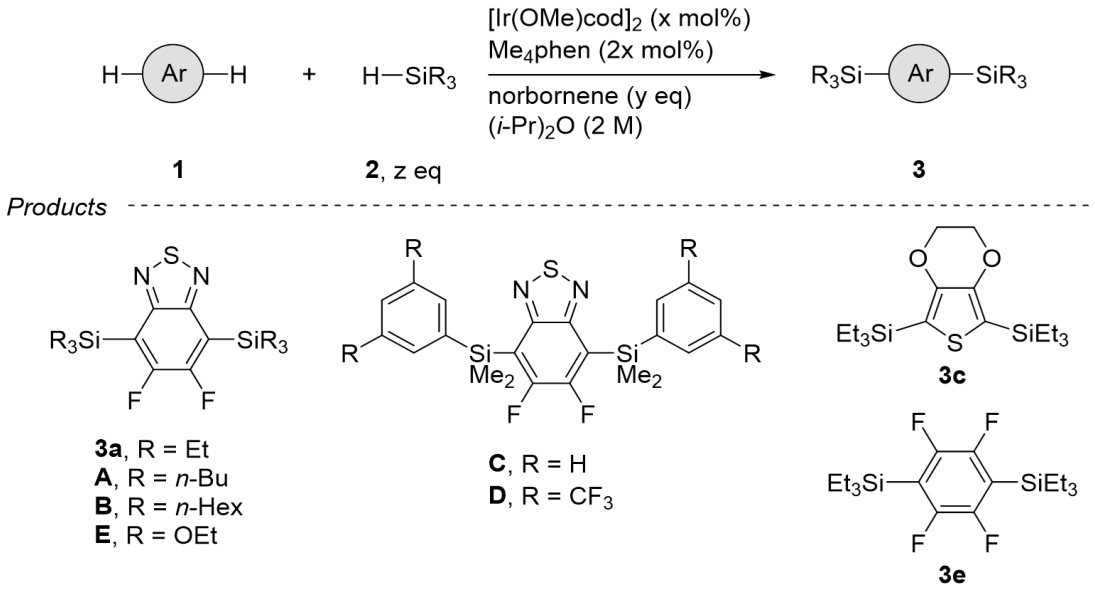
The author has unveiled aryl(triethyl)silanes undergo the cross-coupling reaction with aryl iodides enabled by copper dibromide catalyst. Although the scope of the aryl group is limited to electron-deficeint aromaatics and heteroaromatics, the present reaction can be applied single-coupling, double-coupling, and even cross-coupling polymerization. In view that aryl(triethyl)silanes are readily accessible via catalytic aryl C–H silylation, bi- and teraryls can be prepared easily through silylation the parent aromatic substrates followed by Cu(II)-catalyzed cross-coupling with diiodoarenes.

3-4. Experimental Section and Additional Information

Following information applies to Chapters 4 and 5 unless otherwise stated.

$^{13}C\{^{19}F\}$ NMR spectra in $CDCl_3$ solution were recorded with a JEOL ECA-500 spectrometer. The IR spectra were measured by Shimadzu IR Affinity+ATR. CuBr (purity, 99.999%), CuI (99.999%), $CuCl_2$ (99.999%), and $CuBr_2$ (99.999%) were purchased from Sigma-Aldrich. CuF_2 (99.5%) was purchased from Alfa Aesar. *p*-Iodoanisole and 1,3-dimethyl-2-imidazolidinone (DMI) were purchased from TCI and employed for the cross-coupling after distillation. *m*-Iodoanisole was purchased from Sigma-Aldrich and employed for the cross-coupling after distillation. CsF was purchased from TCI and employed for the cross-coupling after drying with 200 °C *in vacuo* overnight. KF was purchased from Sigma-Aldrich and employed for the cross-coupling after drying. The number-average molecular weight (M_n) and the molecular weight distribution (PDI = M_w/M_n) values of the polymers were estimated by size-exclusion chromatography (Shodex KF-803L and KF-806L) using polystyrene for calibration.

Table 3-6. Ir-catalyzed C–H Silylation of Arenes



Run	Product	x	y	z	Temp. (°C)	Time	Yield /%
1	**3a**	3	5	5	120	20 h	94
2	**A**	2.5	4	4	110	27 h	38
3	**B**	5	5	5	120	43 h	69
4	**C**	5	3	3	80	11 h	67
5	**D**	5	3	6	120	8 d	71
6	**E**	3	5	5	120	16 h	n.d.
7	**3c**	3	2	2	80	22 h	>99
8	**3e**	5	2	2	100	14 h	67

This table shows iridium-catalyzed C–H silylation to prepare the starting materials.

Preparation of 4,7-bis(triethylsilyl)-5,6-difluoro-2,1,3-benzothiadiazole (3a). — *General procedure for preparation of the bis(triethylsilyl)arenes*— Triethylsilane (**2a**, 2.3 g, 20 mmol) was added to a solution of $[Ir(OMe)cod]_2$ (80 mg, 0.12 mmol), 3,4,7,8-Me_4-phen (61 mg, 0.26 mmol), 5,6-difluorobenzo-2,1,3-thiadiazole (**1a**, 694 mg, 4.0 mmol), and norbornene (1.9 g, 20 mmol) in $(i\text{-Pr})_2O$ (2.0 mL) prepared in a 15 mL-vial in a dry box. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 120 °C for 20 h. The reaction mixture was filtered through a Celite pad, and the filtrate was concentrated *in vacuo*. The residue was purified by column chromatography (hexane as an eluent) to give 4,7-bis(triethyl- silyl)-5,6-difluoro-2,1,3-benzothiadiazole (**3a**, 1.5 g, 3.8 mmol, 94% yield) as Colorless oil, R_f 0.65 (hexane). ^1H NMR (400 MHz,

$CDCl_3$) δ 0.96-1.00 (m, 18H), 1.06-1.12 (m, 12H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 4.20, 7.60, 116.2 (dd, *J* = 11.3, 19.5 Hz), 155.0 (dd, *J* = 8.3 Hz), 157.9 (dd, *J* = 24.0, 259 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -114.9 (s, 2F). IR (neat) 2953, 2936, 2909, 2874, 1458, 1395, 1377, 1302, 1277, 1238, 1148, 1003, 976, 887, 839, 725, 712, 687, 604, 592, 463, 447 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 400 (M^+, 2), 371 (50), 344 (27), 343 (100), 315 (36), 191 (13), 105 (5), 77 (13); HRMS calcd for $C_{18}H_{31}F_2N_2SSi_2$ (M + H) 401.1715, found 401.1732.

4,7-Bis(tributylsilyl)-5,6-difluoro-2,1,3-benzothiadiazole (A). Colorless solid, R_f 0.88 (hexane), mp 48-50 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 0.88 (t, *J* = 7.2 Hz, 18H), 1.08-1.12 (m, 12H), 1.28-1.38 (m, 24H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 12.9, 13.9, 26.2, 26.8, 116.8 (dd, *J* = 10.5, 19.5 Hz), 155.0 (dd, *J* = 7.5, 8.3 Hz), 157.7 (dd, *J* = 24.0, 259 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -114.8 (s, 2F). IR (neat) 2955, 2922, 2870, 2855, 1462, 1393, 1296, 1078, 887, 783, 725, 691, 473 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 568 (M^+, 4), 511 (87), 455 (100), 399 (48), 156 (14), 77 (20); HRMS calcd for $C_{30}H_{55}F_2N_2SSi_2$ (M + H) 569.3593, found 569.3565.

4,7-Bis(trihexylsilyl)-5,6-difluoro-2,1,3-benzothiadiazole (B). Colorless oil, R_f 0.83 (hexane). ^1H NMR (400 MHz, $CDCl_3$) δ 0.84 (t, *J* = 7.2 Hz, 18H), 1.07 (t, *J* = 8.0 Hz, 12H), 1.21-1.32 (m, 48H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 13.1, 14.3, 22.7, 23.9, 31.6, 33.5, 116.9 (dd, *J* = 11.3, 19.5 Hz), 155.0 (dd, *J* = 7.6, 8.3 Hz), 157.7 (dd, *J* = 24.0, 258 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -114.8 (s, 2F). IR (neat) 2955, 2920, 2853, 1458, 1395, 1302, 1277, 1148, 839, 760, 708, 691, 594, 484, 473, 446 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 652 (100), 567 (91), 483 (13), 333 (36); HRMS calcd for $C_{42}H_{79}F_2N_2SSi_2$ (M + H) 737.5471, found 737.5456.

4,7-Bis(phenyldimethylsilyl)-5,6-difluoro-2,1,3-benzothiadiazole (C). Colorless solid, R_f 0.65 (hexane), mp 82-83 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 0.83 (s, 12H), 7.29-7.34 (m, 6H), 7.65-7.67 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -0.93— -0.89 (m), 117.1 (dd, *J* = 9.8, 18.1 Hz), 128.0, 129.6, 134.2, 137.0, 154.6 (dd, *J* = 6.8, 7.5 Hz), 157.6 (*J* = 23.3, 259 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -113.9 (s, 2F). IR (neat) 3073, 3049, 2955, 2926, 2853, 1726, 1528, 1458, 1389, 1302, 1279, 1250, 1142, 1111, 1069, 1051, 989, 837, 808, 777, 731, 694, 650, 594, 474, 446 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 440 (M^+, 74), 439 (21), 425 (12), 409 (15), 405 (9), 363 (9), 351 (17), 350 (33), 349 (100), 347 (15), 333(12), 331 (32), 329 (34), 327 (18), 267 (8), 255 (9), 253 (26), 153 (14), 139 (51), 135 (64), 91 (42),

77 (48); HRMS calcd for $C_{22}H_{23}F_2N_2SSi_2$ (M + H) 441.1089, found 441.1099.

4,7-Bis[3,5-bis(trifluoromethyl)phenyldimethylsilyl]-5,6-difluoro-2,1,3-benzothiadiazole (D). Colorless solid, R_f 0.50 (hexane), mp 78-82 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.90 (s, 12H), 7.85 (s, 2H), 8.11 (s, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ -1.34, 116.0 (dd, *J* = 9.0, 18.0 Hz), 123.5 (sept, *J* = 3.8 Hz), 123.6 (q, *J* = 275 Hz), 131.0 (q, *J* = 33 Hz), 134.08-134.13 (m), 140.3, 154.1 (dd, *J* = 6.8, 7.5 Hz), 157.6 (*J* = 23, 260 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -113.2 (s, 2F), -62.8 (2, 12F). IR (neat) 2965, 1614, 1464, 1400, 1358, 1306, 1275, 1256, 1141, 1119, 1093, 9989, 895, 647, 822, 783, 702, 681, 671, 608, 588, 503, 469, 446, 428, 417 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 643 (0.1), 485 (17), 275 (33), 271 (100), 208 (77), 194 (11), 169 (8), 151 (12), 125 (11), 81 (39), 77 (70); Anal. Calcd for $C_{26}H_{18}N_2F_{14}SSi_2$; C, 43.82; H, 2.55; N, 3.93. Found: C, 44.10; H, 2.46, N, 3.90.

2,5-Bis(triethyl)silylthiophene (3b).[2c] CAS registry number: 1085787-57-0.

2,5-Bis(triethylsilyl)-3,4-ethylenedioxythiophene (3c). Colorless oil, R_f 0.28 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.79 (qd, *J* = 1.2, 7.6 Hz, 12H), 0.98 (t, *J* = 7.6 Hz, 18H), 4.13 (s, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 4.05, 7.63, 64.4, 114.8, 148.2. IR (neat) 2952, 2936, 2909, 1541, 1460, 1418, 1352, 1238, 1167, 1090, 1057, 1005, 970, 918, 908, 835, 760, 718, 696,646, 588, 563, 544 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 370 (M^+, 31), 342 (30), 341 (100), 313 (41), 285 (48), 142 (9), 128 (10), 87 (13), 59 (10); HRMS calcd for $C_{18}H_{34}NaO_2SSi_2$ (M + Na) 393.1716, found 393.1726.

2,5-Bis(triethyl)silylfuran (3d).[2c] CAS registry number: 287398-12-3.

1,4-Bis(triethylsilyl)-2,3,5,6-tetrafluorobenzene (3e). Colorless oil, R_f 0.74 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88-1.01 (m, 30H); ^{13}C{^{19}F} NMR (126 MHz, $CDCl_3$) δ 4.14 (t, *J* = 121 Hz), 7.38 (q, *J* = 127 Hz), 116.5, 149.1; ^{19}F NMR (376 MHz, $CDCl_3$) δ -128.0 (4F). IR (neat) 2957, 2940, 2913, 2878, 1458, 1420, 1404, 1379, 1227, 1003, 966, 928, 773, 725, 696, 644, 606, 590, 461, 401 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 378 (M^+, 33), 293 (36), 237 (10), 209 (34), 169 (29), 151 (85), 115 (33), 95 (45), 87 (100), 77 (46), 59 (41).

2-Triethylsilylbenzo[*b*]thiophene (6a).[2c] CAS registry number: 1085787-64-9.
2-Triethylsilylindole (6c).[2c] CAS registry number: 957762-23-1.

3,5-Bis(trifluoromethyl)phenyltriethylsilane (6e).[15] CAS registry number: 851486-73-2.

4-Triethylsilylbenzonitrile (6d).[16] CAS registry number: 882049-63-0.

Preparation of 2-pyridyl(triethyl)silane (6g). 2-Bromopyridine (1.0 mL, 10 mmol) was dissolved in THF (30 mL) and cooled to –78 °C. After the addition of a solution of *n*-BuLi in hexane (2.7 M, 4.6 mL, 12 mmol) over 5 minutes, the resultant solution was stirred at –78 °C for 30 min. Chlorotriethylsilane (2.0 mL, 16 mmol) was added dropwise over 5 minutes and the mixture was stirred at room temperature overnight. The reaction mixture was washed with brine, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 to 92:8) as an eluent to give 2-pyridyl(triethyl)silane (**6g**, 1.8 g, 9.3 mmol, 93% yield) as Colorless oil, R_f 0.24 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.87 (q, *J* = 8.0, 9H), 0.98 (t, *J* = 8.0 Hz, 6H), 7.17 (dd, *J* = 6.4 Hz, 1H), 7.46 (d, *J* = 7.2 Hz, 1H), 7.56 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.79 (d, *J* = 4.4 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 3.04, 7.51, 122.7, 130.0, 133.7, 150.3, 166.6. IR (neat) 2953, 2935, 2910, 2873, 1574, 1558, 1456, 1416, 1237, 1136, 1003, 988, 972, 716, 617, 594 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 193 (M^+, 4), 192 (15), 166 (16), 165 (100), 164 (66), 137 (40), 136 (55), 109 (18), 108 (70), 106 (50), 80 (7); HRMS calcd for $C_{11}H_{20}NSi$ (M + H) 194.1365, found 194.1357.

Preparation of 3-pyridyl(triethyl)silane (6h). 3-Bromopyridine (0.70 mL, 7.3 mmol) was dissolved in Et_2O (20 mL) and cooled to –78 °C. After the addition of a solution of *n*-BuLi in hexane (2.7 M, 3.3 mL, 8.9 mmol) over 5 minutes, the resultant solution was stirred at –78 °C for 45 min. Chlorotriethylsilane (1.4 mL, 11 mmol) was added dropwise over 5 minutes and the mixture was stirred at room temperature overnight. The reaction mixture was washed with brine, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 → 91:9) as an eluent to give 3-pyridyl(triethyl)silane (**6h**[S7], 0.44 g, 2.3 mmol, 31% yield), CAS registry number: 123506-75-2.

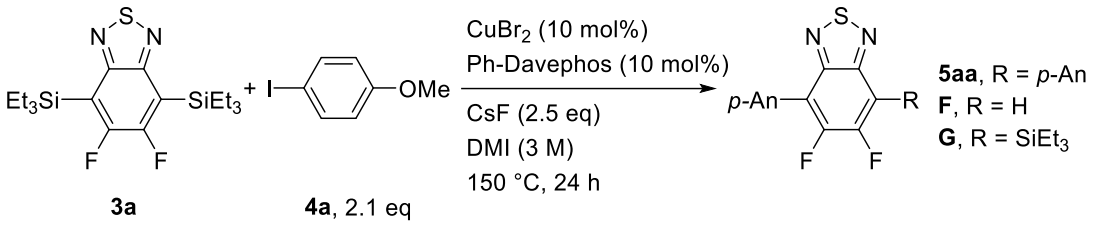
Preparation of 3-(3-buten-1-yl)-2-triethylsilylbenzo[*b*]thiophene (6i). 3-Brombenzo[*b*]thiophene (2.0 mL, 15 mmol) was dissolved in THF (30 mL) and cooled to –78 °C. After the addition of a solution of LDA in hexane (1.1 M, 15 mL, 17 mmol) over 5 minutes, the resultant solution was stirred at –78 °C for 30 min. Chlorotriethylsilane (3.4 mL, 20 mmol) was added dropwise over 5 minutes and the

mixture was stirred at room temperature overnight. The reaction mixture was washed with brine, dried over $MgSO_4$, and dried *in vacuo*. The residue was prepared by by column chromatography using hexane as an eluent to give 3-bromo-2-triethylsilylbenzo[*b*]thiophene (5.0 g, 15 mmol, >99% yield). Thus prepared bromosilylthiophene (2.0 g, 6.1 mmol) was dissolved in THF (30 mL) and cooled to –78 °C. After the addition of a solution of *n*-BuLi in hexane (2.7 M, 2.5 mL, 6.6 mmol) over 5 minutes, the resulting solution was stirred at –78 °C for 5 h. 1-Bromo-3-butene (0.90 mL, 8. 7 mmol) and sodium iodide (0.79 g, 5.3 mmol) were added and the mixture was stirred at room temperature overnight. The reaction mixture was washed with brine, dried over $MgSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography using hexane as an eluent to give **6i** (0.998 g, 3.3 mmol, 54% yield).

3-Bromo-2-triethylsilylbenzo[*b*]thiophene. Colorless oil, R_f 0.76 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.98-1.05 (m, 15 H), 7.35 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.42 (dd, *J* = 7.6, 8.0 Hz, 1H), 7.82 (d, *J* = 8.0 Hz, 1H), 7.85 (d, *J* = 7.6 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 3.80, 7.54, 115.0, 122.2, 123.1, 124.8, 125.1, 133.9, 139.9, 141.9. IR (neat) 2953, 2934, 2907, 2874, 1477, 1450, 1414, 1377, 1319, 1290, 1242, 1161, 1132, 1072, 1003, 988, 972, 937, 903, 878, 831, 750, 723, 714, 696, 610, 592, 573, 550, 534, 519, 503, 426, 401 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 328 (56), 326 (53), 299 (90), 297 (84), 271 (100), 269 (95), 243 (82), 241 (85), 161 (67), 101 (26); HRMS calcd for $C_{14}H_{19}SSiBr$ (M) 326.0160, found 326.0155.

3-(3-Butenyl)-2-triethylsilylbenzo[*b*]thiophene (6g). A pale yellow oil, R_f 0.57 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.70 (q, *J* = 8.0 Hz, 6H), 1.07 (t, *J* = 8.0 Hz, 9H), 2.42 (tddd, *J* = 1.2, 1.6, 6.8, 7.6 Hz, 2H), 3.02 (t, *J* = 7.6 Hz, 2H), 5.06 (ddt, *J* = 1.2, 1.6, 10.4 Hz, 1H), 5.11 (ddt, *J* = 1.6, 1.6, 16.8 Hz, 1H), 5.88 (ddt, *J* = 6.8, 10.4, 16.8 Hz), 7.07-7.11 (m, 1 H), 7.24-7.25 (m, 1H), 7.45 (ddd, *J* = 0.8, 0.8, 7.6 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 4.57, 7.70, 31.8, 33.2, 98.7, 103.7, 116.4, 123.2, 125.1, 127.1, 128.8, 133.3, 136.5, 140.2. IR (neat) 2953, 2934, 2911, 2874, 2155, 1639, 1582, 1458, 1431, 1416, 1337, 1296, 1267, 1234, 1215, 1163, 1126, 1098, 1069, 1038, 1005, 974, 949, 937, 914, 880, 833, 810, 719, 702, 862, 673 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 302 (M^+, 5), 273 (13), 247 (24), 217 (100), 189 (48), 163 (38), 161 (37); HRMS calcd for $C_{18}H_{27}SSi$ (M + H) 303.1603, found 303.1589.

Table 3-7. Screening of the conditions for Cu(II)-catalyzed cross-coupling reaction of **3a** with **4a**



3a **4a**, 2.1 eq

Run	variation from the standard cond.	**3aa** /%[a]	**F** /%[a]	**G** /%[a]
0	none	94[b]	6	0
1	without ligand	26	49	0
2	PPh_3 as a ligand	82	13	0
3	$P(4\text{-}MeOC_6H_4)_3$ as a ligand	85	5	0
4	$P(4\text{-}CF_3C_6H_4)_3$ as a ligand	88	9	0
5	PCy_3 as a ligand	5	13	0
6	1,10-phenanthroline as a ligand	6	6	0
7	XPhos as a ligand	2	8	0
8	Davephos as a ligand	44	31	0
10	5 mol% of $CuBr_2$ and Ph-DavePhos	82	0	0
11	3 mol% of $CuBr_2$ and Ph-DavePhos	78	6	0
12	$(2\text{-}NMe_2C_6H_4)PPh_2$ as a ligand	77	6	0
13	decane as a solvent	0.7	4	6
14	toluene as a solvent	0	2	3
15	dioxane as a solvent	0.1	2	9
16	CPME as a solvent	1	3	10
17	DMF as a solvent	28	8	16
18	DMSO as a solvent	34	12	0
19	DMA as a solvent	15	25	10
20	DMPU as a solvent	38	0	35
21	TMU as a solvent	14	8	33
22	KF as a base	4	0	0
23	KF as a base with 18-crown-6	38	14	0

[a]NMR yield. [b]Isolated yield. TMU = tetramethylurea,

This table shows the details of optimization of the reaction conditions.

Cu(II)-catalyzed cross-coupling reaction of 3a with *p*-iodoanisole (4a). *A general procedure for Cu(II)-catalyzed double cross-coupling using bis(triethylsilyl)arenes.* In a dry box, **3a** (122 mg, 0.31 mmol) was added to a solution of $CuBr_2$ (6.7 mg, 30 μmol), Ph-Davephos (11.5 mg, 30 μmol), CsF (115 mg, 0.76 mmol), and **4a** (148 mg, 0.63 mmol) in DMI (0.1 mL) prepared in a 3.5 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 150 °C for 24 h. The reaction mixture was diluted with dichloromethane and filtrated with glass filter. The filtrate was evaporated and dried *in vacuo* (1300 Pa, 170 °C). The residue was purified by column chromatography using dichloromethane as an eluent to give **4,7-Di(4-methoxyphenyl)-2,1,3-benzothiadiazole** (**5aa**, 110 mg, 0.29 mmol, 94% yield) as yellow solid, R_f 0.33 (hexane–dichloromethane = 1:1), mp 214-215 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.91 (s, 6H), 7.11 (d, ,*J* = 8.8 Hz, 4H), 7.80 (d, *J* = 8.8, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 55.9, 114.5, 118.4 (dd, *J* = 5.2, 9.8 Hz), 123.1, 132.3, 150.6 (dd, *J* = 20.3, 258 Hz), 151.4 (dd, *J* = 3.8, 3.8 Hz), 160.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ -134.1 (s, 2F). IR (neat) 2934, 2837, 1609, 1576, 1518, 1479, 1439, 1400, 1366, 1329, 1296, 1246, 1179, 1153, 1121, 1036, 1013, 893, 839, 826, 795, 787, 752, 710, 665, 602, 575, 529, 515, 449, 424 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 384 (M^+, 100), 369 (27), 341 (9), 298 (4), 297 (4), 207 (7), 192 (8), 149 (4); HRMS calcd for $C_{14}H_{20}F_2KN_2O_2S$ (M + K) 423.0381, found 423.0393.

4,7-Di(3-methoxyphenyl)-2,1,3-benzothiadiazole (5ab). Yellow solid, R_f 0.22 (hexane–dichloromethane = 1:1), mp 143-145 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.89 (s, 6H), 7.06 (dd, *J* = 2.0, 8.4 Hz, 2H), 7.36 (s, 2H), 7.39 (d, *J* = 8.0 Hz, 2H), 7.49 (dd, *J* = 8.0, 8.0 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 55.5, 114.8, 116.4, 118.9 (dd, *J* = 5.2, 10.5 Hz), 123.0, 129.7, 131.5, 150.4 (dd, *J* = 21.1, 260.0 Hz), 150.5 (dd, *J* = 3.7, 3.7 Hz), 159.7; ^{19}F NMR (376 MHz, $CDCl_3$) δ -132.5 (s, 2F). IR (neat) 2361, 2342, 2322, 1580, 1489, 1460, 1402, 1387, 1294, 1267, 1240, 1198, 1167, 1051, 1010, 851, 791, 770, 739, 692, 673, 652 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 384 (M^+, 100), 353 (10), 341 (3), 310 (4), 297 (4), 278 (3), 265 (3), 192 (5), 149 (3); HRMS calcd for $C_{20}H_{14}F_2N_2NaO_2S$ (M + Na) 407.0642, found 407.0658.

4,7-Bis(2-methoxyphenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5ac). Gray solid, R_f 0.22 (hexane–dichloromethane = 1:1), mp 206-207 ºC. ^{1}H NMR (400 MHz, $CDCl_3$, at 65 °C) δ 3.82 (s, 6H), 7.09-7.24 (m, 4H), 7.46-7.50 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$, at 65 °C) δ 56.0, 112.0, 120.9, 130.9, 132.2, Five signals derived from sp^2 carbon cannot be detected because of low intensity.; ^{19}F NMR (376 MHz, $CDCl_3$, at 65 °C) δ -128.3 (s, 2F). IR (neat) 2361, 2338, 1603, 1576, 1493, 1452, 1423, 1339, 1292, 1287, 1250, 1179,

1103, 1024, 1015, 756, 646 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 385 (22), 384 (M^+, 100), 365 (10), 364 (31), 363 (29), 353 (13), 333(12), 291 (9), 271 (8); HRMS calcd for $C_{20}H_{14}F_2N_2NaO_2S$ (M + Na) 407.0642, found 407.0634.

4,7-Di(4-chlorophenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5ae). Pale yellow solid, R_f 0.73 (hexane–dichloromethane = 1:1), mp 264-270 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 7.52-7.56 (m, 4H), 7.76-7.80 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 129.1, 132.1, 135.7, Four signals of sp^2 carbon cannot be detected because of low solubility.; ^{19}F NMR (376 MHz, $CDCl_3$) δ -132.6 (s, 2F). IR (neat) 1503, 1476, 1443, 1393, 1364, 1329, 1306, 1094, 1018, 899, 820, 768, 529 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 392 (M^+, 100), 359 (9), 358 (5), 357 (18), 325 (7), 323 (5), 322 (20), 179 (8), 161 (12); HRMS calcd for $C_{18}H_8Cl_2F_2KN_2S$ (M + K) 430.9390, found 430.9403.

4,7-Di(4-bromophenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5ad). Pale yellow solid, R_f 0.46 (hexane–dichloromethane = 2:1), mp 263-266 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 7.71-7.73 (m, 8H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 123.9, 129.1, 132.0, 132.2, Three signals of sp^2 carbon cannot be detected because of low solubility.; ^{19}F NMR (376 MHz, $CDCl_3$) δ -132.6 (s, 2F). IR (neat) 2922 2853, 1585, 1500, 1476, 1458, 1435, 1383, 1360, 1342, 1329, 1306, 1279, 1179, 1169, 1136, 1123, 1105, 1072, 1011, 961, 947, 893, 862, 847, 835, 816, , 787, 760, 727, 712, 704, 679, 662, 527, 492, 476, 438 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 484 (53), 482 (100), 480 (M^+, 52), 323 (6), 322 (28), 278 (6), 161 (21); HRMS calcd for $C_{18}H_9Br_2F_2N_2S$ (M + H) 480.8821, found 480.8804.

4,7-Di(4-fluorophenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5af). Beige solid, R_f 0.25 (hexane–ichloromethane = 4:1), mp 233-240 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 7.28 (dd, *J* = 8.8, 8.8 Hz, 4H), 7.83 (dd, *J* = 5.2, 8.4 Hz, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 115.9 (*J* = 22.5 Hz), 132.6 (*J* = 8.3 Hz). Five signals of sp^2 carbon cannot be detected because of low solubility.; ^{19}F NMR (376 MHz, $CDCl_3$) δ -111.4 (tt, *J* = 4.9, 8.6 Hz, 2F), -133.2 (s, 2F). IR (neat) 1603, 1518, 1481, 1445, 1398, 1331, 1223, 1159, 1123, 1018, 897, 829, 808, 596, 529 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 360 (M^+, 100), 341 (9), 327 (18), 179 (5); HRMS calcd for $C_{18}H_9F_4N_2S$ (M + H) 361.0423, found 361.0436.

4,7-Di(4-ethoxycarbonylphenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5ag). Ocher solid, R_f 0.12 (hexane–dichloromethane = 1:1), mp 182-184 ºC. ^1H NMR (400 MHz, $CDCl_3$) δ 1.44 (t, *J* = 7.2 Hz, 6H), 4.45 (q, *J* = 7.2 Hz, 4H), 7.92 (d, *J* = 8.4 Hz, 4H), 8.24-8.27 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 14.5, 61.4, 118.6 (dd, *J* = 4.4, 9.7 Hz), 129.8,

130.7, 131.1, 134.5, 150.2 (dd, *J* = 3.7, 3.7 Hz), 150.5 (*J* = 21.1, 261.6 Hz), 166.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ -132.0 (s, 2F). IR (neat) 1717, 1447, 1396, 1296, 1705, 845, 768, 698 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 468 (M^+, 100), 440 (7), 423 (71), 395 (19), 207 (33); HRMS calcd for $C_{24}H_{18}F_2N_2O_4S$ (M + H) 491.0853, found 491.0832.

4,7-Bis(4-diphenylaminophenyl)-2,1,3-benzothiadiazole (5ah). Red powder, R_f 0.60 (hexane–dichloromethane = 1:1), mp = 257-260 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.09 (dddd, *J* = 1.2, 1.2, 7.2, 7.2 Hz, 4H), 7.18-7.22 (m, 12H), 7.28-7.33 (m, 8H), 7.72 (d, *J* = 8.4 Hz, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 117.9 (dd, *J* = 5.3, 9.7 Hz), 121.9, 123.4, 123.8, 125.4, 129.6, 131.5, 147.4, 148.6, 150.4 (dd, *J* = 21.0, 258.6 Hz), 150.7 (dd, *J* = 4.1, 4.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ -133.8 (s, 2F). IR (neat) 1591, 1514, 1489, 1315, 1275, 754, 696, 519 cm^{-1}. HRMS calcd for $C_{42}H_{28}F_2N_4NaS$ (M + Na) 681.1900, found 681.1901.

4,7-Di(4-morpholinophenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5ai). Orange solid, R_f 0.10 (hexane–dichloromethane = 2:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.28-3.31 (m, 8H), 3.89-3.92 (m, 8H), 7.08 (d, *J* = 9.2 Hz, 4H), 7.79 (d, *J* = 8.8 Hz, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 48.7, 67.0, 115.0, 121.4, 131.6, 150.3 (dd, *J* = 20.3, 237.5 Hz), 150.9 (dd, *J* = 3.7, 3.7 Hz), 151.5. One signal of sp^2 carbon cannot be detected because of low intensity.; ^{19}F NMR (376 MHz, $CDCl_3$) δ -134.4. IR (neat) 2864, 2818, 2359, 2334, 2317, 1607, 1518, 1479, 1440, 1400, 1373, 1366, 1333, 1318, 1300, 1292, 1259, 1234, 1196, 1169, 1111, 1067, 1047, 1007, 924, 893, 853, 824, 652, 538 cm^{-1}. HRMS calcd for $C_{26}H_{25}F_2N_4O_2S$ (M + H) 495.1666, found 495.1682.

4,7-Bis(9,9'-dimethyl-9*H*-fluoren-2-yl)-5,6-difluoro-2,1,3-benzothiadiazole (5aj). Yellow solid, R_f 0.18 (hexane–dichloromethane = 2:1), mp = 262-264 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.58 (s, 12H), 7.35-7.42 (m, 4H), 7.48-7.50 (m, 2H), 7.80-7.82 (m, 2H), 7.86 (dd, *J* = 1.6, 7.6 Hz, 2H), 7.92 (s, 2H), 7.93 (d, *J* = 7.6 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 27.3, 47.2, 119.2 (dd, *J* = 5.2, 10.5 Hz), 120.1, 120.6, 122.8, 125.2, 127.3, 128.0, 129.1, 129.7, 138.7, 140.4, 150.5 (dd, *J* = 21.0, 238.2 Hz), 150.8 (dd, *J* = 3.7, 3.7 Hz), 153.8, 154.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ -133.2. IR (neat) 2957, 2918, 2860, 2360, 2342, 2313, 1447, 1398, 1387, 1360, 1325, 1290, 1277, 1015, 901, 853, 835, 756, 732 cm^{-1}. HRMS calcd for $C_{36}H_{27}F_2N_2S$ (M + H) 557.1863, found 557.1876.

4,7-Bis(9*H*-carbazol-9-ylphenyl)-2,1,3-benzothiadiazole (5ak). Yellow powder, R_f 0.26 (hexane–dichloromethane = 4:1), mp = >280 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35

(ddd, *J* = 0.8, 7.4, 7.4 Hz, 4H), 7.48 (ddd, *J* = 1.2, 7.4, 7.4 Hz, 4H), 7.62 (d, *J* = 8.4 Hz, 4H), 7.84 (d, *J* = 8.4 Hz, 4H), 8.16 (d, *J* = 8.4 Hz, 4H), 8.19 (d, *J* = 7.6 Hz, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) All signals cannot be detected because of extremely low solubility.; ^{19}F NMR (376 MHz, $CDCl_3$) δ -132.5 (s, 2F). IR (neat) 1598, 1520, 1477, 1441, 1400, 1362, 1337, 1319, 1223, 1173, 1013, 829, 746, 723, 746, 723, 712, 621, 567, 534, 527, 473, 428, 407 cm^{-1}. HRMS calcd for $C_{42}H_{25}F_2KN_4S$ (M + H) 655.1768, found 655.1762.

4,7-Bis(9,9'-phenylcarbazole-3-yl)-5,6-difluoro-2,1,3-benzothiadiazole (5al). orange powder, R_f 0.48 (hexane–dichloromethane = 1:1), mp = 247-250 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (ddd, *J* = 2.4, 2.4, 2.4 Hz, 2H), 7.46 (d, *J* = 0.8 Hz, 2H), 7.47 (dd, *J* = 0.8, 2.4 Hz, 2H), 7.50-7.54 (m, 2H), 7.61 (dd, *J* = 0.8, 8.4 Hz, 2H), 7.62-7.68 (m, 8H), 7.92 (dd, *J* = 1.6, 8.4 Hz, 2H), 8.23 (ddd, *J* = 1.2, 1.2, 7.6 Hz, 2H), 8.65 (d, *J* = 1.2 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) All signals cannot be detected because of extremely low solubility.; ^{19}F NMR (376 MHz, $CDCl_3$) δ -134.2 (s, 2F). IR (neat) 1599, 1504, 1412, 1360, 1294, 1229, 800, 750, 739, 731, 696 cm^{-1}. HRMS calcd for $C_{42}H_{24}F_2KN_4S$ (M + K) 693.1327, found 693.1295.

2,5-Di(4-methoxyphenyl)thiophene (5ba).[17] CAS registry number 55827-09-3.

2,5-Di(4-methoxyphenyl)-3,4-ethylenedioxythiophene (5ca).[18] CAS registry number 925674-63-1.

2,5-Di(4-cyanophenyl)-3,4-ethylenedioxythiophene (5cm).[19] CAS registry number 1269767-24-9.

2,5-Di(4-methoxyphenyl)furan (5da).[20] CAS registry number 1230-48-4.

1,2,4,5-Tetrafluoro-3,6-di(4-methoxyphenyl)benzene (5ea).[21] CAS registry number 154129-35-8.

1,2,4,5-Tetrafluoro-3,6-di(4-diphenylaminophenyl)benzene (5eh).[22] CAS registry number 1572929-85-1.

2,5-Di(4-ethoxycarbonylphenyl)-3,4-ethylenedioxythiophene (5cg). Orange solid, R_f 0.14 (hexane–dichloromethane = 1:1), mp = 162-168 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.43 (t, *J* = 7.2 Hz, 6H), 4.40 (q, *J* = 7.2 Hz, 4H), 4.44 (s, 4H), 7.83-7.86 (m, 4H), 8.04-8.08 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 14.5, 61.1, 64.7, 116.0, 125.7, 128.4, 130.1, 137.1, 140.1, 166.5. IR (neat) 2984, 1703, 1601, 1584, 1520, 1481, 1439, 1406, 1367, 1269, 1184, 1128, 1105, 1078, 1028, 974, 910, 851, 768, 696 cm^{-1}. HRMS calcd for $C_{24}H_{22}NaO_6S$ (M + Na) 461.1035, found 461.1020.

Cu(II)-catalyzed cross-coupling reaction of 2-(triethylsilyl)benzo[*b*]thiophene (6a) with *p*-iodoanisole (4a). —G*eneral procedure for the Cu(II)-catalyzed single cross-coupling using aryltriethylsilanes*— In a dry box, **6a** (74 mg, 0.30 mmol) was added to a solution of $CuBr_2$ (7.4 mg, 33 □mol), Ph-Davephos (12 mg, 33□□mol), CsF (60 mg, 0.39 mmol), and **4a** (73 mg, 0.31 mmol) in DMI (0.1 mL) prepared in a 3.5 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 150 °C for 24 h. The reaction mixture was filtrated through Celite and the filtrate was dried *in vacuo*. **2-(4-Methoxyphenyl)benzo[*b*]thiophene (7aa)** was obtained in 90% yield (64 mg, 0.27 mmol) by washing with hexane and diethylether. **CAS registry number: 27884-09-9.**[23] ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.94–6.96 (m, sH), 7.28 (ddd, ,*J* = 3.6, 8.0, 8.0 Hz, 1H), 7.33 (ddd, *J* = 4.8, 7.2, 7.2 Hz, 1H), 7.43 (s, 1H), 7.63–7.65 (m, 2H), 7.74 (d, *J* = 7.2 Hz, 1H), 7.80 (d, *J* = 8.0, 1H)

Gram-scale synthesis of 7aa. In a dry box, **6a** (1.23 g, 5.0 mmol) was added to a solution of $CuBr_2$ (112 mg, 0.50 mol), Ph-Davephos (191 mg, 0.50□mol), CsF (980 mg, 6.5 mmol), and **4a** (1.17 g, 5.0 mmol) in DMI (1.6 mL) prepared in a 15 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 150 °C for 24 h. The reaction mixture was diluted with DMI and dichloromethane, washed with water, dried over $MgSO_4$, evaporated, and dried *in vacuo* (100 °C, 1300 Pa). The desired product **7aa** was obtained in 99% yield (1.18 g, 4.9 mmol) by washing with hexane and diethyl ether.

[S18]

2-(4-Cyanophenyl)benzo[*b*]thiophene (7am).[24] CAS registry number: 132932-64-0.

2-(4-Methoxyphenyl)indole (7ba).[25] CAS registry number 5784-95-2.

3,5-Bis(trifluoromethyl)-4'-methoxybiphenyl (7ca).[26] CAS registry number 460743-63-9.

4-Cyano-4'-methoxybiphenyl (7da).[27] CAS registry number 58743-77-4.

2-(4-Methoxyphenyl)pyridine (7ea).[28] CAS registry number 5957-90-4.

3-(4-Methoxyphenyl)pyridine (7fa).[29] CAS registry number 5958-02-1.

6-(Benzo[*b*]thien-2-yl)-quinoline (7an). Pale yellow solid, R_f 0.07 (hexane–dichloromethane = 1:1), mp = 163-171 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34-7.41 (m, 2H), 7.45 (dd, *J* = 4.4, 8.4 Hz, 1H), 7.71 (s, 1H), 7.82-7.84 (m, 1H), 7.86-7.88 (m, 1H), 8.10-8.12 (m, 2H), 8.15-8.17 (m, 1H), 8.21 (dd, *J* = 0.4, 8.0 Hz, 1H), 8.92 (dd, *J* = 1.6, 8.4 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 120.8, 122.0, 122.5, 124.0, 124.87, 124.90, 125.1, 128.1, 128.6, 130.3, 132.6, 136.3, 139.8, 140.8, 143.3, 148.2, 150.8. IR (neat) 1589, 1495, 1450, 1347, 1335, 1119, 876, 826, 741, 725 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 261 (M^+,

100), 229 (3), 216 (6), 130 (10);HRMS calcd for $C_{17}H_{12}NS$ (M + H) 262.0690, found 262.0678.

Cross-coupling reaction of 6a with 2,7-diiodo-9,9-dimethylfluorene (8). In a dry box, **6a** (157 mg, 0.63 mmol) was added to a solution of $CuBr_2$ (6.7 mg, 30 μmol), Ph-Davephos (11.3 mg, 30 μmol), CsF (122 mg, 0.81 mmol), and **8** (133 mg, 0.30 mmol) in DMI (0.1 mL) prepared in a 3.5 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 150 °C for 24 h. The reaction mixture was diluted with dichloromethane and filtrated through glass filter. The filtrate was evaporated and dried *in vacuo* (1300 Pa, 130 °C). **2,7-Bis(6-benzo[*b*]thien-2-yl)-9,9-dimethylfluorene (9)** was obtained in 99% yield (136 mg, 0.297 mmol) by washing with diethylether. **CAS registry number 1217979-14-0.**[30] ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.62 (s, 6H), 7.31–7.39 (m, 4H), 7.63 (d, *J* = 0.4 Hz, 2H), 7.72–7.81 (m, 8H), 7.84–7.87 (m, 2H)

Cross-coupling polymerization reaction of 3c with 2,7-diiodo-9,9-dimethylfluorene (8b). —G*eneral procedure for the Cu(II)-catalyzed cross-coupling polymerization*—In a dry box, **3c** (112 mg, 0.30 mmol) was added to a solution of $CuBr_2$ (6.6 mg, 28 μmol), Ph-Davephos (11.6 mg, 30 μmol), CsF (115 mg, 0.76 mmol), and **8b** (195 mg, 0.303 mmol) in DMI (0.1 mL) prepared in a 3.5 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 150 °C for 7 days. The reaction mixture was diluted with dichloromethane and filtrated through glass filter. **Poly[(2,3-dihydrothieno[3,4-*b*]-1,4-dioxin-5,7-diyl)(9,9-dioctyl-9*H*-fluorene-2,7-diyl)] (10c)**[9a] was obtained in 51% yield as orange solid with n = 12, M_w = 14072, PDI = 2.20 after several precipitations using CH_2Cl_2, Et_2O, and MeOH followed by GPC analysis. CAS registry number: 287924-60-1.

Poly[(5,6-difluoro-2,1,3-benzothiadiazole-4,7-diyl) (9,9-dioctyl-9H-fluorene-2,7-diyl)] (10a)[9c] CAS Registry Number 1630825-26-1

The reaction of 2-(triethylsilyl)-3,4-ethylenedioxythiophene (6b) with CsF.

In a glove-box under argon atmosphere, **6b** (77.0 mg, 0.300 mmol) was added to a mixture of CsF (59.4 mg, 0.391 mmol) and DMI (0.15 mL) prepared in a 3 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 100 °C for 3 h. The resulting mixture was analyzed by ^{1}H NMR and products **1c** and **3c** were detected in 53% and 24% yields, respectively.

3,4-Ethylenedioxythiophene (1c).[31] CAS registry number: 126213-50-1.

Reaction of 2-triethylsilyl-5-tri-*iso*-propyl-3,4-ethylenedioxythiophene (11) with cesium fluoride.. In a glove box, a solution of **11** (82 mg, 0.20 mmol) and cesium fluoride (41 mg, 0.27 mmol) in DMI (0.10 mL) was prepared in a 3 mL-vial in a dry box. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 100 °C for 20 h. The reaction mixture was filtered through Celite and silica-gel, and the filtrate was dried *in vacuo*. The desired product **4a** and **12** were obtained in 18% and 19% yield by GPC, respectively and 37% of the starting material **11** was recovered. The yields of the products in Run 2 were determined by GC analysis. The products in Runs 3, 4, 5 were isolated by neutral silica-gel column chromatography to determine the yields.

2-Tri-*iso*-propylsilyl-5-triethylsilyl-3,4-ethylenedioxythiophene (11). This compound was prepared by the similar procedure for **1d** using chloro(tri-iso-propyl)silane instead of iodomethane as off-white solid, R_f 0.42 (hexane). mp = 58-60 °C ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.80 (q, *J* = 8.0 Hz, 6H), 0.98 (t, *J* = 8.0 Hz, 9H), 1.08 (d, *J* = 7.6 Hz, 18H), 1.37 (sep, *J* = 7.2 Hz, 3 H), 4.10-4.13 (m, 4H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 4.05, 7.63, 12.0, 18.9, 64.3, 64.4, 113.1, 114.9, 148.0, 148.2. IR (neat) 2952, 2863, 1428, 1416, 1352, 1165, 1088, 1051, 1018, 995, 983, 964, 920, 882, 757, 734, 723, 698, 674, 649, 575, 548, 541, 506, 459 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 412 (M^+, 13), 369 (100), 327 (50), 299 (37), 285 (32), 142 (49), 128 (14), 87 (89); HRMS (DART) calcd for $C_{21}H_{41}O_2SSi_2$ (M + H) 413.2366, found 413.2370.

2,5-Bis(tri-*iso*-propylsilyl)-3,4-ethylenedioxythiophene (12). Colorless solid, R_f 0.48 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.09 (d, *J* = 7.6 Hz, 36H), 1.38 (sep, *J* = 7.2 Hz, 6H), 4.10 (s, 4H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 12.0, 18.9, 64.3, 113.2, 148.1. IR (neat) 2941, 2861, 1461, 1427, 1416, 1365, 1349, 1164, 1088, 1053, 1017, 992, 962, 921, 884, 754, 674, 646, 574, 549, 539, 504 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 454 (M^+, 12), 411 (100), 369 (31), 341 (27), 327 (25), 128 (47); HRMS (dart) calcd for $C_{24}H_{47}O_2SSi_2$ (M + H) 455.2835, found 455.2840.

Radical clock experiment using 2-allyloxyiodobenzene (4o). *General procedure for the radical clock experiments.* In a dry box, **6c** (100 mg, 0.30 mmol) was added to a solution of $CuBr_2$ (6.8 mg, 30 μmol), Ph-Davephos (12 mg, 32 μmol), CsF (57 mg, 0.37 mmol), and 2-allyloxyiodobenzene (**4o**, 83 mg, 0.32 mmol) in DMI (0.1 mL) prepared in a 3.5 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 150 °C for 15 h. The reaction mixture was analyzed by GC-MS and ^{1}H NMR after filtration with through a Celite pad. Product **7eo** was isolated in 18% yield (18 mg, 0.053 mmol) by column chromatography using hexane as an eluent

followed by high performance liquid chromatography. **3,5-Bis(trifluoromethyl)-2'-allyloxy-biphenyl (7eo).** Colorless oil, R_f 0.30 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.57 (ddd, *J* = 1.6, 1.6, 4.8 Hz, 2H), 5.24 (ddt, *J* = 1.6, 1.6, 10.4 Hz, 1H), 5.32 (ddt, *J* = 1.6, 1.6, 17.2 Hz, 1H), 5.98 (ddt, *J* = 4.8, 10.8, 17.2 Hz, 1H), 7.02 (dd, *J* = 0.8, 8.4 Hz, 1 H), 7.09 (ddd, *J* = 0.8, 7.6, 7.6 Hz, 1H), 7.35-7.41 (m, 2H), 7.82 (s, 1H), 8.04 (s, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 69.1, 112.9, 117.5, 120.7 (sep, *J* = 3.7 Hz), 121.6, 123.7 (q, *J* = 274 Hz), 127.8, 129.9-130.0 (m), 130.3, 130.8, 131.3 (q, *J* = 33 Hz), 132.6, 140.5, 155.4; ^{19}F NMR (376 MHz, CDCl3) δ -62.9 (s, 6F). IR (neat) 1601, 1582, 1499, 1468, 1460, 1433, 1425, 1379, 1275, 1256, 1229, 1171, 1125, 1107, 1060, 1042, 1018, 995, 928, 897, 843, 752, 721, 706, 681, 623, 441, 412 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 346 (M^+, 100), 331 (14), 317 (6), 305 (14), 285 (38), 236 (37), 217 (15), 188 (8); HRMS calcd for $C_{17}H_{13}F_6O$ (M + H) 347.0871, found 347.0865.

3-(3-Butenyl)-(4-methoxyphenyl)benzo[*b*]thiophene (7ia). Colorless oil, R_f 0.45 (hexane–ethyl acetate = 19:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.45 (tddd, *J* = 1.2, 1.6, 6.8, 7.6 Hz, 2H), 3.05 (t, *J* = 7.6 Hz, 3H), 3.82 (s, 3H), 5.06 (ddt, *J* = 1.2, 1.6, 10.4 Hz, 1H), 5.12 (ddt, *J* = 1.6, 1.6, 17.2 Hz, 1H), 5.90 (ddt, *J* = 6.8, 10.0, 17.2 Hz, 1H), 6.86-6.90 (m, 2 H), 7.11-7.15 (m, 1H), 7.23-7.29 (m, 2H), 7.48 (dd, *J* = 1.6, 8.0 Hz, 1H), 7.50-7.53 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 31.8, 33.2, 55.4, 86.1, 95.7, 114.1, 115.4, 116.4, 123.4, 125.2, 127.0, 128.4, 132.5, 133.2, 136.5, 139.5, 159.8. IR (neat) 2955, 2928, 2836, 2210, 1639, 1604, 1582, 1568, 1508, 1460, 1431, 1416, 1302, 1287, 1246, 1173, 1148, 1125, 1105, 1065, 1028, 993, 955, 912, 854, 829, 810, 785, 748, 719, 698, 650, 640, 617, 538, 529, 498 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 294 (M^+, 57), 279 (18), 266 (12), 253 (100), 240 (60), 221 (54), 209 (32), 195 (32), 165 (20), 152 (25); HRMS calcd for $C_{19}H_{19}OS$ (M + H) 295.1157, found 295.1145.

3-5. References and Notes

1. For recent reports on the utility of 5,6-difluoro-2,1,3-benzothiadiazole, see: (a) Kang, H.; Uddin, M. A.; Lee, C.; Kim, K.-H.; Nguyen, T. L.; Lee, W.; Li, Y.; Wang, C.; Woo, H. Y.; Kim, B. J. *J. Am. Chem. Soc.* **2015**, *137*, 2359. (b) Hu, H.; Jiang, K.; Yang, G.; Liu, J.; Li, Z.; Lin, H.; Liu, Y.; Zhao, J.; Zhang, J; Huang, F.; Qu, Y.; Ma, W.; Yan, H. *J. Am. Chem. Soc*. **2015**, *137*, 14149. (c) Yau, C. P.; Fei, Z. P.; Ashraf, R. S.; Shahid, M.; Watkins, S. E.; Pattanasattayavong, P.; Anthopoulos, T. D.; Gregoriou, V. G.; Chochos, C. L.; Heeney, M. *Adv. Funct. Mater*. **2014**, *24*, 678. (d) Wang, N.; Chen, Z.; Wei, W.; Jiang, Z. *J. Am. Chem. Soc.* **2013**, *135*, 17060. (e) Zhou, H.; Yang, L.; Stuart, A. C.; Price, S. C.; Liu, S.; You, W. *Angew. Chem. Int. Ed*. **2011**, *50*, 2995.
2. For recent reviews, see: (a) Cheng, C.; Hartwig, J. F. *Chem. Rev*. **2015**, *115*, 8946. (b) Bähr, S.; Oestreich, M. *Angew. Chem. Int. Ed*. **2017**, *56*, 52. For selected examples of transition-metal-catalyzed intermolecular dehydrogenative silylation of arenes without directing groups, see: (a) Tsukada, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 5022. (b) Murata, M.; Fukuyama, N.; Wada, J.; Watanabe, S.; Masuda, Y. *Chem. Lett.* **2007**, *36*, 910. (c) Lu, B.; Falck, J. R. *Angew. Chem. Int. Ed.* **2008**, *47*, 7508. (d) Ishiyama, T.; Saiki, T.; Kishida, E.; Sasaki, I.; Ito, H.; Miyaura, N. *Org. Biomol. Chem*. **2013**, *11*, 8162. (e) Klare, H. F. T.; Oestreich, M.; Ito, J.-i.; Nishiyama, H.; Ohki, Y.; Tatsumi, K. *J. Am. Chem. Soc*. **2011**, *133*, 3312. (f) Cheng, C.; Hartwig, J. F. Science **2014**, 343, 853. (g) Cheng, C.; Hartwig, J. F. *J. Am. Chem. Soc*. **2015**, *137*, 592. (h) Murai, M.; Takami, K.; Takeshima, H.; Takai, K. *Org. Lett.* **2015**, *17*, 1798. (i) Murai, M.; Takami, K.; Takai, K. *Chem. Eur. J.* **2015**, *21*, 4566. (j) Yin, Q.; Klare, H. F. T.; Oestreich, M. *Angew. Chem. Int. Ed.* **2016**, *55*, 3204. (k) Lee, K.-S.; Katsoulis, D.; Choi, J. *ACS Catal*. **2016**, *6*, 1493. (l) Fang, H.; Guo, L.; Zhang, Y.; Yao, W.; Huang, Z. *Org. Lett*. **2016**, *18*, 5624. For selected examples of metal-free catalytic intermolecular dehydrogenative silylation of arenes without directing groups, see: (m) Toutov, A. A.; Liu, W.-B.; Betz, K. N.; Fedorov, A.; Stoltz, B. M.; Grubbs, R. H. *Nature* **2015**, *518*, 80. n) Ma, Y.; Wang, B.; Zhang, L.; Hou, Z. *J. Am. Chem. Soc*. **2016**, *138*, 3663. o) Chen, Q.-A.; Klare, H. F. T.; Oestreich, M. *J. Am. Chem. Soc*. **2016**, *138*, 7868.
3. Aryl(trimethyl)silanes and 9,9-dimethyl-9-silafluorenes are reported to undergo oxidant-mediated aryl C–H arylation under transition-metal catalysis see: (a) Funaki, K.; Kawai, H.; Sato, T.; Oi, S. *Chem. Lett.* **2011**, *40*, 1050. (b) Kawasumi,

K.;Mochida, K.; Kajino, T.; Segawa, Y.; Itami, K. *Org. Lett*. **2011**, *14*, 418 (c) Funaki, K.; Sato, T.; Oi, S. *Org. Lett.* **2012**, *14*, 6186. (d) L. T.; Lloyd-Jones, G. C.; Russell, C. A. *Science* **2012**, *337*, 1644. (e) Ball, L. T.; Lloyd-Jones, G. C.; Russell, C. A. *J. Am. Chem. Soc.* **2014**, 136, 254 (f) Ozaki, K.; Kawasumi, K.; Shibata, M.; Ito, H.; Itami, K. *Nat. Commun.* **2015**, *6*, 6251. Also, publications on reactions of gold-catalyzed aryl(trimethyl)silanes with aryldiazonoum salts have emerged very recently. (g) Chakrabarty, I.; Akram, M. O.; Biswasc, S.; Patil, N. T. *Chem. Commun*. **2018**, *54*, 7223. (h) Xie, J.; Sekine, K.; Witzel, S.; Krmer, P.; Rudolph, M.; Rominger, F.; Hashmi, A. S. K. *Angew. Chem. Int. Ed*. DOI: 10.1002/ange.201806427

4. 2-Pyridyl–$SiMe_3$ and 2-benzofuryl–$SiMe_3$ couple with aryl iodides in the presence of a palladium catalyst and a stoichiometric transition-metal promoter, see: (a) Pierrat, P.; Gros, P.; Fort, Y. *Org. Lett*. **2005**, *7*, 697. (b) Napier, S.; Marcuccio, S. M.; Tye, H.; Whittaker, M. *Tetrahedron Lett*. **2008**, *49*, 6314. (c) Matsuda, S.; Takahashi, M.; Monguchi, D.; Mori, A. *Synlett* **2009**, 1941. Also, 8-hydroxy-2-naphthyl–$SiMe_2$(*t*-Bu) reacts with aryl iodides under Pd catalysis assisted by the proximal OH group, see: (d) Akai, S.; Ikawa, T.; Takayanagi, S.; Morikawa, Y.; Mohri, S.; Tsubakiyama, M.; Egi, M.; Wada, Y.; Kita, Y. *Angew. Chem. Int. Ed.* **2008**, *47*, 7673.
5. (a) Ito, H.; Sensui, H.; Arimoto, K. Miura, K.; Hosomi, A. *Chem. Lett.* **1997**, 639. (b) Gurung, S. K.; Thapa, S.; Vangala, A. S.; Giri, R. *Org. Lett.* **2013**, *15*, 5378.
6. Hatanaka Y., Goda, K.-i. Okahara, Y. Hiyama, T. *Tetrahedron* **1994**, *50*, 8301.
7. For similar phenomena using silylamines and fluoride salts, see: (a) Yokozawa, T.; Asai, T.; Sugi, R.; Ishigooka, S.; Hiraoka, S. *J. Am. Chem. Soc.* **2000**, *122*, 8313. (b) Minami, Y.; Komiyama, T.; Shimizu, K.; Hiyama, T.; Goto, O.; Ikehira, H. *Bull. Chem. Soc. Jpn.* **2015**, *88*, 1437. (c) Minami, Y.; Komiyama, T.; Shimizu, K.; Uno, S.; Hiyama, T.; Goto, O.; Ikehira, H. *Synlett* **2017**, *28*, 2407.
8. (a) Knapp, D. M.; Gillis, E. P.; Burke, M. D. *J. Am. Chem. Soc.* **2009**, *131*, 6961; (b) Dick, G. R. Knapp, D. M. Gillis, E. P. Burke, M. D. *Org. Lett.* **2010**, *12*, 2314; (c) Dick, G. R. Woerly, E. M. Burke, M. D. *Angew. Chem. Int. Ed*. **2012**, *51*, 2667.
9. (a) Aubert, P. -H.; Knipper,M.; Groenendaal, L.; Lutsen, L.; Manca, J.; Vanderzande, D. *Macromolecules* **2004**, *37*, 4087. (b) Narayanan, S.; Abbas, A.; Raghunathan, S. P.; Sreekumar, K.; Kartha, C. S.; Joseph, R. *RSC Adv.* **2015**, *5*, 8657. (c) Zhang, X.; Gao, Y.; Li, S.; Shi, X.; Geng, Y.; Wang, F. *J. Polym. Sci. Pol. Chem.* **2014**, *52*, 2367.
10. The formation of the bridged dimer may be attributed to the high Lewis acidity of pentacoordinated silicates. It seems reasonable to assume that the electron-withdrawing aryl groups are located on the bridge sites. See: (a) Frolov, Y. L. Shevchenko, S. G. Voronkov, M. G. *J. Organomet. Chem.* **1985**, *292*,159. (b) Chult,

C.. Corriu, R. J. P Reye, C. Young, J. C. *Chem. Rev.***1993**, *93*,1371.

11. (a) Sch-fer, A.; Reißmann, M.; Sch-fer, A.; Saak, W.; Haase, D.; Mgller, T. *Angew. Chem. Int. Ed.* **2011**, *50*, 12636. (b) Sch-fer, A.; Reißmann, M.; Jung, S.; Sch-fer, A.; Saak, W.; Brendler, E.; Mgller, T. *Organometallics* **2013**, *32*, 4713. (c) Feigl, A.; Chiorescu, I.; Deller, K. H.; Heidsieck, S. U.; Buchner, M. R.; Karttunen, V.; Bockholt, A.; Genest, A.; Rçsch, N.; Rieger, B. *Chem. Eur. J.* **2013**, *19*,12526. (d) Mther, K.; Hrobarik, P.; Hrobarikova, V.; Kaupp, M.; Oestreich, M. *Chem. Eur. J*. **2013**, *19*, 16579. (e) Labbow, R.; Reiß, F.; Schulz, A.; Villinger, A. *Organometallics* **2014**, *33*, 3223.
12. For examples of reactions with silicates involving radical intermediates, see: (a) Yoshida, Y.; Tamao, K.; Kakui, T.; Kurita, A.; Murata, M.; Yamada, K.; Kumada, K. *Organometallics* **1982**, *1*, 369. (b) Corc, V.; Chamoreau, L.; Derat, E.; Goddard, J.-P.; Ollivier, C.; Fen-sterbank, L. *Angew. Chem. Int. Ed.* **2015**, *54*, 11414. (c) Jouffroy, M.; Primer, D. N.; Molander, G. A. *J. Am. Chem. Soc.* **2016**, *138*, 475. (d) Patel, N. R.; Kelly, C. B.; Jouffroy, M.; Molander, G. A. *Org. Lett.* **2016**, *18*, 764.
13. *N*-allyl(2-halo-3-thienyl)carbamates are known to undergo radical cyclization. See: Brugier, D.; Outurquin, F.; Paulmier, C. *J. Chem. Soc. Perkin Trans. 1* **2001**, 37.
14. Abeywickrema, A. N.; J. Beckwith, A. L. *J. Chem. Soc. Chem. Commun*. **1986**, 464.
15. Murai, M.; Takami, K.; Takai, K. *Chem. Eur. J.* **2015**, *21*, 4566.
16. Mita, T.; Tanaka, H.; Michigami, K.; Sato, Y.; *J. Org. Chem.* **2004**, *69*, 8305.
17. Tang, J.; Zhao, X. *RSC Adv.* **2012**, *2*, 5488.
18. Mohanakrishnan, A. K.; Amaladass, P.; Clement, J. A. *Tetrahedron Lett*. **2007**, *48*, 539.
19. Stolić, I.; Mišković, K.; Piantanida, I.; Lončar, M. B.; Glavaš-Obrovac, L.; Bajić, M. *Eur. J. Med. Chem.* **2011**, *46*, 743.
20. Schmidt, B.; Geißler, D. *Eur. J. Org. Chem.* **2011**, 4814.
21. Shang, R.; Fu, Y.; Wang, Y.; Xu, Q.; Yu, H.-Z.; Liu, L. *Angew. Chem. Int. Ed*. **2009**, *48*, 9350.
22. Taneda, M.; Adachi, C.; Nakata, Y. PCT Int. Appl. 2014, WO2014034384.
23. Tamba, S.; Okubo, Y.; Tanaka, S.; Monguchi, D.; Mori, A. *J. Org. Chem.* **2010**, *75*, 6998.
24. Ghosh D.; Lee, H. M. *Org. Lett*. **2012**, *14*, 5534.
25. Zhou, F.; Wang, D.-S.; Driver, T. G. *Adv. Synth. Catal*. **2015**, *357*, 3463.
26. Spivey, A. C.; Gripton, C. J. G.; Hannah, J. P.; Tseng, C.-C.; Paul, P. d.; Parr, N. J.; Scicinski, J. J. *Appl. Organometal. Chem.* **2007**, *21*, 572.
27. Bernhardt, S.; Manolikakes, G.; Kunzm M.; Knochel, P. *Angew. Chem. Int. Ed*. **2011**,

50, 9205.
28. Parmentier, M.; Gros, P.; Fort, Y. *Tetrahedron* **2005**, *61*, 3261.
29. Gavryushin, A.; Kofink, C.; Manolikakes, G. Knochel, P. *Org. Lett.* **2005**, *7*, 4871.
30. Moura, G. L. C.; Simas, A. M. *J. Phys. Chem. C* **2010**, *114*, 6106.
31. Das, S.; Dutta, P. K.; Panda, S.; Zade, S. S. *J. Org. Chem.* **2010**, *75* 4868.

Chapter 4

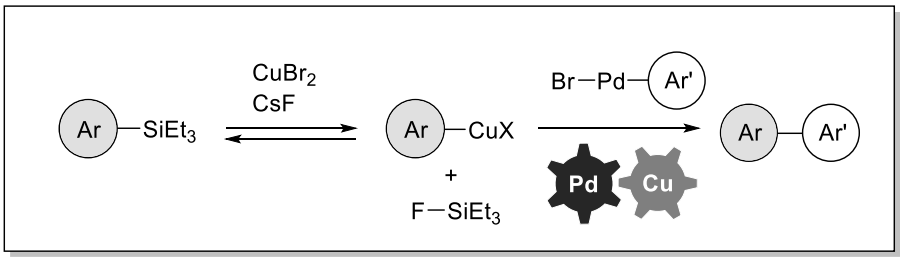
Cross-coupling Reaction of Aryl(triethyl)silanes with Aryl Bromides and Chlorides by Pd/Cu dual Catalysis

Aryl(triethyl)silanes were found to couple with aryl bromides and chlorides by means of palladium and copper dual catalysis. Various arylsilanes and electrophiles were applicable to the present reaction conditions for synthesis of biaryls, teraryls, and polyarylenes. Since such trialkylsilyl groups did not interfere with basic transformations, unsymmetrical thiophenes having different aryl groups at C2 and C5 could be readily prepared.

4-1. Introduction

Aryl(triethyl)silanes have superior properties in various respects as discussed in previous Chapters. In Chapter 3, the author discussed the first cross-coupling reaction of aryl(triethyl)silanes with aryl iodides. Although aryl iodides are reactive enough toward the coupling, they are relatively expensive and sometimes difficult to prepare. In contrast, aryl bromides and chlorides are more attractive electrophilic coupling partners in terms of cost and accessibility. Thus, the author scrutinized the reaction of 2-triethylsilylbenzothiophehene (**1a**) with *p*-bromoanisole (**2a**), and observed coupling product **3aa** was produced in 51% yield as estimated by ^{1}H NMR (Eq. 1).

Although the exact role of the copper salt in the above reactions is unclear, it can not be ruled out that organocopper species are generated from arylsilanes and copper salts.[1] If so, the author expects aryl(triethyl)silanes might couple even with aryl bromides with a palladium catalyst as a co-catalyst like the Sonogashira reaction (Scheme 4-1).[2,3] Considering the formation of such organocopper species from arylsilanes and fluorides is reversible, the author conceives there is no contradiction with the mechanism of the reaction discussed in the prior Chapter.



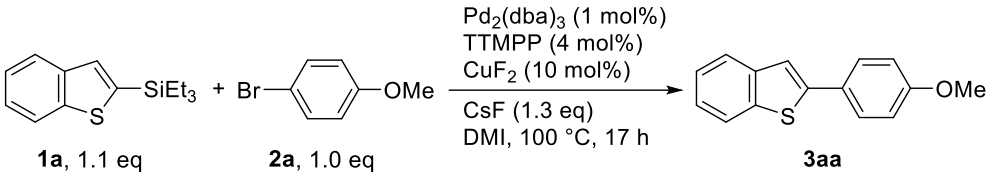
Scheme 4-1. Working Hypothesis for Pd/Cu-catalyzed Cross-coupling

4-2. Result and Discussion

The author screened a wide variety of conditions variables focusing on palladium and copper dual catalytic system and found that **1a** (1.1 eq) coupled with **2a** in the presence of $Pd_2(dba)_3$ (1 mol%), tris(2,4,6-trimethoxyphenyl)phosphine (TTMPP, 4 mol%), CuF_2 (10 mol%), CsF (1.3 eq), and DMI at 100 °C to give **3aa** in 92% yield (Table

4-1, Run 1). Benzothiophene having other trialkylsilyl groups like $SiMe_3$, $SiMe_2$(*t*-Bu), and even Si(*i*-Pr)$_3$ groups also gave **3aa** in comparable yields (Runs 2–4). Negative control experiments showed both palladium and copper are essential for this reaction (Runs 5–6). Use of other ligands such as PPh_3, PCy_3, P[2,6-$(MeO)_2C_6H_3$]$_3$, and P(2,4,6-$Me_3C_6H_2$)$_3$ resulted in decrease in **3aa** yield (Runs 7–10). Copper iodide and copper dibromide instead of CuF_2 led to low yield of **3aa** (Runs 11 and 12).

Table 4-1. Screening the conditions



1a, 1.1 eq **2a**, 1.0 eq **3aa**

*TTMPP = P[2,4,6-$(MeO)_3C_6H_2$)]$_3$

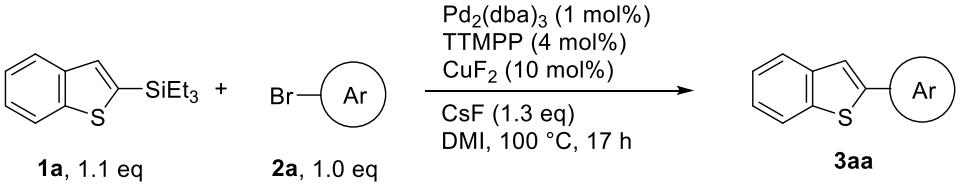
Run	Variation from the standard conditions	Yield of **3aa** (%)[b]
1	none	92[c]
2	$SiMe_3$ instead of $SiEt_3$	96
3	$SiMe_2$(*t*-Bu) instead of $SiEt_3$	94
4	Si(*i*-Pr)$_3$ instead of $SiEt_3$	91
5	without CuF_2	6
6	without $Pd_2(dba)_3$	trace
7	PPh_3 instead of TTMPP	67
8	PCy_3 instead of TTMPP	trace
9	P[2,6-$(MeO)_2C_6H_3$]$_3$ instead of TTMPP	77
10	P(2,4,6-$Me_3C_6H_2$)$_3$ instead of TTMPP	14
11	CuI instead of CuF_2	14
12	$CuBr_2$ instead of CuF_2	35

[a] Unless otherwise noted, a mixture of **1a** (1.1 eq), **2a** (0.3 mmol), $Pd_2(dba)_3$ (1 mol%), TTMPP (4 mol%), CuF_2 (10 mol%), and CsF (1.3 eq) in DMI (2 M) was heated at 100 °C for 17 h. [b] Isolated yields.

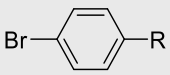
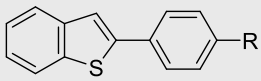
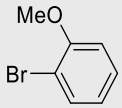
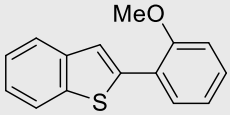
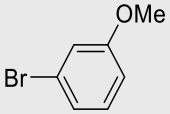
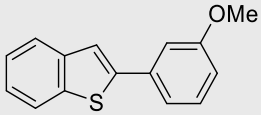
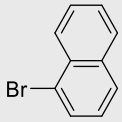
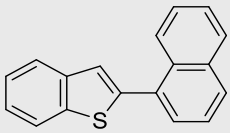
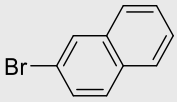
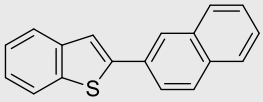
A range of aryl bromides performed as good electrophiles as shown in Table 4-2. The reaction of 4-bromotoluene (**2b**) and *N*,*N*-dimethyl-4-bromoaniline (**2c),** *N*,*N*-diphenyl-4-bromoaniline (**2d)** also proceeded without any serious problems (Runs 1–3). Alhough electron-deficient aryl bromides **2e–2g** containing a F, CF_3, or CN group required higher temperature with P(*t*-Bu)$_2$(2-biphenyl) as a ligand, desired coupled products **3ae**-**3ag** were formed in high yields (Runs 4 and 5). *m*- and *o*-Substituted variants (**2h** and **2i**) also led to coupled products **3ah** and **3ai** in excellent yields (Runs 6 and 7). The coupling of 9-bromoanthrathene (**2l**) as well as 1- and 2-bromonaphtharene

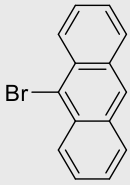
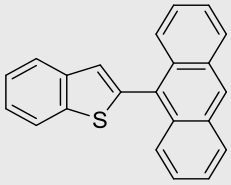
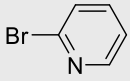
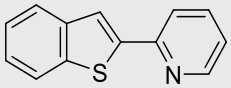
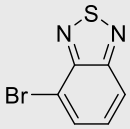
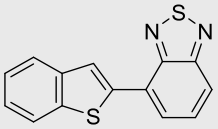
(**2j** and **2k**) took place smoothly to give **3al**–**3ak** in excellent yields, respectively (Runs 8–10). Such heteroaryl bromide as 2-pyridyl bromide (**2m**) gave the coupled product **3am** in a moderate yield. At last, 4-(2-thienyl)benozthiadiazole **3an** could be synthesized under the optimized conditions.

Table 4-2. Scope of Aryl Bromides[a]



1a, 1.1 eq **2a**, 1.0 eq **3aa**

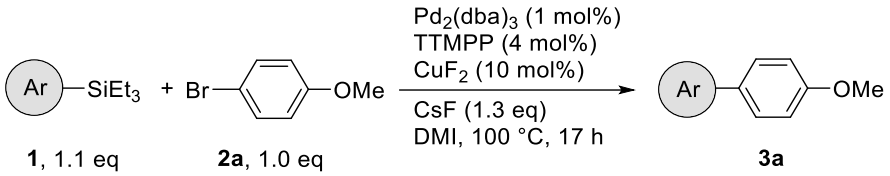
Run	Aryl Bromides **2**	Product, Yield /%[b]
		
1	**2b**, R = Me	**3ab**, 85%
2	**2c**, R = NMe_2	**3ac**, 97%
3	**2d**, R = NPh_2	**3ad**, 94%
4[c]	**2e**, R = F	**3ae**, 93%
5[c]	**2f**, R = CF_3	**3af**, 89%
6[c]	**2g**, R = CN	**3ag**, 84%
7	 **2h**	 **3ah**, 91%
8	 **2i**	 **3ai**, 96%
9	 **2j**	 **3aj**, 92%
10[d]	 **2k**	 **3ak**, 92%

11			
	2l	**3al**, 92%	
12 [c]			
	2m	**3am**, 62%	
13			
	2n	**3an**, 74%	

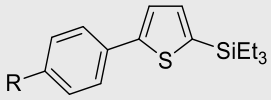
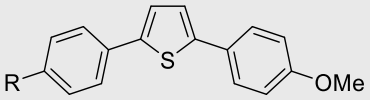
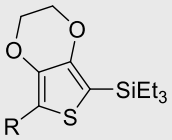
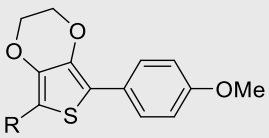
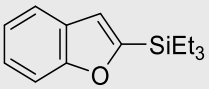
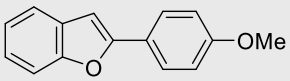
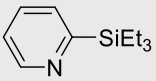
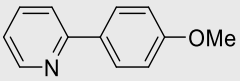
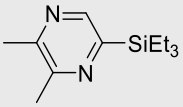
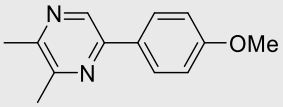
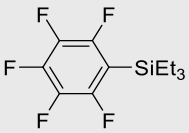
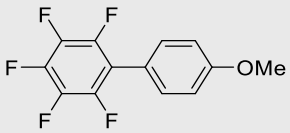
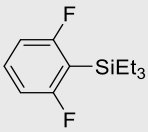
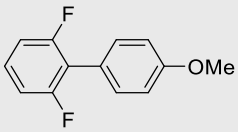
[a] Unless otherwise noted, a mixture of **1a** (1.1 eq), **2** (0.3 mmol), $Pd_2(dba)_3$ (1 mol%), TTMPP (4 mol%), CuF_2 (10 mol%), and CsF (1.3 eq) in DMI (2 M) was heated at 100 °C for 17 h. [b] Isolated yields. [c] heated at 120 °C and using P(*t*-Bu)$_2$(2-biphenyl) instead of TTMPP. [d] heated at 120 °C

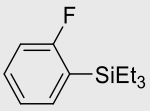
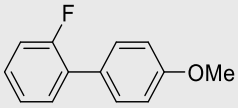
The author next envisaged the scope of aryl(triethyl)silanes **1a** using *p*-bromoanisole (**2ab**) as an electrophilic coupling partner (Table 4-3). 2-Substituted thienylsilanes **1b–1d** gave diarylthiophene **3ba–3da** in excellent yields (Runs 1–3). When monosilylthiophene **1e** was employed, monarylthiophene **3ea** along with diarylthiophene **5aa** were obtained in 38% and 53%, respectively as discussed in Chapter 3 (Run 4). 2-Benzofurylsilane **1f** also acts as a good nucleophile (Run 5). In the cases of 2-pyridyl- and 2-pyrazylsilanes, $PPh_2(2\text{-}NMe_2C_6H_4)$ was a more effective ligand (Runs 6 and 7). Not only heteroarylsilanes but also electron-deficient phenyl(triethyl)silanes were applicable to the reaction. For example, penta-, di-, and *o*-monofluorophenylsilanes **1i**–**1k** were activated by CsF to react with **2a** producing corresponding biaryls **3ia**–**3ka** in moderate yields, respectively (Runs 8–10).

Table 4-3. Scope of Aryl(trialkyl)silanes[a]

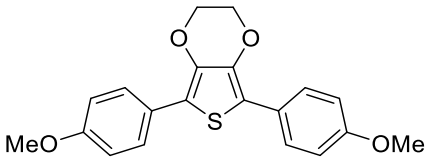


1, 1.1 eq **2a**, 1.0 eq **3a**

Run	Arylsilane **1**	Product, Yield /%[b]
		
1	**1b**, R = H	**3ba**, 91
2	**1c**, R = F	**3ca**, 92
		
3	**1d**, R = Me	**3da**, 87
4	**1e**, R = H	**3ea**, 38
5	 **1f**	 **3fa**, 69
6[c,d]	 **1g**	 **3ga**,90
7[c,d]	 **1h**	 **3ha**,77
8[c,e]	 **1i**	 **3ia**, 53
9[c,d,f]	 **1j**	 **3ja**, 54

10[d,g]			
	1k	**3ka**, 52	

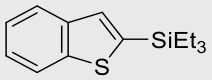
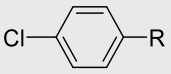
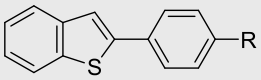
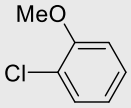
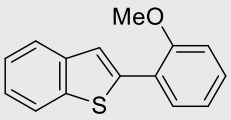
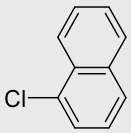
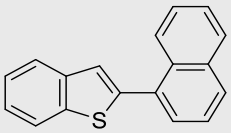
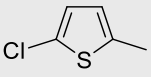
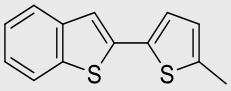
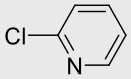
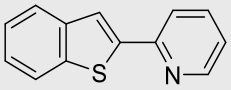
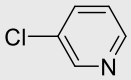
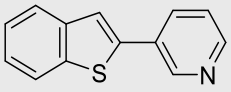
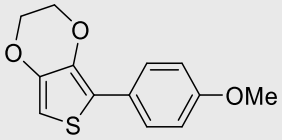
[a] Unless otherwise noted, a mixture of **1** (1.1 eq), **2a** (0.3 mmol), $Pd_2(dba)_3$ (2 mol%Pd), TTMPP (4 mol%), CuF_2 (10 mol%), and CsF (1.3 eq) in DMI (2 M) was heated at 100 °C for 17 h. [b] Isolated yields. [c] Run at 120 °C [d] $PPh_2(2\text{-}NMe_2C_6H_4)$ instead of TTMPP [e] XPhos instead of TTMPP [f] Run for 3 days [g] Run at 140 °C for 24 h.

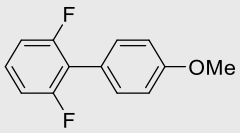


5aa, 53% (based on **2a**)

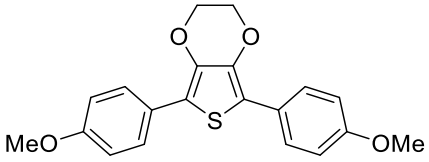
Aryl chlorides **4** are more attractive electrophile than bromides and iodides in view of cost and availability. Thus, the author decided to expand the scope of electrophiles to less reactive aryl chlorides. Under the abovementioned standard conditions, *p*-chlorotoluene (**4b**), however, did not react due to its low reactivity toward oxidative addition to palladium(0). After further experimentations, he disclosed XPhos enhanced reactivity of palladium(0) to cleave the carbon–chlorine bond:[4] **1a** coupled with **4b** using Xphos (4 mol%) instead of TTMPP to give desired product **3ab** in a high yield (Table 4-4, Run 1). *p*-Chloroanisole (**4a**) and *p*-chlorobenzotrifluoride (**4f**) were also applicable to the reaction showing that electron-rich and -deficient aryl chloride were good electrophilic coupling partner for the reaction (Runs 2 and 3). Steric hindrance in *o*-chloroanisole (**4h**) and 1-chloronaphtharene (**4j**) did not hamper the reaction (Run 4 and 5). Also such other heteroaryl chlorides as 2-chlorothiophene **4o**, 2-chloropyridine (**4m**), and 3- chloropyridine (**4p**) coupled with **1a** with high efficiency (Runs 6–8). As with the case with Table 4-3, Run 4, the reaction of **1e** with **4a** furnished the mixture of **3ea** and **5aa** (Run 9). Lastly, the author shows the reaction of a 6-membered arylsilane like **1j** was ascertained to occur without any serious problems (Run 10).

Table 4-4. Scope of Aryl(trialkyl)silanes

Run	Arylsilane **1**	**4**	Product, Yield (%)[b]
			
1	**1a**	**4b**, R = Me	**3ab**, 78
2	**1a**	**4a**, R = MeO	**3aa**, 84
3[c]	**1a**	**4f**, R = CF_3	**3af**, 83
4	**1a**	 **4h**	 **3ah**, 83
5	**1a**	 **4j**	 **3aj**, 65
6	**1a**	 **4o**	 **3ao**, 82
7	**1a**	 **4m**	 **3am**, 84
8	**1a**	 **4p**	 **3ap**, 73
9	**1e**	**4a**	 **3ea**, 38

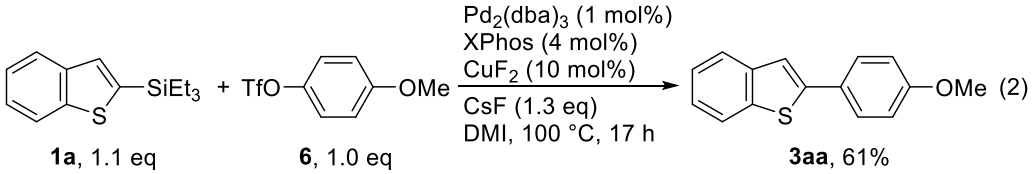
10[d]	**1j**	**4a**	 **3ja**, 78

[a] Unless otherwise noted, a mixture of **1** (1.1 eq), **4** (0.3 mmol), $Pd_2(dba)_3$ (1 mol%), XPhos (4 mol%), CuF_2 (10 mol%), and CsF (1.3 eq) in DMI (2 M) was heated at 100 °C for 17 h. [b] Isolated yields. [c] Run at 110°C for 24 h. [d] Run at 120 °C and using P(*t*-Bu)$_2$(2-biphenyl) instead of TTMPP. for 2 days.

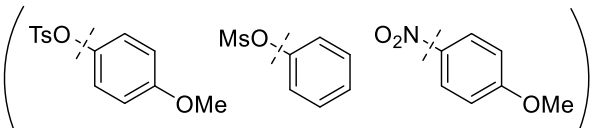


5aa, 35% (based on **4a**)

There are many reports on the cross-coupling using phenol-based electrophile like aryl triflates, tosylates, and mesylates.[5] Thus, he subsequently examined their reactivity toward **1a** using each of TTMPP and XPhos. Employing *p*-anisyltrifrates (**6**), the desired reaction occurred and **3aa** was observed in 61% yield by ^{1}H NMR analysis in the presence of XPhos (Eq. 4-3), though TTMPP gave **3aa** in 10% yield. Other electrophilic coupling partner like *p*-anisyltosylate and phenylmesylate resulted in no coupled product. Inspired by recent paper by Nakao who developed the Suzuki-Miyaura coupling with nitroarenes,[6] the author tried the coupling between **1a** and *p*-nitroanisole under Nakao's conditions, but his attempt failed.



1a, 1.1 eq **6**, 1.0 eq **3aa**, 61%

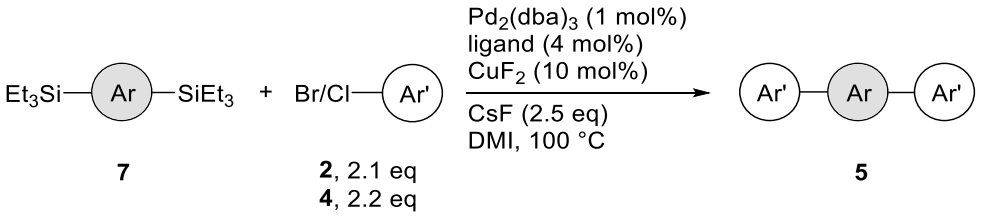


unsuccessful electrophiles

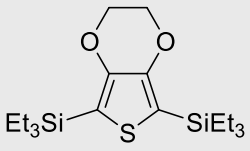
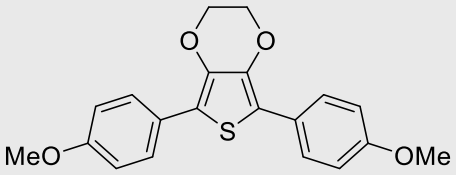
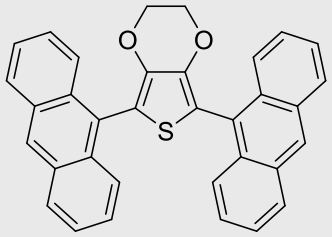
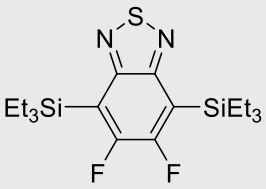
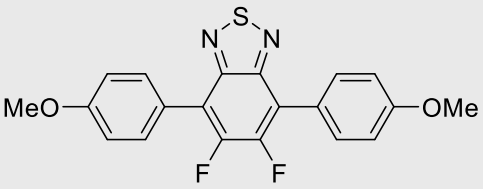
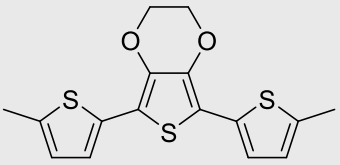
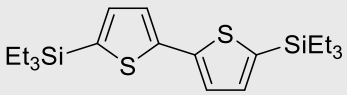
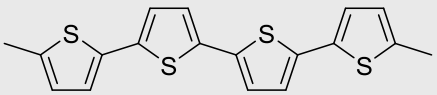
The present coupling is applicable to double coupling using disilylarenes **7** to prepare teraryls **5** (Table 4-5). Fow instance, 2,5-dislyl-3,4-ethylenedioxythiphene (**7a**) doubly coupled **2a** or **2l** to give multiarylated thiophene **5aa** and **5al** in excellent yields, respectively (Runs 1 and 2). Furthermore, 4,7-disilyl-5,6-dufluorobenzothidiazole (**7b**) also underwent the coupling after slight modification (Run 3). Finally, the author achieved silicon-based synthesis of oligothiophene:[7] **7a** and bis(thiethylsilyl)bithiophene (**7c**)

coupled with **4o** to produce ter- and quaterthiophenes **5ao** and **5co** in high yields, respectively (Runs 4 and 5).

Table 4-5. Scope of Aryl(trialkyl)silanes



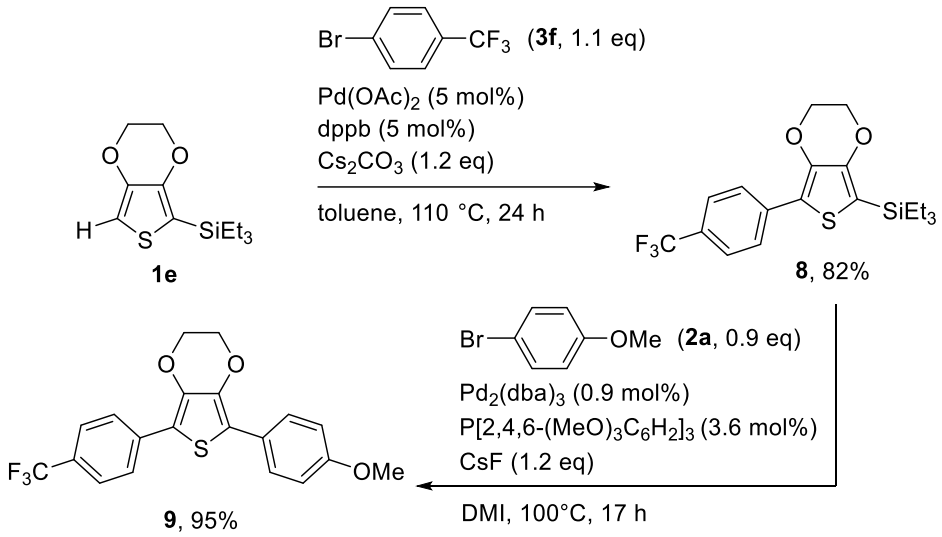
7 **2**, 2.1 eq; **4**, 2.2 eq **5**

Run	Arylsilane **7**	**2** or **4**	time	Product, Yield /%[b]
1	 **7a**	**2a**	22 h	 **5aa**, 90
2	**7a**	**2l**	22 h	 **5al**, 89
3	 **7b**	**2a**	4 d	 **5ba**, 61
4	**7a**	**4o**	20 h	 **5ao**, 76
5[c]	 **7c**	**4o**	2 d	 **5co**, 71

[a] Unless otherwise noted, a mixture of **7** (0.3 mmol), **2** (2.1 eq) or **4o** (2.2 eq), $Pd_2(dba)_3$ (1 mol%), ligand (4 mol%), CuF_2 (10 mol%), and CsF (2.5 eq) in DMI (2 M) was heated at 100 °C. Employed

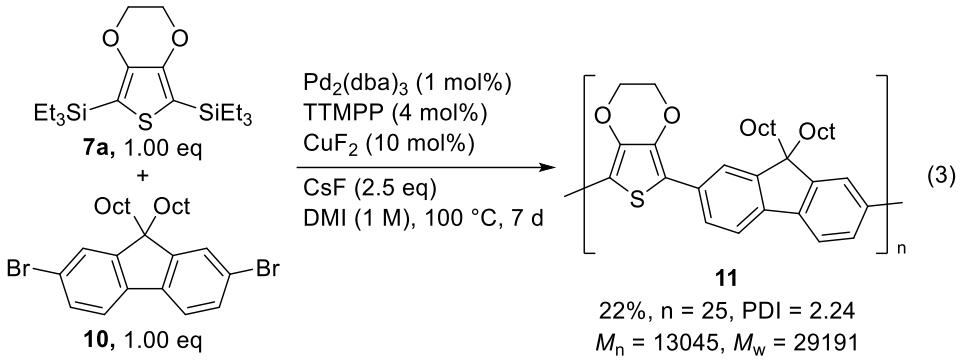
ligand: Runs 1 and 2, TTMPP; Run 3, $PPh_2(2\text{-}NMe_2C_6H_4)$; Runs 4 and 5, XPhos. [b] Isolated yields. [c] $Pd[P(o\text{-tolyl})_3]_2$ (2 mol%) and XPhos (8 mol%) were used.

Because aryl(trialkyl)silanes are generally inert under most of the reaction conditions reported, a combination of a C–H coupling and the present cross-coupling reaction allows to access to differently arrayed polyaryls with ease (Scheme 4-2). For example, $Pd(OAc)_2$-catalyzed C–H arylation of 2-triethylsilylthiophene **1e** with **3f** gave a monoarylated silylthiophene **8** without damaging the silicon group.[8] Subsequently, the coupling of **8** with **2a** under the optimized conditions produced a target unsymmetrical diarylthiophenes **9** in a excellent overall yield.



Scheme 4-2. Application for Synthesis of Unsymmetrical Diarylthiophenes

The author demonstrated synthesis of polyarylenes from disilylarenes and dibromoarenes successfully. Indeed, copolymer, poly(ethylenedioxythienylidene-fluorenylidene) **11** with M_n = 13045 and PDI = 29191 was obtained by the reaction of 2,5-bis(triethyl)silyl-3,4-ethylenedioxythiophene (**7a**) and 2,7-dibromo-9,9-dioctyl-fluorene (**10**) after reprecipitation (Eq. 3).[9]



He proposes a reaction mechanism shown in Figure 4-1. First, silicates derived from arylsilanes and CsF is assumed to react with CuF_2 to give arylcopper(II).[10,11] Sequential transmetallation between the resulting arylcopper(II) and aryl-palladium-bromide,[12] formed by Pd(0) and aryl bromides, followed by reductive elimination would give the coupled product, regenerating Pd(0) and Cu(II).

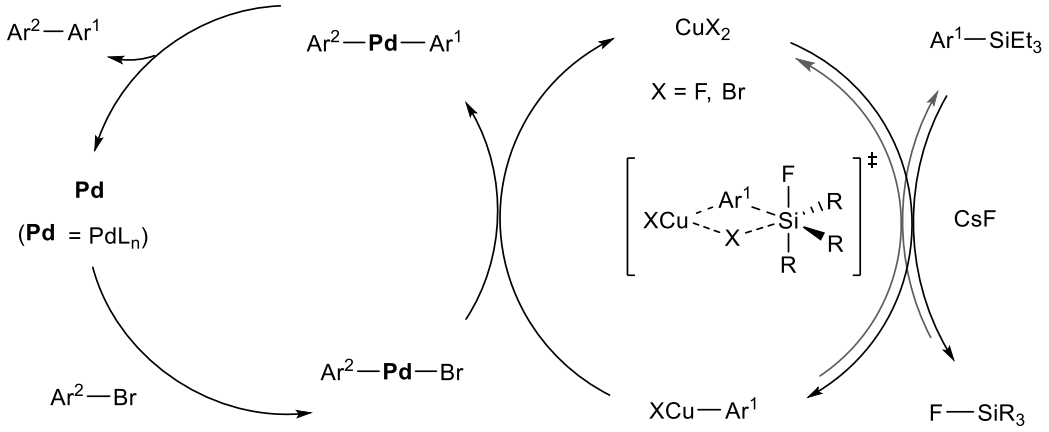


Figure 4-1. Proposed Catalytic Cycle

4-3. Conclusion

In summary, the author presented the first cross-coupling reaction between aryl(trialkyl)silanes with aryl bromides and chlorides using Pd/Cu dual catalysis. To run the reaction smoothly, both a palladium catalyst and a copper catalyst are essential. A wide steric range of silyl group from $SiMe_3$ to $Si(i\text{-}Pr)_3$ was applicable to the reaction. Synthesis of such useful molecules for material science as oligothiophenes, unsymmetrical diarylthiophenes, and polyarylenes were accessible with his novel reaction.

4-4. Experimental Section and Additional Information

$Pd_2(dba)_3$, tris(2,4,6-trimethoxyphenyl)phosphine (TTMPP), (di-*tert*-butylphosphino)-biphenyl (JohnPhos), and 2-dicyclohexylphosphino-2',4',6'-triisopropylbiphenyl (XPhos) were purchased from Sigma-Aldrich.

2-(Triethylsilyl)benzo[*b*]thiophene (1a).[13] CAS registry number: 1085787-64-9.
2-(Trimethylsilyl)benzo[*b*]thiophene.[14] CAS registry number: 17998-85-5.
2-(Tri-*iso*-propylsilyl)benzo[*b*]thiophene.[14] CAS registry number: 749243-15-0.

Preparation of 2-(*t*-butyldimethylsilyl)benzo[*b*]thiophene. To a THF (100 mL) solution of benzo[*b*]thiophene (3.9 g, 29 mmol) cooled at –78 °C under argon atomosphere was added a solution of LDA in hexane (1.13 M, 30.0 mL, 34 mmol) over 5 minutes, and the resulting solution was stirred at –78 °C for 1 h before addition of chloro-*t*-butyldimethylsilane (4.5 g, 41 mmol). The reaction mixture was stirred at room temperature overnight, washed with water and brine, and the organic layer was dried over $MgSO_4$ and concentrated *in vacuo* to give a resude which was purified by column chromatography using hexane as an eluent to give the title compound in 94% yield (6.8 g, 27 mmol) as colorless solid, mp = 30-32 °C, R_f 0.66 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.36 (s, 6H), 0.97 (s, 9H), 7.29-7.36 (m, *2*H), 7.48 (s, 1H), 7.82 (d, *J* = 7.2 Hz, 1H), 7.88 (d, *J* = 7.2 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ -4.87, 17.1, 26.5, 122.2, 123.5, 124.1, 124.2, 132.2, 139.5, 141.1, 143.8. IR (KBr) 3019, 2953, 2930, 2858, 1493, 1470, 1453, 1418, 1253, 1216, 969, 832, 757, 669, 564, 475, 466, 450, 442, 426, 414, 403 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 248 (M^+, 10), 235 (2), 191 (100), 177 (6), 134 (17), 56 (10); HRMS (DART) calcd for $C_{14}H_{21}SSi$ (M + H) 249.1133, found 249.1138.

2-Triethylsilyl-5-phenylthiophene (1b).[14] CAS registry number: 1996626-97-1.
2-Triethylsilyl-5-(4-fluorophenyl)thiophene (1c).[15] CAS registry number: 1997318-09-8.

Preparation of 2-triethylsilyl-5-methyl-3,4-ethylenedioxythiophene (1d). 2-Triethylsilyl-3,4-ethylenedioxythiophene (1.19 g, 4.6 mmol) was dissolved in THF (10 mL), and the resulting solution was cooled to –78 °C under argon atomosphere. After the addition of a solution of LDA in hexane (1.08 M, 5.50 mL, 6.0 mmol) over 1 minutes, the resultant solution was stirred at –78 °C for 2 h. Iodomethane (0.34 mL, 5.5 mmol) was added dropwise over 1 minutes and the mixture was stirred at room temperature overnight. After the reaction mixture was washed with water and brine, the organic layer was dried over $MgSO_4$ and concentrated *in vacuo* to give a residue, which was purified

by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 → 97:3 graduent) as an eluent to give **1d** in 96% yield (1.20 g, 4.4 mmol) as Colorless oil, R_f 0.14 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.77 (q, *J* = 7.6 Hz, 6H), 0.97 (t, *J* = 7.6 Hz, 9H), 2.24 (s, 3H), 4.12-4.17 (m, 4H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 4.16, 7.57, 11.5, 64.5, 64.6, 103.4, 118.0, 138.8, 147.6. IR (neat) 3418, 2952, 2935, 2911, 2874, 1638, 1595, 1481, 1449, 1430, 1244, 1203, 1141, 1107, 1055, 1031, 1007, 900, 773, 732, 720, 700, 646, 598, 556, 536, 517, 463, 445, 425 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 270 (M^+, 36), 241 (94), 213 (85), 185 (100), 156 (11), 107 (10), 93 (16), 59 (38); HRMS (DART) calcd for $C_{13}H_{23}O_2SSi$ (M + H) 271.1188, found 271.1189.

Preparation of 2-Triethylsilyl-3,4-ethylenedioxythiophene (1e). To a THF (70 mL) solution of 3,4-ethylenedioxythiophene (4.2 g, 30 mmol) cooled at –78 °C under argon atmosphere was added an LDA solution in hexane (1.08 M, 28.0 mL, 30 mmol) over 1 minute, and the resultant solution was stirred at –78 °C for 2 h before chlorotriethylsilane (5.1 mL, 40 mmol) was added dropwise over 1 minutes. The mixture was stirred at room temperature overnight, washed with water and brine. The organic phase was dried over $MgSO_4$ and concentrated *in vacuo* to give a residue, which was purified by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 to 97:3 graduent) as an eluent to give **6** in 72% yield (5.5 g, 21 mmol) as Colorless oil, R_f = 0.45 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.79 (q, *J* = 8.0 Hz, 6H), 0.98 (t, *J* = 8.0 Hz, 9H), 4.17 (s, 4H), 6.56 (s, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 4.00, 7.52, 64.57, 64.60, 105.2, 108.8, 142.6, 147.6. IR (neat) 3019, 2953, 2932, 2875, 1487, 1468, 1454, 1441, 1423, 1364, 1337, 1215, 1186, 1150, 1136, 1073, 1058, 899, 669, 517, 460 cm^{-1}. MS (EI, 70 eV) m/z (%) 256 (M^+, 51), 228 (23), 227 (96), 200 (16), 198 (86), 170 (100), 86 (14), 71 (17), 59 (9), 55 (8), 53 (8); HRMS (ESI) calcd for $C_{12}H_{21}O_2SSi$ (M + H) 257.1032, found 257.1040.

2-(Triethylsilyl)benzo[*b*]furan (1f).[15] CAS registry number: 60981-58-0.
2-Triethylsilylpyridine (1g).[16] CAS registry number: 19854-22-9.

Preparation of 2-triethylsilyl-4,5-dimethylpyrazine (1h).
In a glove box under argon atmosphere, 2,3-dimethylpyradine (538 mg, 5.0 mmol) and triethylsilane (870 mg, 7.5 mmol) were added sequentially to a solution of $[Ir(OMe)(cod)]_2$ (111 mg, 0.17 mmol), 3,4,7,8-tetramethyl-1,10-phenanthroline (78 mg, 0.33 mmol) and 2-norbornene (700 mg, 7.4 mmol) in *i*-Pr_2O (2.5 mL) placed in a 15 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was

heated at 100 °C for 2 days. The reaction mixture was filtered through a Celite pad, and the filtrate was concentrated *in vacuo* to give a residue, which was purified by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 → 91:9 graduent) as an eluent to give **1h** in 97% yield (1.03 g, 4.6 mmol) as Colorless oil, R_f 0.33 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.82-0.88 (m, 6H), 0.96-1.01 (m, 9H), 2.51 (s, 3H), 2.55 (s, 3H), 8.31 (s, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 2.94, 7.43, 22.3, 22.6, 146.3, 151.1, 153.3, 156.4. IR (neat) 3033, 2912, 1818, 1722, 1698, 1638, 1550, 1523, 1456, 1445, 1415, 1377, 1333, 1239, 1163, 1132, 1012, 972, 928, 764, 637, 583, 414 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 222 (M^+, 27), 194 (100), 193 (42), 166 (55), 165 (59), 137 (78), 135 (45); HRMS (DART) calcd for $C_{12}H_{23}N_2Si$ (M + H) 223.1631, found 223.1629.

Preparation of perfluorophenyl(triethyl)silane (1i).
In a glove box, pentafluorobenzene (989 mg, 5.9 mmol) and triethylsilane (832 mg, 7.2 mmol) were added sequentially to a solution of $[Ir(OMe)(cod)]_2$ (65 mg, 0.098 mmol), 3,4,7,8-tetramethyl-1,10-phenanthroline (47 mg, 0.020 mmol) and 2-norbornene (389 mg, 4.1 mmol) in *i*-Pr_2O (2.1 mL) all placed in a 15 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 110 °C for 24 h. The reaction mixture was filtered through a Celite pad, and the filtrate was concentrated *in vacuo* to give a residue, which was purified by column chromatography using hexane as an eluent in twice followed by bulb to bulb distillation (90 °C, 1300 Pa) to give **1i** in 28% yield (470 mg, 1.7 mmol) as Colorless oil, R_f 0.76 (hexane). ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.89-0.93 (m, 6H), 0.96-0.99 (m, 9H); ^{13}C {^{19}F} NMR (126 MHz, $CDCl_3$) δ 4.17 (t, *J* = 121 Hz), 7.27, (q, *J* = 128 Hz), 108.6, 137.3, 141.9, 149.4; ^{19}F NMR (376 MHz, $CDCl_3$) δ -161.4 (dd, *J* = 14.3, 14.3 Hz, 2F), -151.9 (t, *J* = 18.8 Hz, 1F), -126.6 (d, *J* = 17.6 Hz, 2F). IR (neat) 2959, 2914, 2879, 1597, 1419, 1356, 1258, 1240, 1169, 1005, 848, 741, 700, 476, 743, 454 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 282 (M^+, 13), 253 (100), 225 (7), 197 (60).

1-Triethylsilyl-2,6-difluorobenzene (1j).[17] CAS registry number: 651027-02-0.
1-Triethylsilyl-2-fluorobenzene (1k).[18] CAS registry number: 851368-02-0.

Pd/Cu-catalyzed cross-coupling reaction between 2-triethylsilylbenzo[*b*]thiophene (1a) and *p*-bromoanisole (2a). —*General procedure for the single cross-coupling reaction.*— In a glove-box under argon atmosphere, **1a** (83 mg, 0.34 mmol) and **2a** (57 mg, 0.30 mmol) were added sequentially to a solution of $Pd_2(dba)_3$ (2.7 mg, 2.9 μmol),

tris(2,4,6-trimethoxyphenyl)phosphine (6.3 mg, 12 μmol), CuF_2 (3.2 mg, 32 μmol), and CsF (61 mg, 0.41 mmol) in DMI (0.15 mL) prepared in a 3 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 100 °C for 17 h. The reaction mixture was filtered through Celite, and the filtrate was concentrated *in vacuo*. Desired product **3aa** was isolated in 92% yield (65 mg, 0.28 mmol) by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 to 40:60 gradient) as an eluent.

2-(4-Methoxyphenyl)benzo[*b*]thiophene (3aa).[19] CAS registry number: 27884-09-9.
2-(4-Methoxyphenyl)-5-phenylthiophene (3ba).[20] CAS registry number: 59086-11-2.

2-(4-Methoxyphenyl)-5-(*p*-fluorophenyl)thiophene (3ca). Yellowish green solid, mp = 173-176 °C, R_f 0.22 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.85 (s, 3H), 6.93 (d, *J* = 8.8 Hz, 2H), 7.08 (dd, *J* = 8.8, 8.8 Hz, 2H), 7.16 (d, *J* = 4.0 Hz, 1H), 7.19 (d, *J* = 3.6 Hz. 1H), 7.54-7.59 (m, 4H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 55.5, 114.4, 115.9 (d, *J* = 21.7 Hz), 123.1, 124.0, 127.0, 127.2, 127.3 (d, *J* = 8.3 Hz), 130.8 (d, *J* = 2.9 Hz), 141.5, 143.7, 159.4, 162.3 (d, *J* = 248.0 Hz); ^{13}F NMR (376 MHz, $CDCl_3$) δ -114.8 (tt, *J* = 7.9, 9.4 Hz). IR (neat) 3011, 2957, 2837, 1604, 1542, 1492, 1456, 1439, 1417, 1293, 1275, 1235, 1178, 1159, 1113, 1099, 1031, 1011, 940, 831, 810, 794, 632, 617, 496 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 284 (M^+, 100), 269 (80), 241 (34), 207 (8), 142 (12), 139 (8); HRMS (DART) calcd for $C_{17}H_{14}FOS$ (M + H) 285.0749, found 285.0736.

2-(4-Methoxyphenyl)-5-methyl-3,4-ethylenedioxythiophene (3da). Colorless solid, mp = 119-121 °C, R_f 0.28 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.26 (s, 3H), 3.81 (s, 3H), 4.21-4.23 (m, 2H), 4.24-4.26 (m, 2H), 6.86-6.90 (m, 2H), 7.56-7.60 (m, 2H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 10.9, 55.4, 64.5, 64.8, 109.4, 112.8, 114.1, 126.2, 127.1, 137.1, 138.3, 158.0. IR (neat) 2963, 2940, 2919, 1603, 1530, 1501, 1452, 1435, 1413, 1377, 1365, 1313, 1297, 1270, 1246, 1179, 1136, 1094, 1045, 1033, 997, 976, 920, 901, 841, 829, 796, 763, 692, 634, 598, 589, 544, 520, 479, 455 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 262 (M^+, 64), 252 (100), 235 (45), 219 (32), 151 (65), 64 (52); HRMS (ESI) calcd for $C_{14}H_{15}O_3S$ (M + H) 263.7419, found 263.0735.

2-(4-Methoxyphenyl)benzo[*b*]furan (3ea).[19] CAS registry number: 19234-04-9.
2-(4-Methoxyphenyl)pyridine (3fa).[21] CAS registry number: 5957-90-4.
5-(4-Methoxyphenyl)-2,3-dimethylpyrazine (3ga).[22] CAS registry number: 1391986-80-3.

2,3,4,5,6-Pentafluoro-4'-methoxy-1,1'-biphenyl (3ha).[23] CAS registry number: 51207-29-5.

2,6-Difluoro-4'-methoxy-1,1'-biphenyl (3ia).[24] CAS registry number: 717101-32-1.

2-Fluoro-4'-methoxy-1,1'-biphenyl (3ja).[24] CAS registry number: 72093-47-1.

2-(2-Methoxyphenyl)benzo[*b*]thiophene (3ab).[25] CAS registry number: 81344-86-7.

2-(3-Methoxyphenyl)benzo[*b*]thiophene (3ac).[26] CAS registry number: 101219-33-4.

2-(4-Methylphenyl)benzo[*b*]thiophene (3ad).[19] CAS registry number: 25664-47-5.

2-(4-Dimethylaminophenyl)benzo[*b*]thiophene (3ae).[19] CAS registry number: 927189-54-6.

2-(4-Diphenylaminophenyl)benzo[*b*]thiophene (3af).[27] CAS registry number: 1686144-81-9.

2-(4-Fluorophenyl)benzo[*b*]thiophene (3ag).[19] CAS registry number: 936734-96-2.

2-(4-Trifluoromethylphenyl)benzo[*b*]thiophene (3af).[19] CAS registry number: 1250258-62-8.

2-(4-Cyanophenyl)benzo[*b*]thiophene (3ai).[25] CAS registry number: 132932-64-0.

2-(1-Naphthyl)benzo[*b*]thiophene (3aj).[26] CAS registry number: 78176-92-8.

2-(2-Naphthyl)benzo[*b*]thiophene (3ak).[19] CAS registry number: 17164-77-1.

2-(9-Anthryl)benzo[*b*]thiophene (3al).[28] CAS registry number: 7530-55-4.

2-(2-Pyridyl)benzo[*b*]thiophene (3am).[29] CAS registry number: 38210-35-4.

2-(2,1,3-Benzothiadiazol-4-yl)benzo[*b*]thiophene (3an). Red solid, mp = 101-104 °C, R_f 0.50 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35-7.41 (m, 2H), 7.65 (dd, *J* = 7.2, 8.4 Hz, 1H), 7.86-7.90 (m, 2H), 7.91 (dd, *J* = 0.8, 7.2 Hz, 1H), 7.97 (dd, *J* = 0.8, 8.8 Hz, 1H), 8.54 (s, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 121.1, 122.2, 124.5, 124.8, 125.3, 125.6, 127.1, 127.6, 129.7, 139.3, 139.7, 140.7, 152.4, 155.7. IR (neat) 1531, 1515, 1480, 1455, 1434, 1190, 1154, 1096, 856, 849, 813, 804, 735, 717, 700, 555, 515, 446 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 268 (M^+, 10), 252 (63), 235 (31), 189 (38), 151 (100); HRMS (DART) calcd for $C_{14}H_9N_2S_2$ (M + H) 269.0207, found 269.0201.

2-(5-Methyl-2-thienyl)-benzo[b]thiophene (3ao).[30] CAS Registry Number: 1401352-33-7.

2-(3-Pyridyl)benzo[*b*]thiophene (3ap).[31] CAS registry number: 38210-35-4.

2-(2,6-Difluorophenyl)-5-methylthiophene (3ja). Colorless oil, R_f 0.35 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.54 (d, *J* = 0.8 Hz, 3H), 6.78–6.81 (m, 1H), 6.93–7.00 (m, 2H), 7.14–7.20 (m, 1H), 7.35 (dt, *J* = 3.6, 0.8 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$)

δ 15.3, 111.9 (dd, *J* = 20.3, 6.8 Hz), 112.6 (t, *J* = 16.9 Hz), 125.4, 127.0 (t, *J* = 3.0 Hz), 127.7 (t *J* = 43.6 Hz), 129.5 (t, *J* = 5.7 Hz), 141.8 (t, *J* = 4.1), 159.8 (dd, *J* = 252, 7.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −110.648 (t, *J* = 6.4 Hz); IR (NaCl) 2968, 2947, 2920, 261, 1620, 1574 1488, 1466 1284, 1271, 1252, 1241, 1204, 1168, 1058, 1000, 945, 801, 781, 754, 742, 718, 681, 615, 593, 552, 530, 433 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 210 (M^+, 90), 209 (100), 177 (7), 157 (9), 151 (2), 97 (8); HRMS (DART) calcd for $C_{11}H_9F_2S$ (M + H) 210.0393, found 210.0396.

Double cross-coupling reaction of 2,5-bis(triethylsilyl)-3,4-ethylenedioxythiophene (7a) with *p*-bromoanisole (2a). —*General procedure for the double cross-coupling reaction.*— In a glove-box under argon atmosphere, **7a** (111 mg, 0.30 mmol) and **2a** (118 mg, 0.63 mmol) were added sequentially to a solution of $Pd_2(dba)_3$ (2.6 mg, 2.8 μmol), tris(2,4,6-trimethoxyphenyl)phosphine (6.4 mg, 12 μmol), CuF_2 (2.9 mg, 29 μmol), and CsF (114 mg, 0.75 mmol) in DMI (0.15 mL) placed in a 3 mL-vial. The vial was closed with a screw PTFE septum cap, and the resultant mixture was heated at 100 °C for 22 h. The reaction mixture was iltered through a Celite pad, and the filtrate was concentrated *in vacuo*. The desired product **5aa** (96 mg, 0.27 mmol) was isolated by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 → 55:45 graduent) as an eluent in 90% yield.

2,5-Bis(triethylsilyl)-3,4-ethylenedioxy-thiophene (7a).[16] CAS registry number: 2045351-23-1.

4,7-Bis(triethylsilyl)-5,6-difluoro-2,1,3-benzothiadiazole (7b).[16] CAS registry number: 2045351-08-2.

Preparation of 5,5'-bis(triethyl)silyl-2,2'-bithiophene (7c). 2,2'-Bithiophene (**8**, 1.70 g, 10.2 mmol) and chlorotriethylsilane (3.40 mL, 20.3 mmol) was dissolved in dried THF (20 mL) and cooled to –78 °C under argon atomosphere. After the addition of a solution of LDA in hexane (1.08 M, 20.0 mL, 21.6 mmol) over 5 minutes, the resultant solution was stirred at –78 °C for 1 h. After the mixture was stirred at room temperature overnight, the resulting solution was washed with water and brine, the organic solution was dried over $MgSO_4$ and dried *in vacuo*. Desired chemical **9** was isolated in 79% yield (3.17 g, 8.03 mmol) by column chromatography using hexane as an eluent as colorless oil, R_f 0.53 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.77–0.83 (m, 12H), 0.99–1.03 (m, 18H), 7.12 (d, *J* = 3.2 Hz, 2H), 7.26 (d, *J* = 3.6 Hz, 2H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 4.49, 7.49, 125.0, 135.6, 136.3, 142.6; IR (NaCl) 2954, 2936, 2909, 2875, 1458, 1419, 237, 1209, 1197 1072, 1009, 990, 872, 796, 736, 721, 705, 583, 497, 475, 461, 441 cm^{-1}. MS

(EI, 70 eV) *m/z* (%) 394 (M^+, 100), 365 (85), 337 (43), 309 (56), 140 (22), 112 (30), 87 (22); HRMS (DART) calcd for $C_{20}H_{35}S_2Si_2$ (M + H) 395.1719, found 395.1710.

2,5-Di(4-methoxyphenyl)-3,4-ethylenedioxy-thiophene (5aa).[32] CAS registry number: 925674-63-1.

2,5-Di(9-Anthryl)-3,4-ethylenedioxythiophene (5al).[8] CAS registry number: 1313877-83-6.

4,7-Di(4-methoxyphenyl)-5,6-difluoro-2,1,3-benzothiadiazole (5ba).[16] CAS registry number: 1477530-99-6.

5,5''-Dimethyl-3',4'-ethylenedioxy-2,2':5',2''-terthiophene (5ao). a pale yellow solid, Rf 0.24 (hexane). mp = 132–133 °C, 1H NMR (400 MHz, CDCl3) δ 2.49 (d, J = 1.2 Hz, 6H), 4.36 (s, 4H), 6.70 (qd, J = 1.2, 3.6 Hz, 2H), 7.00 (d, J = 3.6 Hz, 2H); 13C {1H} NMR (101 MHz, CDCl3) δ 15.4, 65.0, 109.4, 122.9, 125.5, 132.3, 137.1, 138.7; IR (NaCl) 3063, 2981, 2967, 2938, 2913, 2874, 2855, 1717, 1714, 1600, 1599, 1551, 1536, 1513, 1455, 1441, 1369, 1323, 1279, 1240, 1221, 1163, 1127, 1091, 1050, 1011, 955, 872, 855, 843, 758 cm–1. MS (EI, 70 eV) m/z (%) 334 (M+, 100), 306 (5), 278 (7), 250 (5), 167 (8), 141 (89), 125 (13), 97 (13); HRMS (DART) calcd for C16H15O2S3 (M + H) 335.0234, found 335.0221.

5,5'''-Dimethyl-2,2':5',2'':5'',2'''-quaterthiophene (5co).[33] CAS registry number: 118347-89-0

Sequential arylation of 2-triethylsilyl-3,4-ethylenedioxy-thiophene (1e) via C–H/C–Si Activation. In a glove-box, **1e** (0.52 g, 2.0 mmol) and *p*-bromobenzotrifluoride (0.50 mg, 2.2 mmol) were added sequentially to a solution of $Pd(OAc)_2$ (25 mg, 0.11 mmol), 1,4-bis(diphenylphosphino)butane (43 mg, 0.10 mmol), and Cs_2CO_3 (0.79 mg, 2.4 mmol) in toluene (10 mL) placed in a 15 mL-vial in a dry box. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 110 °C for 24 h. The reaction mixture was filtered through a Celite pad, and the filtrate was dried *in vacuo* to give a residue, which was purified by column chromatography using hexane as an eluent to give monoarylated thiophene **7** in 82% yield (665 mg, 1.7 mmol).

The arylated thiophene **7** (90 mg, 0.22 mmol) and **2a** (37 mg, 0.20 mmol) were added sequentially to a solution of $Pd_2(dba)_3$ (1.8 mg, 2.0 μmol), tris(2,4,6-trimethoxy-phenyl)phosphine (4.4 mg, 8.3 μmol), CuF_2 (2.1 mg, 21 μmol), and CsF (42 mg, 0.27 mmol) in DMI (0.10 mL) all placed in a 3 mL-vial in the glove-box. The vial was closed with a screw PTFE septum cap, and the resultant mixture was heated at 100 °C for 17 h. The reaction mixture was filtered through a Celite pad, and the filtrate was dried *in vacuo*

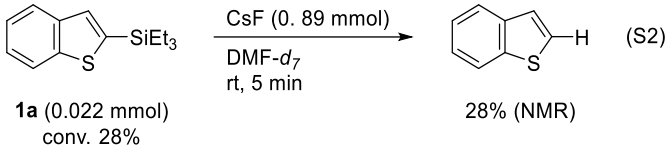
to give a residue, which was purified by column chromatography using hexane and ethyl acetate (hexane : ethyl acetate = 100:0 → 90:10 graduent) as an eluent to give 2-triethylsilyl-5-(4-trifluoromethylphenyl)-3,4-ethylenedioxythiophene (**8)** in 95% yield (74 mg, 0.19 mmol) as Colorless oil, R_f 0.25 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.83 (q, *J* = 8.0 Hz, 6H), 1.01 (t, *J* = 8.0 Hz, 9H), 4.22-4.25 (m, 2H), 4.28-4.31 (m, 2H), 7.57 (d, *J* = 8.0 Hz, 2H), 7.82 (d, *J* = 8.4 Hz, 2H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 4.00, 7.54, 64.3, 64.8, 108.6, 120.7, 124.4 (q, *J* = 273 Hz), 125.6 (q, *J* = 3.7 Hz), 125.8, 128.0 (q, *J* = 33.1 Hz), 136.9, 140.0, 148.1; ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.4 (s). IR (neat) 3432, 2954, 2937, 2911, 2875, 1615, 1577, 1565, 1519, 1472, 1455, 1433, 1409, 1361, 1324, 1291, 1271, 1264, 1241, 1194, 1166, 1125, 1087, 1069, 1048, 1014, 958, 931, 910, 840, 785, 760, 734, 721, 701, 672, 645, 636, 599, 564, 545, 521, 503, 492, 483, 473, 464, 462, 453, 422, 416, 405 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 400 (M^+, 65), 371 (100), 343 (56), 315 (81), 286 (17), 189 (24); HRMS (DART) calcd for $C_{19}H_{24}F_3O_2SSi$ (M + H) 401.1218, found 401.1221.

2-(4-Methoxyphenyl)-5-(4-trifluoromethylphenyl)-3,4-ethylenedioxythiophene (9). Colorless solid, mp = 156-160 °C, R_f 0.22 (hexane–ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.82 (s, 3H), 4.33-4.36 (m, 4H), 6.92 (d, *J* = 8.8 Hz, 2H), 7.58 (d, *J* = 8.0 Hz, 2H), 7.68 (d, *J* = 8.8 Hz, 2H), 7.82 (d, *J* = 8.4 Hz, 2H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 55.5, 64.6, 64.8, 112.6, 114.3, 117.2, 124.4 (q, *J* = 271.9 Hz), 125.4, 125.6 (q, *J* = 3.7 Hz), 125.8, 127.7, 127.8 (q, *J* = 33.0 Hz), 136.7, 137.7, 140.1, 158.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.4 (s). IR (neat) 2996, 2921, 2359, 1610, 1525, 1509, 1487, 1455, 1440, 1407, 1361, 1320, 1290, 1277, 1249, 1169, 1136, 1104, 1085, 1065, 1034, 1009, 972, 915, 857, 836, 830, 776, 759, 737, 696, 669, 634, 597, 543, 528, 501 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 392 (M^+, 100), 377 (22), 308 (15), 252 (32), 189 (35), 151 (97); HRMS (DART) calcd for $C_{20}H_{16}F_3O_3S$ (M + H) 393.0772, found 393.0766.

Cross-coupling copolymerization of 2,5-bis(triethylsilyl)-3,4-ethylenedioxy-thiophene (4a) with 2,7-dibromo-9,9-dioctylfluorene (11). In a glove-box, **4a** (111.0 mg, 0.299 mmol) and **10** (164.1 mg, 0.299 mmol) were added sequentially to a solution of $Pd_2(dba)_3$ (2.8 mg, 3.1 μmol), tris(2,4,6-trimethoxyphenyl)phosphine (6.7 mg, 13 μmol), CuF_2 (3.2 mg, 32 μmol), and CsF (115 mg, 0.757 mmol) in DMI (0.3 mL) prepared in a 3 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was heated at 100 °C for 7 days. The reaction mixture was filtered through Celite, and the filtrate was dried *in vacuo*. Desired polymer **Poly[(2,3-dihydrothieno[3,4-*b*]-1,4-dioxin-5,7-diyl)(9,9-dioctyl-9*H*-fluorene-2,7-diyl)] (11).**[34] (CAS registry number:

287924-60-1.) was isolated in 22% yield (37.3 mg, 0.670 mmol) by reprecipitation from CH_2Cl_2/MeOH and washing with Et_2O.

Desilylation of 2-triethylsilylbenzothiophene with CsF (Eq. 9).



*# The result of this experiment indicates **1a** reacted with CsF to give an anionic specie, which probably was the corresponding silicate.*

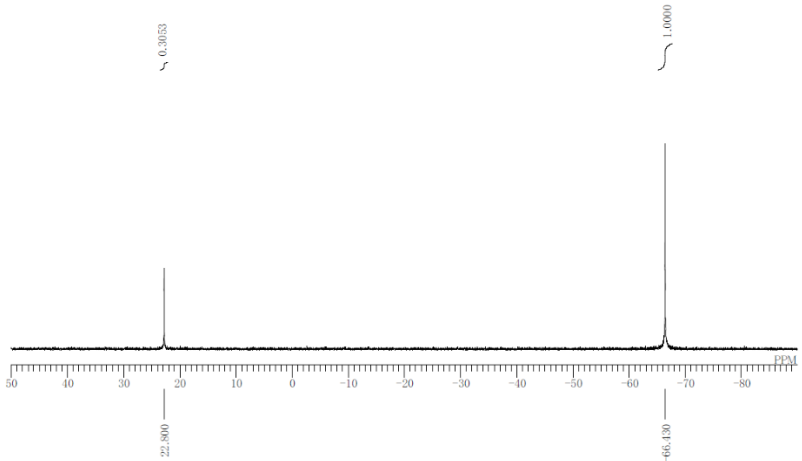
Into a dry Pyrex NMR tube were added **1a** (5.4 mg, 0.022 mmol), dimethylformamide-d_7 (0.75 mL), and CsF (13.5 mg, 0.089 mmol) under argon atmosphere. The resultant mixture was stirred by an irradiation of ultrasound at room temperature for 5 min. ^{1}H NMR analysis showed the generation of benzothiophene in 28% yield together with **1a** (conversion 28%) and $O(SiEt_3)_2$ (as presumed by GC-Mass analysis). No signal was observed in ^{19}F NMR analysis.

Examination of reactivity of CuF_2 toward Pd(0)

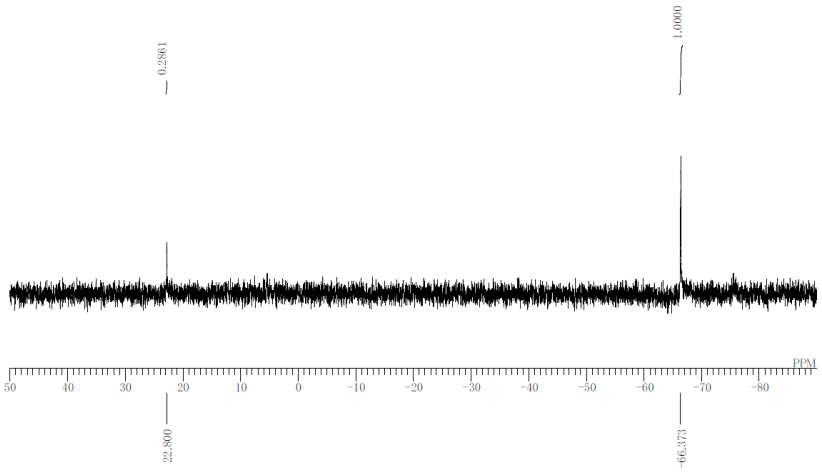
 # The result of this experiment indicates CuF_2 did not oxidize Pd(0) at least in this case.

Into a dry Pyrex NMR tube were added tris(2,4,6-trimethoxyphenyl)phosphine (TTMPP, 7.2 mg, 0.014 mmol), dimethylformamide-d_7 (0.75 mL), and CuF_2 (2.4 mg, 0.024 mmol) under argon atmosphere. The resultant mixture was heated at 100 °C for 16 hours. ^{31}P NMR analysis of the mixture showed TTMPP hardly ligated to CuF_2. ^{19}F NMR analysis showed there was little difference between the abovementioned mixture and a mixture of $Pd_2(dba)_3$ (16.5 mg, 0.018 mmol), TTMPP (42.4 mg, 0.080 mmol), and CuF_2 (9.1 mg, 0.090 mmol) in DMF-d_7 (0.75 mL) heated at 100 °C for 17 hours. This result maybe indicated CuF_2 did not oxidize Pd(0) at least.

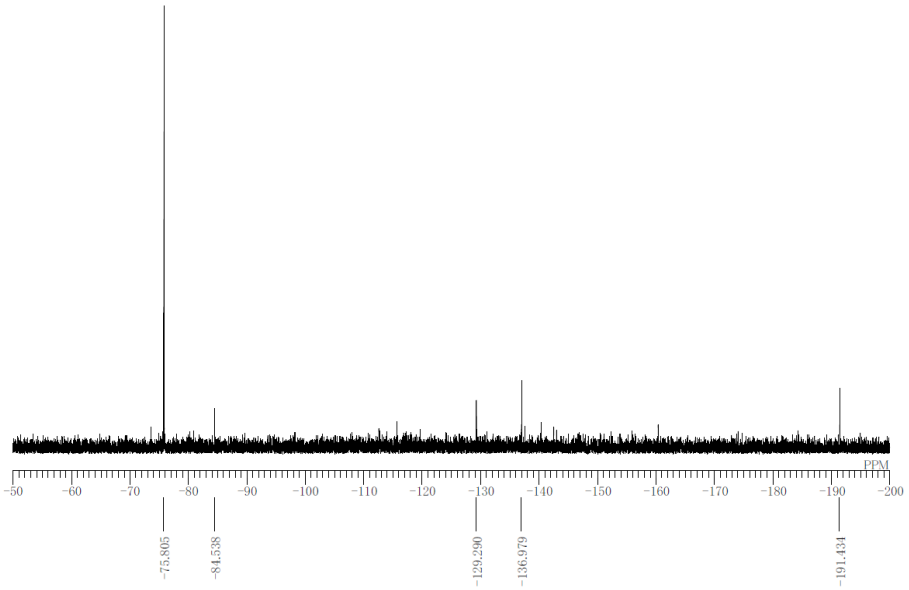
^{31}P NMR of TTMPP (δ = –66.4 ppm) including a slight amount of TTMPP oxide (δ = –22.8 ppm)[25]



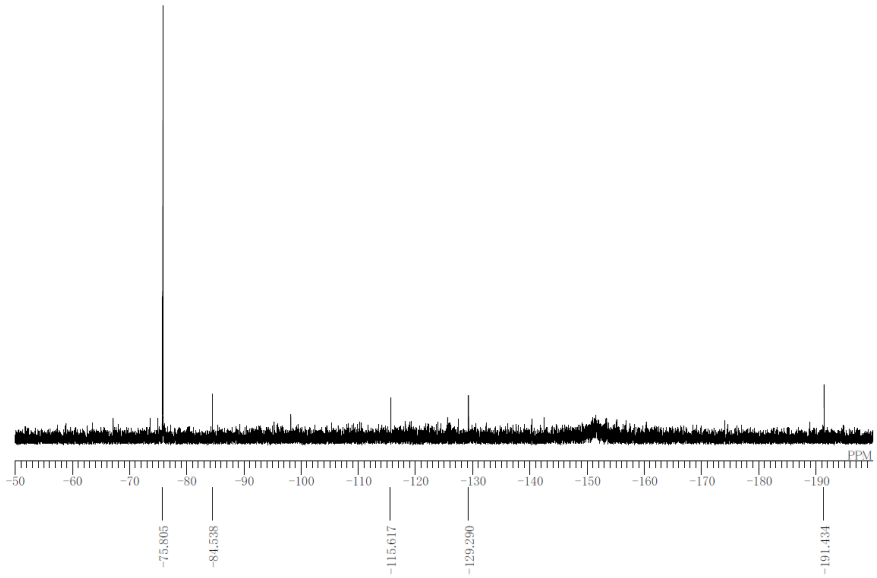
^{31}P NMR of the mixture of TTMPP and CuF_2 after heating



^{19}F NMR of the the mixture of TTMPP and CuF_2 *without* palladiun after heating



^{19}F NMR of the the the mixture of TTMPP and CuF_2 *with* palladiun after heating



4-5. References

1. For examples of transformations from arylsilanes into aryl copper species with bases, see: (a) Ito, H.; Sensui, H.; Arimoto, K.; Miura, K.; Hosomi, A. *Chem. Lett*. **1997**, 639. (b) Tsubouchi, A.; Muramatsu, D.; Takeda, T. *Angew. Chem., Int. Ed*. **2013**, *52*, 12719. (c) Gurung, S. K.; Thapa, S.; Vangala, A. S.; Giri, R. *Org. Lett*. **2013**, *15*, 5378. (d) Cornelissen, L.; Vercruysse, S.; Sanhadji, A.; Riant, O. *Eur. J. Org. Chem*. **2014**, 35. (e) Cornelissen, L.; Cirriez, V.; Vercruysse, S.; Riant, O. *Chem. Commun*. **2014**, 50, 8018. (f) Cornelissen, L.; Lefrancq, M.; Riant, O. *Org. Lett*. **2014**, *16*, 3024. (g) Takeda, T.; Obata, R.; Muramatsu, D.; Takeda, Y.; Tsubouchi, A. *Chem. Commun*. **2014**, *50*, 15156. (h) T. Takeda, Y. Takeda, A. Tsubouchi, *Chem. Lett*. **2015**, *44*, 809. (i) Cornelissen, L.; Nagy, A.; Leyssens, T.; Riant, O. *Synlett* **2017**, *28*, 2465.
2. Sonogashira, K.; Tohda Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, *16*, 4467.
3. For Pd/Cu-catalyzed cross-coupling reactions of organosilicon reagents, see: (a) Suginome, M.; Kinugasa, H.; Ito, Y. T*etrahedron Lett*. **1994**, *35*, 8635. (b) Nakao, Y.; Imanaka, H.; Sahoo, A. K.; Yada, A.; Hiyama, T. *J. Am. Chem. Soc.* **2005**, *127*, 6952. (c) Nakao,Y.; Sahoo,A. K.; Yada, A.; Chen, J.; Hiyama, T. *Sci. Technol. Adv. Mater.* **2006**, *7*, 536. (d) Nakao,Y.; Imanaka, H.; Chen, J.; Yada, A.; Hiyama, T. *J. Organomet. Chem.* **2007**, *692*,585. (e) Nakao,Y.; Ebata, A.; Chen, J.; Imanaka, H.; Hiyama, T. *Chem. Lett.* **2007**, 36, 606. (f) Nakao, Y.; Chen, J.; Tanada, M.; Hiyama, T. *J. Am. Chem. Soc.* **2007**, *129*, 11694. (g) Chen, J.; Tanaka, M.; Sahoo, A. K.; Takeda, M.; Yada, A.; Nakao,Y.; Hiyama, T. *Bull. Chem. Soc. Jpn*. **2010**, *83*, 554. (h) Shimizu, K.; Minami, Y.; Nakao,Y.; Goto, O.; Ikehira, H.; Hiyama, T. *Chem. Lett.* **2013**, *42*, 45. (i) Ohgi, A.; Semba, K.; Hiyama, T. Nakao, Y. *Chem. Lett*. **2016**, *45*, 973.
4. (a) Gouda, K.-i.; Hagiwara, E.; Hatanaka, Y.; Hiyama, T. *J. Org. Chem*. **1996**, *61*, 7232. (b) Mowery, M. E.; DeShong, P. *Org. Lett.* **1999**, *1*, 2137. (c) Molander, G. A.; lannazzo, L. *J. Org. Chem.* **2011**, *76*, 9182.
5. (a) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett*. **1990**, *31*, 2719. (b) Zhang, L.; Wu, J. *J. Am. Chem. Soc*. **2008**, *130*, 12250. (c) Zhang, L.; Qing, J.; Yang, P.; Wu, J. *Org. Lett.* **2008**, *10*, 4971.
6. Yadav, R. M.; Nagaoka, M.; Kashihara, M.; Zhong, R.-L.; Miyazaki, T.; Sakaki, S.; Nakao, Y. *J. Am. Chem. Soc*. **2017**, *139*, 9423.
7. Mishra, A.; Ma, C.-Q.; Bäuerle, P. *Chem. Rev.* **2009**, *109*, 1141.
8. Liu, C.-Y.; Zhao, H.; Yu, H. *Org. Lett*. **2011**, *13*,4068.

9. (a) Aubert, P. -H.; Knipper,M.; Groenendaal, L.; Lutsen, L.; Manca, J.; Vanderzande, D. *Macromolecules* **2004**, *37*, 4087. (b) Narayanan, S.; Abbas, A.; Raghunathan, S. P.; Sreekumar, K.; Kartha, C. S.; Joseph, R. *RSC Adv.* **2015**, *5*, 8657.
10. Ball showed direct transmetallation between Cu–F and Ar–Si(OR)$_3$ in the following report: J. R. Herron, Z. T. Ball, *J. Am. Chem. Soc*. **2008**, *130*, 16486. In the author's case, however, no reaction occurred when 2-SiEt$_3$-5-Si(*i*-Pr)$_3$-thiophene was treated with CuF_2 as described in Eq. 4, Chapter 3. Accordingly, he proposes the transmetallation step involves silicates.
11. Espinet showed that arylsilanes and CuF_2 generate arylcopper(I) and biaryls in the following report: J. delPozo, J. A. Casares, P. Espinet, *Chem. Eur. J*. **2016**, *22*, 4274. However, no homo-coupling product was observed in case of in Eq. 4, Chapter 3. Accordingly, he does not consider arylcopper(I) is formed from the arylsilanes and CuF_2.
12. For transmetallation between arylpalladium halides and organocopper species, see: (a) Bumagin, N.A.; Ponomaryov, A.B. *J. Organomet. Chem.* **1985**, *291*, 129. (b) Semba, K.; Ariyama, K.; Zheng, H.; Kameyama, R.; Sakaki, S.; Nakao, Y. *Angew. Chem. Int. Ed.* **2016**, *55*, 6275.
13. N.-Kumada, K.; Osawa, S.; Sasaki, M.; Chataigner, I.; Shigeno, M.; Kondo, Y. *J. Org. Chem.* 2017, *82*, 9487.
14. Hansen, M. M.; Clayton, M. T.; Godfrey, A. G.; Grutsch Jr., J. L. Keast, S. S.; Kohlman, D. T.; McSpadden, A. R.; Pedersen, S. W.; Ward, J. A.; Xu, Y-C. *Synlett* **2004**, *15*, 1351.
15. Guo, L.; Chatupheeraphat, A.; Rueping, M. *Angew. Chem. Int. Ed*. **2016**, *55*, 11810.
16. Komiyama, T.; Minami, Y.; Hiyama, T. *Angew. Chem. Int. Ed.* **2016**, *55*, 15787.
17. Schlosser M.; Heiss, C. *Eur*. *J. Org. Chem.* **2003**, 4618.
18. Heiss, C.; Rausis, T.; Schlosser, M. *Synthesis* **2005**, 617.
19. Tamba, S.; Okubo, Y.; Tanaka, S.; Monguchi, D.; Mori, A. *J. Org. Chem*. **2010**, *75*, 6998.
20. V.-Céspedes, S.; Chepiga, K. M.; Möller, N.; Schäfer, A. H.; Glorius, F. *ACS Catal.* **2016**, *6*, 5954.
21. Parmentier, M.; Gros, P.; Fort, Y.; *Tetrahedron* **2005**, *61*, 3261.
22. Singh, P. P.; Aithagani, S. K.; Yadav, M.; Singh, V. P.; Vishwakarma, R. A.; *J. Org. Chem*. **2013**, *78*, 2639.
23. Perry, G. J. P.; Quibell, J. M.; Panigrahi, A.; Larrosa, I. *J. Am. Chem. Soc*. **2017**, *139*, 11527
24. Chen, W.-B. Xing, C.-H.; Dong, J.; Hu, Q.-S. *Adv. Synth. Catal*. **2016**, *358*, 2072.

25. Ghosh D.; Lee, H. M. *Org. Lett*. **2012**, *14*, 5534.
26. Zhang, X.; Zeng, W.; Yang, Y.; Huang, H.; Liang, Y. *Synlett* **2013**, *24*, 1687.
27. Yamaguchi, E.; Wang, C.; Fukazawa, A.; Taki, M.; Sato, Y.; Sasaki, T.; Ueda, M.; Sasaki, N.; Higashiyama, T.; Yamaguchi, S. *Angew. Chem. Int. Ed*. **2015**, *54*, 4539.
28. Bíró, A. B.; Kotschy, A. *Eur. J. Org. Chem*. **2007**, 1364
29. Liu, Z.; Dong, N.; Xu, M.; Sun, Z.; Tu, T. *J. Org. Chem.* **2013**, *78*, 7436
30. Kuhl, N.; Hopkinson, M. N.; Glorius, F. *Angew. Chem. Int. Ed*. **2012**, *51*, 8230.
31. Bíró, A. B.; Kotschy, A. *Eur*. *J. Org. Chem*. **2007**, 1364.
32. Mohanakrishnan, A. K.; Amaladass, P.; Clement, J. A. *Tetrahedron Lett*. **2007**, *48*, 539.
33. Belhboub, A.; Hermet, P.; Alvarez, L.; Parc, R. L.; Rols, S.; Selvati, A. C. L; Jousselme, B.; Sato, Y.; Suenaga, K.; Rahmani, A.; Bantignies, J.-L. *J. Phys. Chem. C* **2016**, *120*, 28802.
34. Aubert, P.-H. Martin Knipper, M.; Groenendaal, L.; Lutsen, L.; Manca, J.; Vanderzande, D. *Macromolecules* **2004**, *37*, 4087.

Chapter 5

Copper-catalyzed Aryl–Alkyl Bond-forming Coupling Between Aryl(triethyl)silanes and Alkyl Halides

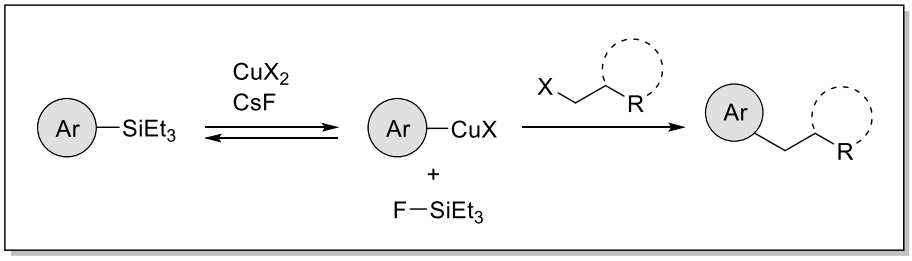
Aryl(trialkyl)silanes underwent coupling reaction with alkyl (pseudo)halides in the presence of copper iodide/phenanthroline catalyst and cesium fluoride. Alkyl halides including iodides, bromides, chlorides, and even tosylates participated the reaction showing a wide range of functional group tolerance.

5-1. Introduction

Silicon-based coupling reactions with aryl and alkenyl halides have been well developed so far. On the other hand, there were a few reports on the reactions using alkyl (pseudo)halides as an electrophilic coupling partner.[1–5] Fu first reported such reaction of aryl(trimethoxy)silanes with *primary* alkyl halides using a palladium catalyst and a bulky phosphine ligand, which prevent a β-hydride elimination on the palladium center.[3a] Shortly after, nickel catalysts were also found to be effective for the reaction with *primary* and *secondary* alkyl halides.[3b] A decade later, Tuchimoto/Takeda demonstrated HOMSi-type reagents reacted with alkyl halides with the aid of a copper catalyst.[4a] Similar reactions were also reported by Riant, who employed benzylic and allylic halides as the alkyl electrophiles.[4b–e]

Although aryl(trialkyl)silanes are becoming promising reagents as discussed before, the cross-coupling reaction between such silanes and alkyl (pseudo)halides are limited to only two examples.[5] Indeed, phenyl(trialkyl)silanes bearing hydroxymethyl or carbonyl groups at their ortho positions couple with alkyl halides using stoichiometric copper mediators through the Brook rearrangement.

As the author described in Chapters 3 and 4, aryl(triethyl)silanes undergo the cross-coupling reaction with aryl halides by means of a $CuBr_2$ single catalyst or palladium(0)/CuF_2 dual catalysts. For success of the both reactions, a catalytic amount of the copper salt is necessary. Although the role of the copper salts is unclear, there is a possibility that organocopper species are generated from arylsilanes and copper salts.[6,7] He envisaged that aryl(triethyl)silanes might couple directly even with alkyl halides in the presence of a copper catalyst (scheme 5-1).



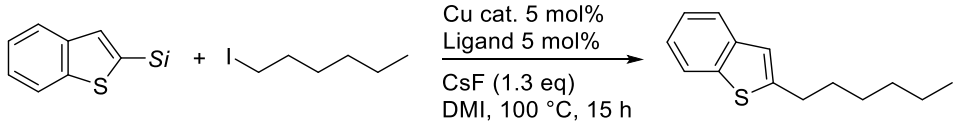
Scheme 5-1. Working Hypothesis of Cross-coupling Between Aryl(triethyl)silanes and Alkyl Halides.

5-2. Result and Discussion

During the study described in Chapter 4, the author found that 2-triethylsilylbenzo[*b*]thiophene (**1a**, 1.1 eq) reacted with 1-iodohexane (**2a**) in the presence of 5 mol% of copper difluoride and 1.3 equivalents of cesium fluoride in 1,3-dimethyl-2-

imidazolidinone (DMI) at 100 °C to give 2-hexylbenzo[*b*]thiophene (**3aa**) in 69% yield (Table 5-1, Run 1). Without the catalyst, **3aa** was formed but in only 48% yield (Run 2). This result probably implys that an silicate generated in situ underwent nucleophilic attack to **2a** directly.[8] Use of such ligands as 2,2-bipyridyl (bpy) and 1,10-phenanthroline (phen) improved yield, though other ligands like phosphines and *N*-heterocyclic carbenes were futile. When the sort of copper salts were examined, cuprous iodide was found best to catalyze the reaction to give **3aa** in 86% yield (Runs 5–7). In all cases, formation of a protodesilylated product was observed. Stoichiometric reaction of **1a** toward **2a** resulted in a slightly lower yield (Run 8). Other trialkylsilyl groups like $SiMe_3$, TBS, and $Si(i\text{-}Pr)_3$ were also applicable to the present coupling reaction (Runs 9−11).

Table 5-1. Screening the Conditions



1a, 1.1 eq **2a** **3aa**

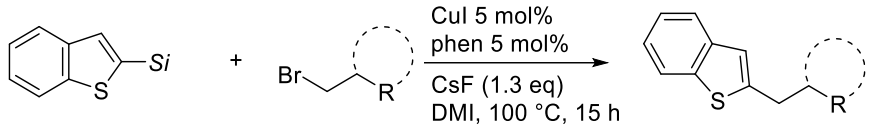
Run	**1a**, *Si*	Cu cat.	Ligand	Yield of **3aa** (%)[b]
1	**1a**, $SiEt_3$	CuF_2	-	69
2	**1a**, $SiEt_3$	-	-	48
3	**1a**, $SiEt_3$	CuF_2	bpy	83
4	**1a**, $SiEt_3$	CuF_2	phen	88
5	**1a**, $SiEt_3$	CuI	phen	92 (86)[c]
6	**1a**, $SiEt_3$	CuBr	phen	90
7	**1a**, $SiEt_3$	$CuBr_2$	phen	80
8[d]	**1a**, $SiEt_3$	CuI	phen	83
9	**1a'**, $SiMe_3$	CuI	phen	92
10	**1a''**, $SiMe_2t$-Bu	CuI	phen	86
11	**1a***, $Si(i\text{-}Pr)_3$	CuI	phen	86

[a] Unless otherwise noted, a mixture of **1a** (1.1 eq), **2a** (0.3 mmol), Cu cat. (5 mol%), ligand (5 mol%), and CsF (1.3 eq) in DMI (2 M) was stirred at 100 °C for 15 h. The purity of the employed CuF_2 is 99.5%, and that of CuI, CuBr, and $CuBr_2$ is 99.999% [b] NMR yields. [c] Isolated yield. [d] 1.0 Equivalent of **1a** was used. bpy = 2,2-bipyridyl, phen = 1,10-phenanthroline.

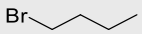
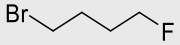
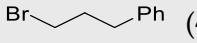
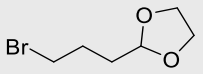
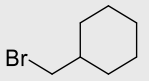
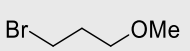
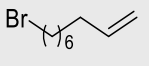
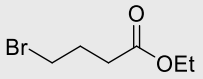
The author next examined the scope of electrophiles. Because alkyl bromides are more practical than alkyl iodides in view of commercial availability and stability in air, he first tested the reaction of **1a** with butyl bromide (**2b**) and isolated butylated product

3ab in 78% yield (Table 5-2, Run 1). Fluorine, phenyl, or acetal moiety on alkyl bromide **4c**–**4e** tolerated the reaction to give **3ac**–**3ae** in good yields (Runs 2–4). A branched primary alkyl-type electrophile, cyclohexylmethyl bromide (**2f**) coupled with **1a** afforded product **3af** in 61% yield of (Run 5). The same product **3af** was obtained in 84% yield by replacing **1a** by $SiMe_3$-type reagent **1a'** (Run 6). Likewise, methoxy-, vinyl-, and ethoxycarbonyl-substituted alkyl bromides **2g**–**2i** reacted with **1a'** giving rise to **3ag**–**3ai** in good yields, whereas **1a** performed slightly less efficiently (Runs 7−12). Unfortunately, *secondary* alkyl halides like iodocyclohexane did not participate in the present reaction at all.

Table 5-2. Scope of Alkyl Bromides 4



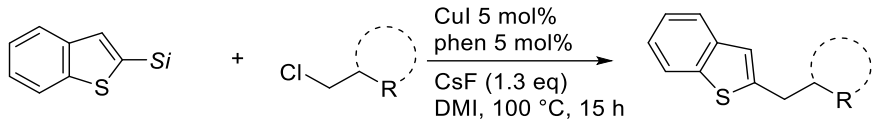
1a or **1a'**, 1.1 eq **4** **3a**

Run	**1**, *Si*	Alkyl Bromides **4**	Product, Yield /%[b]
1	**1a**, $SiEt_3$	 (**4b**)	**3ab**, 78
2	**1a**, $SiEt_3$	 (**4c**)	**3ac**, 81
3	**1a**, $SiEt_3$	 (**4d**)	**3ad**, 81
4	**1a**, $SiEt_3$	 (**4e**)	**3ae**, 59
5	**1a**, $SiEt_3$	 (**4f**)	**3af**, (61)
6	**1a'**, $SiMe_3$	**4f**	**3af**, 84
7	**1a**, $SiEt_3$	 (**4g**)	**3ag**, (38)
8	**1a'**, $SiMe_3$	**4g**	**3ag**, 84
9	**1a**, $SiEt_3$	 (**4h**)	**3ah**, 66
10	**1a'**, $SiMe_3$	**4h**	**3ah**, 83
11	**1a**, $SiEt_3$	 (**4i**)	**3ai**, (20)
12	**1a'**, $SiMe_3$	**4i**	**3ai**, 68

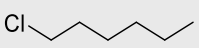
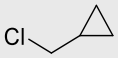
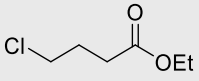
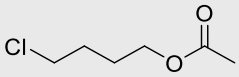
[a] Unless otherwise noted, a mixture of **1a** or **1a'** (1.1 eq), **2** (0.3 mmol), CuI (5 mol%), phen (5 mol%), and CsF (1.3 eq) in DMI (2 M) was stirred at 100 °C for 15 h. [b] Isolated yields. Numbers in the parenthesis mean NMR yields.

He next examined use of alkyl chlorides **5** instead of alkyl bromides **4** and unveiled that hexyl chloride (**5a**) underwent the reaction with **1a** to produce **3aa** without any serious problems (Table 5-3, Run 1). Cycropropylmethyl chloride (**5j**) gave normal coupled product **3aj** without ring-opened product **3aj*** (Runs 2 and 3). This probably indicates homolytic cleavage of carbon–chlorine bond is not involved in its catalytic cycle.[9] Ethoxycarbonyl and acetoxy groups on alkyl chlorides **5i** and **5k** could be tolerated under the conditions (Runs 4–6).

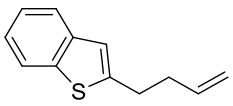
Table 5-3. Scope of Aryl Chlorides 5



1a or **1a'**, 1.1 eq **5** **3a**

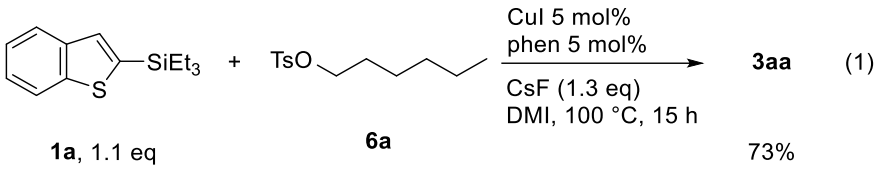
Run	**1**, SiR_3	Alkyl halides **5**	Yield of **3** /%[b]
1	**1a**, $SiEt_3$	 (**5a**)	**3aa**, 80
2	**1a**, $SiEt_3$	 (**5j**)	**3aj**, (56)
3	**1a'**, $SiMe_3$	**5j**	**3aj**, 79
4	**1a**, $SiEt_3$	 (**5i**)	**3ai**, 42
5	**1a'**, $SiMe_3$	**5i**	**3ai**, 47
6	**1a**, $SiEt_3$	 (**5k**)	**3ak**, 51

[a] Unless otherwise noted, a mixture of **1a** or **1a'** (1.1 eq), **2** (0.3 mmol), CuI (5 mol%), phen (5 mol%), and CsF (1.3 eq) in DMI (2 M) was stirred at 100 °C for 15 h. [b] Isolated yields. Numbers in the parenthesis are NMR yields.



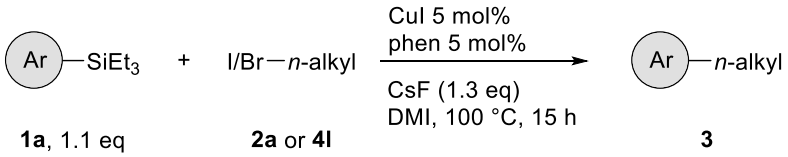
3aj* (not detected)

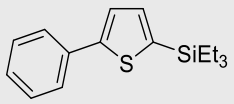
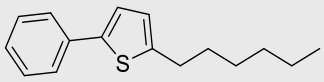
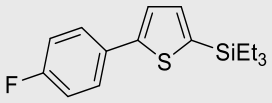
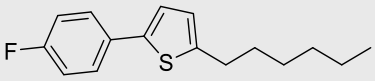
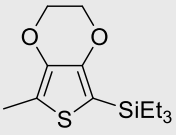
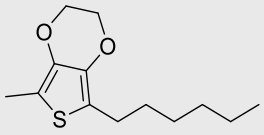
Alkyl tosylates also participated in this reaction. For example, hexyl tosylate (**6a**) reacted with **1a** to give **3aa** in 73% yield (Eq. 1).

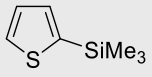
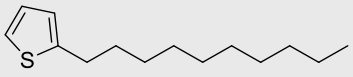
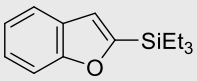
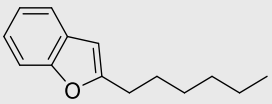
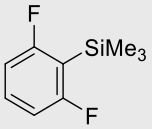
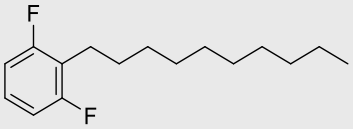


Alkylation of aryl(trialkyl)silanes by the aryl–alkyl bond-forming reaction is summarized in Table 5-4. 2-Triethylsilylthiophenes **1b**–**1d** reacted with **2a** to give hexylthiophenes **3ba**–**3da** in good yields (Runs 1–3). Commercially available 2-trimethylsilylthiophene (**1e'**) also reacted with 1-bromodecane (**4l**) and gave 2-dodecrylthiophene (**3el**) in 75% yield (Run 4). In this case, thienyl anion migration appears negligibile, as only a trace amount of 2-$SiMe_3$-5-decylthiophene was detected by GC-MS. Triethylsilyl-substituted benzo[*b*]furan (**1f**) was activated to furnish **3fa** in 62% yield (Run 5). Similarly, electron-deficient phenyl(trialkyl)silanes were found to show enough reactivity. For example, 2,6-difluorophenyl(trimethyl)silane (**1g'**) with **4l** produced **3gl** in excellent yield (Run 6). Of note, triethyl analog **1g** gave **3gl** in similar yield but separation of **3gl** and a slight amount of silicon residue, probably $O(SiEt_3)_2$, was difficult.

Table 5-4. Scope of Arylsilanes 1

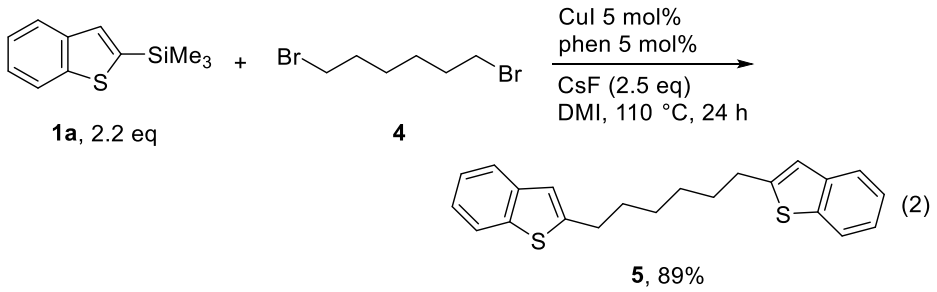


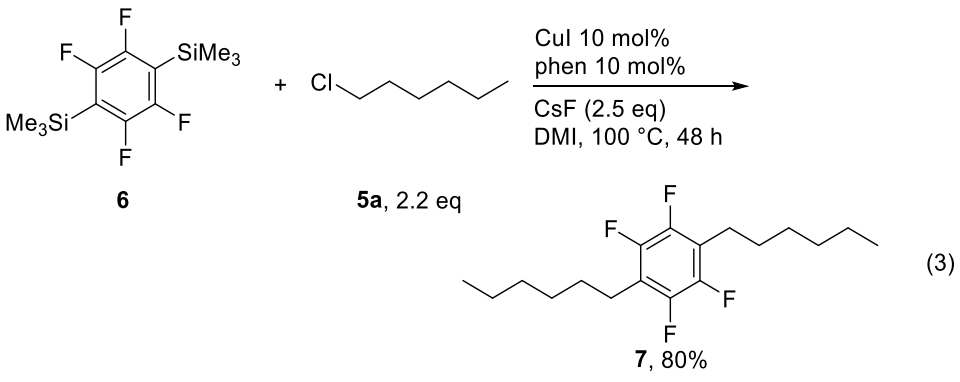
	Arylsilane **1**	**2a** or **4l**	Product, Yield /%[b]
1	 **1b**	**2a**, I–*n*-Hex	 **3ba**, 77
2	 **1c**	**2a**, I–*n*-Hex	 **3ca**, 69
3	 **1d**	**2a**, I–*n*-Hex	 **3da**, 70

4	 **1e'**	**4l**, Br–*n*-Dec	 **3el**, 75
5	 **1f'**	**2a**, I–*n*-Hex	 **3fa**, 62
6	 **1g'**	**4l**, Br–*n*-Dec	 **3gl**, 88

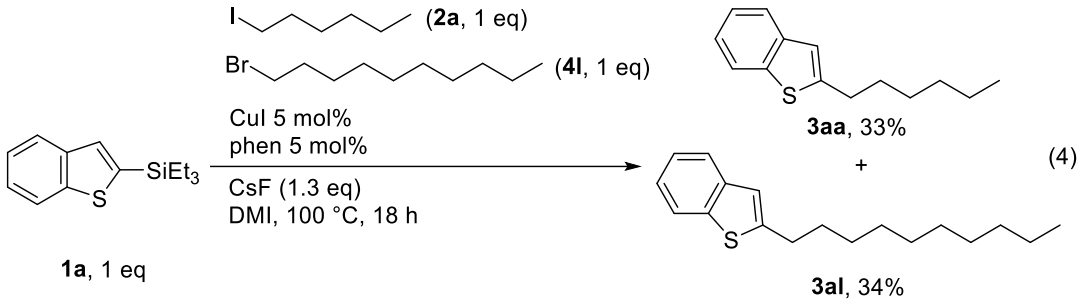
[a] Unless otherwise noted, a mixture of **1** (1.1 eq), **2a** or **4l**(0.3 mmol), CuI (5 mol%), phen (5 mol%), and CsF (1.3 eq) in DMI (2 M) was heated at 100 °C for 15 h. [b] Isolated yields. [c] 120 °C. d 1.0 Equivalent of 2-trimethylsilylthiophene (**1e'**) was used.

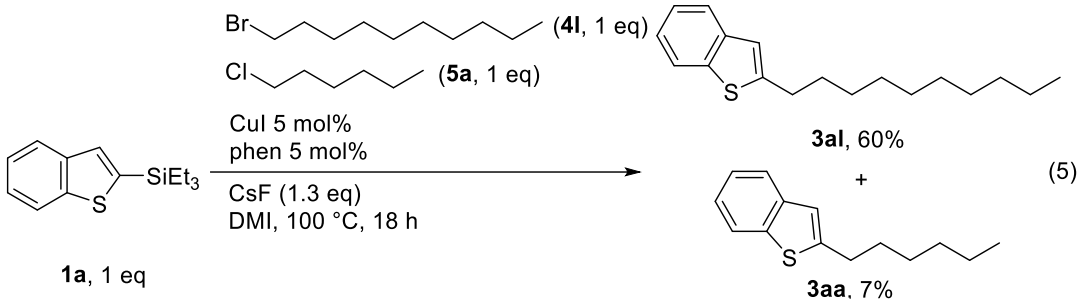
The author applied the present method to double coupling reaction using a terminal alkyl dihalides. For example, diarylalkane **5** was produced by the coupling of 2.2 equivalents of **1a'** with 1,6-dibromohexane (**4**) using CsF in 2.5 qquivalents and heating at 110 °C for 24 h (Eq. 2). In addition, 1,4-$(SiMe_3)_2$-C_6F_4 (**6**) doubly coupled with 1-chlorohexane (**5a**) to give 1,4-dihexyltetrafluorobenzene **7** in 80% yield (Eq. 3).





To compare the reactivity of alkyl halides in the present reaction, he run the competition experiments in the presence of two kinds of halides. For example, when the reaction of **1a** with 1-iodohexane (**2a**) and 1-bromodecane (**4l**) was carried out, corresponding products **3aa** and **3al** were obtained in a similar yield (Eq. 4). In contrast, the reaction of **1a** in the presence of 1-bromohexane (**4l**) and 1-chlorohexane (**5a**) produced **3aa** (60% yield) and **3aa (**7% yield), respectively (Eq. 5). Thus, the reactivity order of alkyl halides falls in the following order: alkyl iodides ≈ alkyl bromides > alkyl chlorides.





5-3. Conclusion

In conclusion, the author has disclosed that stable aryl(trialkyl)silanes undergo the cross-coupling reaction with alkyl (pseudo)halides by means of copper iodide/phenanthroline catalytic system and cesium fluoride as an activator of the C–Si bond. The present reaction is available to use primary alkyl iodides, bromides, chlorides, and even tosylates including various functional groups. The result of cyclopropyl chloride probably indicates the present reaction does not contain single-electron-transfer. The present coupling and C–H silylation reaction provide us with novel synthetic route to synthesize arenes bearing long alkyl chains.

5-4. Experimental Section and Additional Information

The IR spectra were measured by JASCO FT/IR-4200. 1-Iodohexane was purchased from TCI and used after distillation.

Copper-catalyzed cross-coupling reaction of 2-(triethylsilyl)benzo[*b*]thiophene (1a) and 1-iodohexane (2a). —*General procedure for the present cross-coupling reaction*— In a glove-box, **1a** (82 mg, 0.33 mmol) and **2a** (65 mg, 0.31 mmol) were added sequentially to a solution of CuI (2.9 mg, 15 μmol), 1,10-phenanthroline (2.7 mg, 15 μmol), and CsF (59 mg, 0.39 mmol) in DMI (0.15 mL) set in a 3 mL-vial. The vial was closed with a screw PTFE septum cap and the resultant mixture was stirred at 100 °C for 15 h. The reaction mixture was filtered through a Celite pad, and the filtrate was concentrated *in vacuo*. The residue was purified by column chromatography using hexane as an eluent to give 2-(hexyl)benzo[*b*]thiophene[10] (**3a,** 58 mg, 0.27 mmol, 86% yield)**.** CAS registry number: 71948-96-4.

2-(*n*-Butyl)benzo[*b*]thiophene (3ab).[11] CAS registry number: 17890-53-8.

2-(4-Fluorobutyl)benzo[*b*]thiophene (3ac). A pale yellow oil, R_f 0.17 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72–1.92 (m, 4H), 2.96 (d, *J* = 7.2 Hz, 2H), 4.48 (dt, *J* = 47.2, 5.6 Hz, 2H), 7.01 (s, 1H), 7.25 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.30 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 1H), 7.76 (d, *J* = 8.0 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 26.9 (d, *J* = 4.5 Hz), 29.8 (d, *J* = 20.3 Hz), 30.4, 83.9 (d, *J* = 165 Hz), 120.9, 122.2, 122.8, 123.6, 124.2, 139.4, 140.2, 145.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ −218.545 (tt, *J* = 46.2, 22.2 Hz). IR (NaCl) 3057, 2960, 2944, 2904, 2864, 1457, 1436, 1389, 1306, 1155, 1133, 1066, 1039, 1014, 975, 934, 908, 857, 828, 746, 727, 708, 576, 498, 422 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 208 (M^+, 32), 184 (15), 160 (10), 147 (100); HRMS (DART) calcd for $C_{12}H_{14}FS$ (M + H) 209.0800, found 209.1795.

2-(3-Phenylpropyl)benzo[*b*]thiophene (3ad). a pale yellow solid, mp = 54–57 °C（再結は？）, R_f 0.24 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.08 (tt, *J* = 7.6, 7.6 Hz, 2H), 2.71 (t, *J* = 7.6 Hz, 2H), 2.92 (t, *J* = 7.6 Hz, 2H), 7.00(s, 1H), 7.19–7.31 (m, 7H), 7.66 (d, *J* = 8.0 Hz, 1H), 7.76 (d, *J* = 7.6 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 30.2, 32.7, 35.2, 120.8, 122.2, 122.8, 123.5, 124.2, 126.0, 128.5, 128.6, 139.4, 140.3, 141.8, 146.2. IR (NaCl) 3060, 3026, 2936, 2856, 1603, 1496, 1456, 1436, 1066, 908, 857, 822, 744,

726, 699, 455, 420 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 252 (M^+, 29), 160 (9), 148 (100), 147 (68), 115 (28), 91 (13); HRMS (DART) calcd for $C_{17}H_{17}S$ (M + H) 253.1051, found 253.1060.

2-[3-(1,3-Dioxolan-2-yl)propyl]benzo[*b*]thiophene (3ae). A yellow oil, R_f 0.19 (hexane–ethyl acetate = 20:1). ^1H NMR (400 MHz, $CDCl_3$) δ 1.74–1.81 (m, 2H), 1.84–1.93 (m, 2H), 2.96 (t, *J* = 6.8 Hz, 2H), 3.82–4.01 (m, 4H), 4.90 (t, *J* = 4.4 Hz, 1H), 7.01 (d, *J* = 0.4 Hz, 1H), 7.24 (ddd, *J* = 7.6, 7.6, 1.6 Hz, 1H), 7.30 (ddd, *J* = 7.6, 7.6, 1.2 Hz, 1H), 7.65 (d, *J* = 7.6 Hz, 1H), 7.75 (d, *J* = 7.6 Hz, 1H); ^{13}C {^1H} NMR (101 MHz, $CDCl_3$) δ 25.5, 30.7, 33.2, 65.0, 104.3, 120.8, 122.2, 122.8, 123.5, 124.1, 139.4, 140.3, 146.1. IR (neat) 3427, 3057, 2949, 2878, 2248, 1458, 1435, 1666, 1458, 1435, 1411, 1134, 1065, 1044, 939, 910, 827, 735, 469 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 248 (M^+, 20), 186 (18), 185 (17), 160 (100), 147 (31), 86 (16), 73 (29).

2-(Cyclohexylmethyl)benzo[*b*]thiophene (3af).[12] CAS registry number: 71948-96-4.

2-(4-Methoxybutyl)benzo[*b*]thiophene (3ag). Colorless oil, R_f 0.17 (hexane–ethyl acetate = 20:1). ^1H NMR (400 MHz, $CDCl_3$) δ 1.64–1.71 (m, 2H), 1.79–1.86 (m, 2H), 2.92 (t, *J* = 7.6 Hz, 2H), 3.33 (s, 3H), 3.41 (t. *J* = 6.4 Hz, 2H), 7.00 (s, 1H), 7.24 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.29 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.65 (d, *J* = 8.0 Hz, 1H), 7.75 (d, *J* = 8.0 Hz, 1H); ^{13}C {^1H} NMR (101 MHz, $CDCl_3$) δ 27.8, 29.2, 30.7, 58.7, 72.5, 120.1, 122.2, 122.8, 123.5, 124.1, 139.4, 140.3, 164.4. IR (NaCl) 3058, 2978, 2932, 2863, 2827, 2808, 1457, 1436, 1387, 1306, 1193, 1156, 1119, 1066, 1015, 908, 856, 824, 744, 727, 709, 496, 475 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 220 (M^+, 38), 188 (15), 184 (20), 173 (11), 160 (100), 147 (72), 134 (9); HRMS (DART) calcd for $C_{13}H_{17}OS$ (M + H) 221.1000, found 221.1006.

2-(8-Nonen-1-yl)benzo[*b*]thiophene (3ah). Colorless oil, R_f 0.52 (hexane). ^1H NMR (400 MHz, $CDCl_3$) δ 1.28–1.37 (m, 8H), 1.72 (tt, *J* = 7.6, 7.6 Hz, 2H), 2.03 (dt, *J* = 5.1, 5.1 Hz, 2H), 4.93 (d, *J* = 10.4 Hz, 1H), 4.98 (d, *J* = 17.2 Hz, 1H), 5.80 (ddt, *J* = 17.0, 10.0, 6.8 Hz, 1H), 6.94 (s, 1H), 7.22 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.23 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.64 (d, *J*= 7.6 Hz, 1H), 7.74 (d, *J* = 8.0 Hz, 1H); ^{13}C {^1H} NMR (101 MHz, $CDCl_3$) δ 29.0, 29.1, 29.2, 29.4, 30.1, 31.2, 33.9, 114.3, 120.5, 122.2, 122.8, 123.4, 124.1, 139.3, 139.4, 140.3, 146.9. IR (NaCl) 3072, 3058, 2927, 2853, 1639, 1458, 1436, 1066, 994, 909, 820, 743, 726 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 258 (M^+, 13), 173 (5), 161 (10), 160 (8), 148 (62), 147 (100); HRMS (DART) calcd for $C_{17}H_{23}S$ (M + H) 259.1521, found

259.1516.

2-(3-Ethoxycarbonylpropyl)benzo[*b*]thiophene (3ai). A pale yellow oil, R_f 0.17 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.25 (t, *J* = 7.2 Hz, 3H), 2.07 (dd, *J* = 7.6, 7.6 Hz, 2H), 2.39 (t, *J* = 7.6 Hz, 2H), 2.96 (t, *J* = 7.2 Hz, 2H), 4.13 (q, *J* = 7.2 Hz, 2H), 7.01 (s, 1H), 7.25 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.30 (dd, *J* = 7.2, 7.2 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 1H), 7.76 (d, *J* = 8.0 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 14.4, 26.3, 30.1, 33.4, 60.5, 121.2, 122.2, 122.9, 123.7, 124.2, 139.4, 140.2, 145.2, 173.3. IR (NaCl) 3057, 2979, 2937, 2869, 1733, 1457, 1437, 1374, 1304, 1246, 1225, 1183, 1158, 1145, 1026, 747, 727 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 248 (M^+, 30), 203 (16), 173 (7), 161 (16), 160 (100), 147 (39), 134 (4); HRMS (DART) calcd for $C_{14}H_{17}O_2S$ (M + H) 249.0949, found 249.0948.

2-(4-Acetoxybutyl)benzo[*b*]thiophene (3aj). Colorless oil, R_f 0.14 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.68–1.75 (m, 2H), 1.77–1.85 (m, 2H), 2.04 (s, 3H), 2.92 (t, *J* = 7.2 Hz, 2H), 4.09 (t, *J* = 7.2 Hz, 2H), 7.00 (s, 1H), 7.24 (dd, *J* = 8.0, 8.0 Hz, 1H), 7.30 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.66 (d, *J* = 7.6 Hz, 1H), 7.75 (d, *J* = 8.0 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 21.1, 27.5, 28.0, 30.4, 64.2, 120.9, 122.2, 122.8, 123.6, 124.2, 139.4, 140.2, 145.9, 171.3. IR (NaCl) 3060, 2944, 2860, 1738, 1457, 1436, 1387, 1306, 1242, 1065, 1044, 1016, 858, 825, 747, 727, 430 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 248 (M^+, 30), 187 (15), 161 (16), 160 (100), 148 (12), 147 (75); HRMS (DART) calcd for $C_{14}H_{17}O_2S$ (M + H) 249.0949, found 249.0958.

2-(Cyclopropylmethyl)benzo[*b*]thiophene (3ak). Colorless oil, R_f 0.52 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.27–0.30 (m, 2H), 0.58–0.63 (m, 2H), 1.05–1.15 (m, 1H), 2.79 (d, *J* = 6.8 Hz, 2H), 7.01 (s, 1H), 7.23 (dd, *J* = 7.2, 7.2 Hz, 1H), 7.29 (dd, *J* = 7.6, 7.6 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 1H), 7.75 (d, *J* = 7.6 Hz, 1H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 5.18, 12.2, 35.7, 120.5, 122.2, 122.8, 123.5, 124.1, 139.5, 140.2, 146.4. IR (NaCl) 3072, 3058, 3000, 2915, 2885, 2824, 1460, 1431, 1421, 1186, 1156, 1014, 938, 917, 866, 830, 795, 756, 745, 727, 666, 569 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 188 (M^+, 31), 173 (6), 160 (26), 147 (100), 115 (16); HRMS (DART) calcd for $C_{12}H_{13}S$ (M + H) 189.0738, found 189.0744.

5-Hexyl-2-phenylthiophene (3ba).[13] CAS registry number: 1486382-46-0.

5-Hexyl-2-(*p*-fluorophenyl)thiophene (3ca). Colorless solid, mp = 47–50 °C, R_f 0.52

(hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.89 (t, *J* = 6.4 Hz, 3H), 1.31–1.40 (m, 6H), 1.69 (tt, *J* = 7.6, 7.6 Hz, 2H), 2.80 (t, 7.6 Hz, 2H), 6.72 (d, *J* = 3.2 Hz, 1H), 7.01–7.06 (m, 3H), 7.50 (dd, *J* = 8.8, 5.2 Hz, 2H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 14.3, 22.7, 28.9, 30.4, 31.7, 31.8, 115.8 (d, *J* = 21.8 Hz), 122.7, 125.1, 127.2 (d, *J* = 8.3 Hz), 131.2 (d, *J* = 3.0 Hz), 140.6, 145.9, 162.1 (d, *J* = 248 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −218.485 (tt, *J* = 7.9, 6.0 Hz). IR (NaCl) 2952, 2921 2852, 1511, 1466, 1239, 832, 804, 500, 480, 470, 461, 454, 443, 423, 407 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 262 (M^+, 21), 192 (14), 191 (100), 133 (5); HRMS (DART) calcd for $C_{16}H_{20}FS$ (M + H) 263.1270, found 263.1278.

2-Hexyl-5-methyl-3,4-ethylenedioxythiophene (3da). Colorless oil, R_f 0.24 (hexane–ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (t, *J* = 6.8 Hz, 3H), 1.27–1.36 (m, 6H), 1.52–1.59 (m, 2H), 2.19 (s, 3H), 2.57 (t, *J* = 7.6 Hz, 2H), 4.13–4.17 (m, 4H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 10.8, 14.2, 22.8, 25.7, 29.0, 30.8, 31.7, 64.7, 64.8, 107.6, 113.7, 137.1, 137.5. IR (NaCl) 2957, 2927, 2871, 2857, 2255, 1535, 1455, 1435, 1363, 1148, 1123, 1088, 1059, 976, 947, 908, 735, 650, 465 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 240 (M^+, 16), 170 (10), 169 (100), 113 (6), 59 (13); HRMS (DART) calcd for $C_{13}H_{21}O_2S$ (M + H) 241.1262, found 241.1260.

2-Decylthiophene (3el).[14] CAS registry number: 24769-39-9.
2-Hexylbenzo[*b*]furan (3fa).[15] CAS registry number: 39195-67-0.
2-Decyl-1,3-difluorobenzene (3gl).[16] CAS registry number: 1207202-37-6.

Copper-catalyzed double cross-coupling reaction of 2-(trimethylsilyl)benzo-[*b*]thiophene (1a') with 1,6-dibromohexane (4). In a glove-box, **1a'** (136 mg, 0.66 mmol) and **4** (72 mg, 0.30 mmol) were added sequentially to a solution of CuI (2.7 mg, 14 μmol), 1,10-phenanthroline (2.7 mg, 15 μmol), and CsF (113 mg, 0.75 mmol) in DMI (0.15 mL) prepared in a 3 mL-vial. The vial was closed with a screw PTFE septum cap, and the resultant mixture was stirred at 100 °C for 15 h. The reaction mixture was cooled to room temperature, filtered through a Celite pad, and the filtrate was conccentrated *in vacuo*. The residue was purified by column chromatography using hexane as an eluent to give 1,6-di(benzo[*b*]thiophen-2-yl)hexane (**5**, 93 mg, 0.26 mmol, 89% yield) as colorless solid, mp = 93–95 °C, R_f 0.17 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.45 (m, 4H), 1.75 (tt, *J* = 7.2, 7.2 Hz, 4H), 2.89 (t, *J* = 7.6 Hz, 4H), 6.98 (s, 2H), 7.24 (ddd, *J* = 7.2, 7.2, 1.2 Hz, 2H), 7.30 (ddd, *J* = 7.6, 7.6, 1.2 Hz, 2H), 7.65 (d, *J* = 8.0 Hz, 2H), 7.75 (d, *J* = 7.6 Hz, 2H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 28.9, 30.8, 31.1, 120.6, 122.2, 122.8, 123.5, 124.1, 139.4, 140.3, 146.7. IR (NaCl) 3067, 3049, 3011, 2923, 2851, 1456, 1434, 1308,

1415, 1150, 1131, 1066, 1008, 940, 86, 829, 740, 727 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 350 (M^+, 35), 215 (10), 161 (16), 160 (11), 148 (47), 147 (100) 115 (9); HRMS (DART) calcd for $C_{22}H_{23}S_2$ (M + H) 351.1241, found 351.1241.

Copper-catalyzed double cross-coupling reaction of 1,4-bis(trimethylsilyl)-2,3,5,6-tetrafluorobenzene (6) and 1-chlorohexane (5a). In a glove-box, **6** (89 mg, 0.30 mmol) and **5a** (81 mg, 0.67 mmol) were added sequentially to a solution of CuI (5.9 mg, 30 μmol), 1,10-phenanthroline (5.7 mg, 32 μmol), and CsF (113.5 mg, 0.747 mmol) in DMI (0.15 mL) prepared in a 3 mL-vial. The vial was closed with a screw PTFE septum cap, and the resulting mixture was stirred at 100 °C for 48 h. The reaction mixture was filtered through a Celite pad, and the filtrate was concentrated *in vacuo*. The residue was purified by column chromatography using hexane as an eluent to give 3,6-di(*n*-hexyl)-1,2,4,5-tetrafluorobenzene (**7**, 77 mg, 0.24 mmol, 80% yield) as a pale yellow oil, R_f 0.85 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (t, *J* = 6.8 Hz, 6H), 1.26–1.38 (m, 12H), 1.58 (tt, *J* = 7.6, 7.6 Hz, 4H), 2.68 (t, 7.6 Hz, 4H); ^{13}C {^{1}H} NMR (101 MHz, $CDCl_3$) δ 14.2, 22.7, 22.8 (t, *J* = 1.6 Hz), 29.0, 29.5, 31.6, 117.9–118.4 (m), 143.4–146.2 (m); ^{19}F NMR (376 MHz, $CDCl_3$) δ −146.5 (s). IR (NaCl) 2958, 2931, 2860, 2363, 2339, 1485, 1269, 1120, 1022, 1003, 937, 912, 473, 464, 432, 406 cm^{-1}. MS (EI, 70 eV) *m/z* (%) 318 (M^+, 100), 248 (23), 247 (41), 178 (37), 176 (55), 163 (49), 71 (90), 55 (24).

Competition experiment between 1-iodohexane (2a) and 1-bromodecane (4l) toward 2-triethylsilylbenzo[*b*]thiophene (1a). In a glove-box, **1a** (74 mg, 0.30 mmol), **2a** (62 mg, 0.29 mmol), and **4l** (66 mg, 0.30 mmol) were added sequentially to a solution of CuI (2.9 mg, 15 μmol), 1,10-phenanthroline (2.7 mg, 15 μmol), and CsF (60 mg, 0.39 mmol) in DMI (0.15 mL) placed in a 3 mL-vial. The vial was closed with a screw PTFE septum cap, and the resultant mixture was stirred at 100 °C for 18 h. The reaction mixture was filtered through a Celite pad, and the filtrate was asseyed by gas chromatography to reveal oupled products **3aa** and **3al** were formed in 33% and 34% yields, respectively.

Competition experiment between 1-bromodecane (4l) and 1-chlorohexane (5a) toward 2-triethylsilylbenzo[*b*]thiophene (1a). This experiment was operated in a manner similar to the above competition experiment. Coupled products **3al** and **3aa** were dproduced in 60% and 7% yields, respectively, as asseyed by GLC.

2-Decylbenzo[*b*]thiophene (3al).[10] CAS registry number: 959234-20-9.

5-5. References

1. For a review on cross-coupling reaction with alkyl halides, see: Kambe, N.; Iwasaki, T.; Terao, J. *Chem. Soc. Rev.* **2011**, *40*, 4937.
2. For Pd-catalyzed cross-coupling of reactive organosilanes with alkyl halides, see: (a) Lee, J.-Y.; Fu, G. C. *J. Am. Chem. Soc.* **2003**, *125*, 5616. For the Tsuji-Trost reaction using reactive silanes as an nucleophile, see: (b) Yoshida, J.; Tamao, K.; Takahashi,; M. Kumada, M. *Tetrahedron Lett.* **1978**, *19*, 2161. (c) Brescia, M.-R.; DeShong, P. *J. Org. Chem*. **1998**, *63*, 3156. (d) Kabalka, G. W.; Dong, G.; Venkataiah, B.; Chen, C. *J. Org. Chem*. **2005**, *70*, 9207. (e) Dey, R.; Chattopadhyay, K.; Ranu, B. C. *J. Org. Chem.* **2008**, *73*, 9461. (f) Srimani, D.; Bej, A.; Sarkar, A. *J. Org. Chem.* **2010**, *75*, 4296. (g) Frye, E. C.; O'Connor, C. J.; Twigg, D. G.; Elbert, B.; Laraia, L.; Hulcoop, D. G.; Venkitaraman,; A. R. Spring, D. R. *Chem. Eur. J*. **2012**, *18*, 8774.
3. For Ni-catalyzed cross-coupling of reactive organosilanes with alkyl halides, see: (a) Powell, D. A.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 7788. (b) Strotman, N. A.; Sommer, S.; Fu, G. C. *Angew. Chem., Int. Ed*. **2007**, *46*, 3556. (c) Dai, X.; Strotman, N. A.; Fu, G. C. *J. Am. Chem. Soc.* **2008**, *130*, 3302. (d) Wu, Y.; Zhang, H.-R.; Cao, Y.-X.; Lan, Q.; Wang, X.-S. *Org. Lett*. **2016**, *18*, 5564. For Ni/photoredox Ir-catalyzed cross-coupling of organosilicates with alkyl halides, see: (e) Lévêque, C.; Corcé, V.; Chenneberg, L.; Ollivier, C.; Fensterbank, L. *Eur. J. Org. Chem.* **2017**, 2118.
4. For Cu-catalyzed cross-coupling of reactive organosilanes with alkyl halides, see: (a) Tsubouchi, A.; Muramatsu, D.; Takeda, T. *Angew. Chem., Int. Ed.* **2013**, *52*, 12719. (b) Cornelissen, L.; Vercruysse, S.; Sanhadji, A.; Riant, O. *Eur. J. Org. Chem.* **2014**, 35. (c) Cornelissen, L.; Cirriez, V.; Vercruysse, S.; Riant, O. *Chem. Commun.* **2014**, *50*, 8018. (d) Cornelissen, L.; Lefrancq, M.; Riant, O. *Org. Lett.* **2014**, *16*, 3024. (e) Cornelissen, L. Nagy, A. Leyssens, T. Riant, O. *Synlett* **2017**, *28*, 2465.
5. (a) Taguchi, H. Takami, K. Tsubouchi, A. Takeda, T. *Tetrahedron Lett.* **2004**, *45*, 429. (b) Tsubouchi, A. Matsuda, H. Kita, T. Takeda, Y. *Chem. Lett.* **2009**, *38*, 1180.
6. (a) Suginome, M.; Kinugasa, H.; Ito, Y. *Tetrahedron Lett.* **1994**, *35*, 8635. (b) Ito, H.; Sensui, H.; Arimoto, K.; Miura, K.; Hosomi, A. *Chem. Lett.* **1997**, 639. (c) Gurung, S. K.; Thapa, S.; Vangala, A. S.; Giri, R. *Org. Lett*. **2013**, *15*, 5378. (d) Takeda, T.; Obata, R.; Muramatsu, D.; Takeda, Y.; Tsubouchi, A. *Chem. Commun.* **2014**, *50*, 15156. (e) Takeda, T.; Takeda, Y.; Tsubouchi, A. *Chem. Lett.* **2015**, *44*, 809.
7. For reviews of copper-catalyzed cross-coupling reactions of other organometallic

reagents based on magnesium, boron, and so on with alkyl halides, see: (a) Beletskaya, I. P.; Cheprakov, A. V. Coord. *Chem. Rev*. **2004**, *248*, 2337. (b) Terao, J. Kambe, N. Acc. *Chem. Res.* **2008**, *41*, 1545. (c) Thapa, S.; Shrestha, B.; Gurung, S. K.; Giri, R. *Org. Biomol. Chem.* **2015**, *13*, 4816.

8. Base-promoted reactions of organosilicon reagents with such electrophiles as aldehydes, perfluoroarenes, and carbon dioxide were reported. These reactions are considered to take place via formation of silicates. See: (a) Effenberger, F.; Spiegler, W. *Chem. Ber*. **1985**, *118*, 3900. (b) Pilcher, A. S.; DeShong, P. *J. Org. Chem*. **1996**, *61*, 6901. (c) Suzawa, K.; Ueno, M.; Wheatley, A. E. H.; Kondo, Y. *Chem. Commun.* **2006**, 4850. (d) Wang, Y. Watson, M. D. *J. Am. Chem. Soc.* **2006**, *128*, 2536. (e) Y.-Kobayashi,; M. Inamoto,; K. Kondo, Y. *Chem. Lett*. **2014**, *43*, 477.
9. The isomerization of the cyclopropylmethyl radical to the butenyl radical has been reported. See: Maillard, B.; Forrest, D.; Ingold, U. K. J. Am. Chem. Soc. 1976, 98, 7024.
10. Guilarte, V.; F.-Rodríguez, M. A.; G.-García, P.; Hernando, E.; Sanz, R. *Org. Lett.* **2011**, *13*, 5100.
11. Urban, S.; Beiring, B.; Ortega, N.; Paul, D.; Glorius, F. *J. Am. Chem. Soc*. **2012**, *134*, 15241.
12. Vechorkin, O.; Proust, V.; Hu, X. *Angew. Chem. Int. Ed.* **2010**, *49*, 3061.
13. Vamvounis, G.; Pivrikas, A.; Shaw, P. E.; Burn, P. L. *Thin Solid Films* **2013**, 190.
14. Pu, S.; Zhu, S.; Rao, Y.; Liu, G.; Wei, H. *J. Mol. Struct.* **2009**, 89.
15. Ackermann, L.; Kaspar, L. T. *J. Org. Chem.* **2007**, *72*, 6149.
16. Wunderlich, S. H.; Knochel, P. *Angew. Chem. Int. Ed*. **2009**, *48*, 9717.

Chapter 6

Conclusion and Perspective

The author has investigated the cross-coupling chemistry with triorganosilyl-substituted arenes, *inter alia*, trialkylsilyl-type reagents. Although this type of reagents exhibits attractive properties for organic synthesis, preparation of cross-coupling-active triorganosilyl-type reagents necessitates a multi-step process, whereas simple trialkylsilyl-type reagents do not participate in the typical cross-coupling reaction before the author started the present study. Throughout the present dissertation, he has provided the straightforward procedure for preparation of reactive triorganosilyl-type reagents and the requisite catalytic conditions for the cross-coupling reactions based on the silyl reagents. These results are summarized as follows.

In Chapter 1, the author presented a brief history of the cross-coupling reaction, classic and modern preparative methods of organosilicon reagents, and detailed story of evolution process of the silicon-based cross-coupling reaction. At the end of this chapter, research problems of the silicon-based cross-coupling chemistry are discussed, and the contents of the present Dissertation are briefly summarized.

In Chapter 2, the author shows the iridium-catalyzed C–H silylation is suitable for synthesis of aryl– and alkenyl–HOMSi reagents starting with the corresponding arenes and alkenes straightforwardly. This particular method allows one to access to various HOMSi reagents with ease as demonstrated by rapid and straightforward synthesis of oligoarylene monomer for organic solar sell.

In Chapter 3, he unveiled that aryl(triethyl)silanes coupled with aryl iodides successfully with the aid of cupric bromide in a catalytic amount and cesium fluoride in a stoichiometric amount. Such silane reagents were easily obtained by catalytic aryl C–H silylation, although the cross-coupling reaction with the triorganosilyl reagents was unprecedented. A variety of arylsilane reagents based on $SiMe_3$, $SiEt_3$, $SiMe_2$(*t*-Bu), and $Si(i\text{-}Pr)_3$ as well as various aryl iodides were shown to be applicable to the synthesis of biaryls, teraryls, and polyarylenes.

In Chapter 4, aryl bromides and chlorides were shown to participate in the cross-coupling reaction with aryl(triethyl)silanes. The collaborative use of a palladium and copper catalyst is essential for the reaction. As with Chapter 3, a wide range of nucleophiles and electrophiles were demonstrated to be applicable to the present coupling reaction. In addition, he showcased a systematic synthesis of unsymmetric diarylthiophenes via C–H arylation of monosilylthiophene followed by his cross-coupling.

In Chapter 5, the author showed that alkyl halides should be added to the list of applicable electrophiles for aryl(triethyl)silane-based cross-coupling reaction. Cuprous iodide was definitely shown to catalyze such reaction smoothly. Various alkyl halides including iodides, bromides, and chlorides bearing such functionalities like vinyl, carbonyl, and cyclopropyl underwent the coupling reaction and gave the desired alkylarenes easily.

The present study allows to access to various target molecules through the cross-coupling using stable, less toxic, and readily accessible trialkylsilyl-type reagents. In fact, some oligoarenes were already synthesized through the combination of catalytic C–H siltation and his presented coupling reactions in recent papers (Kondo, Y. et al. *J. Org. Chem.* **2017**, *82*, 9487.; Martin, R. et al. *J. Am. Chem. Soc.* **2019**, *141*, 127.). The author hopes to emphasize that the trialkylsilyl-type reagents are generally inert against various transformations, and thus the present study has a potential to innovate synthetic routes for highly functionalized organic molecules using robust silicon reagents as the basic reagents for the construction of carbon frameworks.

List of Publications

Original Papers

(1) "**Straightforward Synthesis of HOMSi Reagents via sp^2C–H Silylation**"
Yasunori Minami, Takeshi Komiyama, Tamejiro Hiyama
Chemistry Letters, **2015**, *44*, 1065–1067.
(Chapter 2)

(2) "**Aryl(triethyl)silanes for Biaryl and Teraryl Synthesis by Copper(II)-Catalyzed Cross-coupling Reaction**"
Takeshi Komiyama, Yasunori Minami, Tamejiro Hiyama
Angewandte Chemie International Edition, **2016**, *55*, 15787–15791.
(Chapter 3)

(3) "**Palladium/Copper Dual Catalysis for Cross-coupling of Aryl(trialkyl)silanes with Aryl Bromides**"
Takeshi Komiyama, Yasunori Minami, Yuki Furuya, Tamejiro Hiyama
Angewandte Chemie International Edition, **2018**, *57*, 1987–1990.
(Chapter 4)

(4) "**Copper-catalyzed Cross-coupling Reaction between Aryl(trialkyl)silanes and Alkyl Halides**"
Takeshi Komiyama, Yasunori Minami, Tamejiro Hiyama
Chemistry Letters, **2018**, *47*, 1048–1050.
(Chapter 5)

(5) "**Cross-coupling Reaction using Aryl(triethyl)silanes with Aryl Chlorides: An Easy to Access to Oligothiophenes**"
Takeshi Komiyama, Yasunori Minami, Tamejiro Hiyama
Chemistry Letters, **2019**, *in press.* DOI:10.1246/cl.181018
(Chapter 4)

Review/Account

(6) "**Recent Advances in Transition-Metal-Catalyzed Synthetic Transformations of Organosilicon Reagents**"
Takeshi Komiyama, Yasunori Minami, Tamejiro Hiyama
ACS Catalysis, **2017**, *7*, 631–651. (*Review*)

(7) "**Recent Progress in the Cross-coupling Reaction using Triorganosilyl-type Reagents**"
Takeshi Komiyama, Yasunori Minami, Tamejiro Hiyama
Synlett, **2017**, *28*, 1873–1884. (*Account*)

The following publications are not included in the dissertation.

(8) "**Synthesis of HOMSi Reagents by Pd/Cu-Catalyzed Silylation of Bromoarenes with Disilanes**"
Yasunori Minami, Kenta Shimizu, Chisato Tsuruoka, Takeshi Komiyama, Tamejiro Hiyama
Chemistry Letters, **2014**, *43*, 201–203.

(9) "**Catalytic Carbon–Nitrogen Bond-forming Cross-coupling using *N*-Trimethylsilylamines**"
Yasunori Minami, Takeshi Komiyama, Kenta Shimizu, Tamejiro Hiyama, Osamu Goto, Hideyuki Ikehira
Bulletin of the Chemical Society of Japan, **2015**, *88*, 1437–1446.

(10) "**Nickel-catalyzed *N*-Arylation using *N*-TMS-carbazole**"
Yasunori Minami, Takeshi Komiyama, Kenta. Shimizu, Shuichi Uno, Tamejiro Hiyama, Osamu Goto, Hideyuki Ikehira
Synlett, **2017**, *28*, 2407–2410.