Title
Catalytic Silylation of C-H Bonds: Reaction Development, Mechanism, and Applications and Development of Degradable Polymers from Biorenewable Sources

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Catalytic Silylation of C-H Bonds: Reaction Development, Mechanism, and Applications

and

Development of Degradable Polymers from Biorenewable Sources

by

Chen Cheng

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy
in
Chemistry
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Graduate Division
of the
University of California, Berkeley

Committee in charge:

Professor John F. Hartwig, Chair
Professor Thomas J. Maimone
Professor Alexander Katz

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Abstract

Catalytic Silylation of C-H Bonds: Development, Mechanism, and Applications
and
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Doctor of Philosophy in Chemistry

University of California, Berkeley

Professor John F. Hartwig, Chair

The following dissertation discusses the development of catalytic silylation reactions of alkenyl, aryl, and heteroaryl C-H bonds, some mechanistic studies on the Ir-catalyzed silylation of terminal alkenes and Rh-catalyzed silylation of arenes, and applications of the Ir-catalyzed C-H silylation to the functionalization of complex active pharmaceutical ingredients (APIs).

Chapter 1 provides a review of the utility and importance of C-H silylation, challenges and limitations of traditional approaches to constructing C-Si bonds, and limitations of catalytic C-H silylation, and some mechanistic insight on C-H silylation.

Chapter 2 describes a method for the catalytic silylation of terminal alkenyl C-H bonds to construct either Z- or E-vinylsilanes with high diastereoselectivity under mild conditions. The switch in the diastereoselectivity is resulted from a switch in the ligand. Mechanistic studies suggest that the reaction proceed through insertion and beta-elimination, not through direct C-H activation.

Chapter 3 describes a method for the Rh-catalyzed silylation of unactivated aryl C-H bonds with high sterically derived regioselectivity. This method represents the first one to construct C-Si bonds from C-H and Si-H bonds under mild conditions with arene as the limiting reagent. Examples in which the regioselectivities are superior to or different from those of the C-H borylation are demonstrated. The resulting arylsilanes are stable to many typical organic functional groups interconversions yet amenable to further functionalization under conditions orthogonal to those of arylboranes, rendering this method useful for the construction of synthetic building blocks.

Chapter 4 discusses the mechanism of the Rh-catalyzed silylation, including isolation of the catalyst resting state, rate measurements, rate law derivation, and kinetic isotope effect (KIE) experiments. A plausible catalytic cycle is proposed. The influence of the electronic properties of

the arene substituents on the reversibility and relative rates for individual steps of the mechanism, and on the regioselectivity of the C-H bond cleavage and functionalization, is discussed.

Chapter 5 describes a method for the Ir-catalyzed silylation of aryl and heteroaryl C-H bonds. This method requires slightly higher reaction temperature than the Rh-catalyzed silylation described in Chapter 3, but is compatible with a much broader range of functional groups, including many heteroaromatic moieties. Silylation and functionalization of APIs is demonstrated.

Chapter 6 provides a brief discussion on the current state of the art on C-H silylation and the challenges to be overcome.

Chapter 7 describes the synthesis of polysilylethers (PSEs) using a monomer derived from a biorenewable feedstock. The monomer contains an alcohol and a silyl hyride moiety, which allows for polymerization through catalytic dehydrogenative coupling of an alcohol and a silyl hydride to form polymers with silyl ether linkages. High molar mass products were achieved, and the degree of polymerization was controlled by varying the amount of an AA-type monomer in the reaction. The PSEs possess good thermal stability and a low glass transition temperature ($T_g \approx -67$ ℃). The PSEs was degraded in acidic aqueous solutions to a low-molecular weight diol, which could be further biodegraded or used as building blocks for other polymers. To demonstrate the utility of the PSEs, polyurethanes were synthesized with low molar mass hydroxy-telechelic PSEs.

Chapter 8 describes making new siloxane-containing, degradable polymers from biorenewable feedstock, as well as attempts to improve the synthetic route to access the monomer described in Chapter 7. Specifically, instead of using silyl ether linkages as handles for polymerization and degradation, Si-O-Si linkages were incorporated into monomers, which lead to polymers containing Si-O-Si linkages. Polyurethane, polycarbonate, polyesters, and polyamides were synthesized. Polyurethanes containing siloxane linkages were hydrolyzed under mildly acidic conditions, achieving controlled polymer degradation.

Chapter 9 describes the synthesis of a macrolactone containing a Si-O-Si linkage from undecenonic acid, and the ring-opening polymerization (ROP) of this macrolactone by a well-defined Zn-complex. ABA triblock copolymers were also synthesized with polyesters made from this macrolactone as the mid-block.

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Finally, I wish to express gratitude to my parents for their continuous care, understanding, and support. With graduate school behind me, I shall finally go back and visit them.

Chapter 1: A Brief Overview of Catalytic C-H Silylation

1.1 Introduction

Methods for efficient, catalytic functionalization of unactivated C-H bonds with boron[1] and silicon[2] reagents are valuable to the fields of synthetic chemistry and materials science. Methods for catalytic borylation of aryl and alkyl C-H bonds have been widely adopted because of the utility of aryl- and alkylboron products, the mild conditions of the borylation reactions, the broad scope of substrates that react, and the high number of turnovers (up to 25000 turnovers).[3-4] The scope, mechanism, and applications of the borylation of C-H bonds have been reviewed.[1] Highly active catalysts for the borylation of C-H bonds generated from the combination of $[Ir(cod)OMe]_2$ and a bipyridine or phenanthroline ligand are now widely used. The most commonly used catalyst for the borylation of aryl C-H bonds contains 4,4'-di-*tert*-butylbipyridine (dtbpy) as ligand;[3, 5] the most active catalyst currently for the borylation of alkyl or heteroaryl C-H bond contains 3,4,7,8-tetramethyl-1,10-phenanthroline (Me_4Phen) as ligand.[6-8]

Because of their diagonal relationship in the periodic table,[9] silicon and boron have related properties and reactivity at bonds to these elements. For example, both boron and silicon display semiconductor properties and form air- and moisture-unstable hydrides and chlorides.[9] Moreover, both boron[10] and silicon[11] hydrides add to alkenes, although the boron hydrides add to alkenes without a catalyst in many cases.

Consistent with the effect of this diagonal relationship, both C-B and C-Si bonds can be constructed by C-H bond functionalization. The boryl and silyl groups can then serve as temporary functional groups suitable for further functionalization. For example, both arylboron[12] and arylsilicon[13-14] reagents undergo cross-coupling with electrophiles in the presence of an appropriate catalyst, and both classes of compound undergo oxidation by H_2O_2 to form alcohols under similar conditions.[15-16] In addition, both classes of compounds undergo halogenations, including fluorination,[17-18] bromination,[19-20] and iodination,[19-20] and they undergo aminations.[21-22]

Although there are similarities between boron and silicon reagents for C-H bond functionalization, there are significant differences. First, in contrast to aryl- and alkylboron compounds, aryl- and alkylsilanes are useful precursors to commercial polymers and co-polymers.[23] Second, the natural abundance of silicon in earth's crust is four orders of magnitude higher than that of boron.[24] Third, silanes are more stable than boranes for storage and handling. Thus, a silane should be economically more favorable than a borane as a reagent for generating organic derivative by C-H bond functionalization, and the silane products can be used as both intermediates for organic synthesis and monomers for important polymers.

Arylsilanes are traditionally prepared by addition of chlorosilanes[25-26] or cyclosiloxanes[27-28] to Grignard or organolithium reagents. The main limitation of this method is the incompatibility of Grignard and organolithium reagents with many functional groups. In addition, large scale

synthesis using this method would incur a large amount of stoichiometric metal salt byproducts, which would be undesirable.

Alternatively, arylsilanes can be prepared by cross-coupling of aryl halides with hydrosilanes[29-30] or disilanes[31-33] catalyzed by transition metal-complexes. While this approach overcomes the functional group incompatibility of Grignard and organolithium reagents, this approach still requires pre-functionalization of the arene, and the regioselectivity of silylation is limited by the halogenation step.

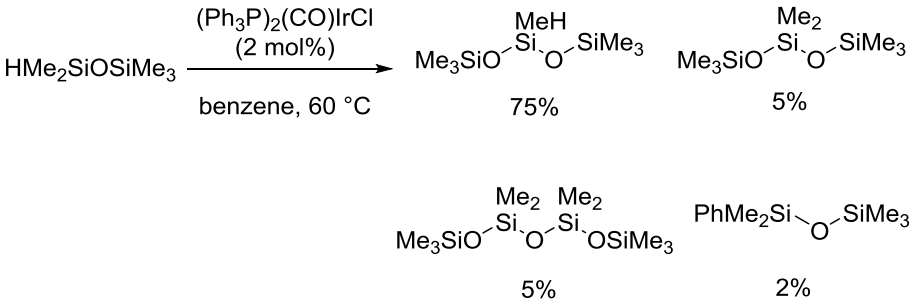
Thus, methods to prepare organosilanes by silylation of C-H bonds is an attractive goal because it eliminates the requirement for pre-functionalization of the arene and could form products with distinct regioselectivity from the sequence of halogenation and silylation by catalytic coupling or Grignard intermediates. However, the silylation of C-H bonds is much less developed than the borylation of C-H bonds, and the application of silylation of C-H bonds to synthetic chemistry has been limited by the inefficiency of the silylation reaction. Often, high temperatures and a large excess of the substrate, relative to the silane, are required. However, catalysts have been discovered recently that lead to the silylation of alkyl and aryl C-H bonds in a more practical manner.

1.2 Methods for the Silylation of Aryl C-H Bonds

Examples of the silylation of aryl C-H Bonds can be divided into three classes: 1) intramolecular, 2) directed intermolecular, and 3) undirected intermolecular silylations of C-H bonds. Intramolecular silylation produces the products of the silylation of C-H bonds in good yields with a 1:1 molar ratio of arene to silane, but this strategy requires tethering a suitable silane to the arene substrates. Intermolecular Silylation of C-H bonds directed by a coordinating group on the arene eliminates tethering the silane to the arene, but it is limited to substrates that have suitable groups that will coordinate the catalyst. In addition, directed silylation of arene C-H bonds has been limited to *ortho*-functionalization. Until recently, undirected intermolecular silylation of arene C-H bonds had required high temperatures and a large excess of arene. These characteristics limited the synthetic utility of the silylation of C-H bonds. A system discovered by Cheng and Hartwig has overcome this restriction.[34] For this dissertation, only the undirected C-H silylation reactions are reviewed here. A more comprehensive review has been written by Cheng and Hartwig.[35]

Curtis and co-workers reported the first catalytic silylation of arenes.[36] When pentamethyldisiloxane ($HMe_2SiOSiMe_3$) was heated in benzene in the presence of Vaska's complex, $(Ph_3P)_2(CO)IrCl$, at 60 ℃, $PhMe_2SiOSiMe_3$ was obtained in 2% yield, along with various products from silane redistribution (Scheme 1). Similarly, when tetramethyldisiloxane ($HMe_2SiOSiMe_2H$) was heated in benzene with Vaska's complex as the catalyst, 1-2% $PhMe_2SiOSiMe_2H$ was detected among the various products.

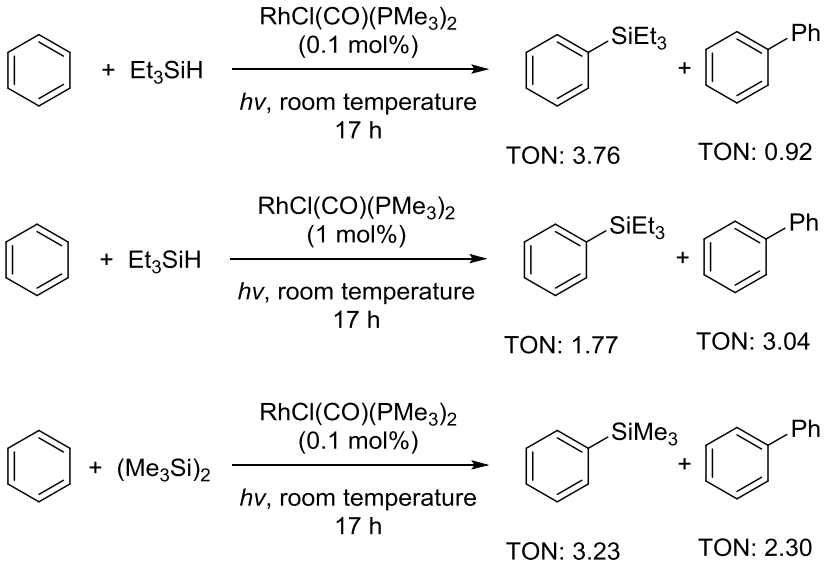
Scheme 1. Silylation of benzene catalyzed by Vaska's complex.[36]



To confirm that the source of the phenyl groups in the products was benzene, and not Ph_3P, the reaction was run in C_6D_6. The resulting phenylsiloxanes contained C_6D_5 groups, indicating that C-H or C-D bond cleavage of benzene occurred. To probe the maximum turnover number (TON) of this catalysis, a sealed ampule of pentamethyldisiloxane in benzene was heated at 100 ℃ for 49 d in the presence of 2% Vaska's complex. The total TON for all phenylsiloxane products was 13.4.

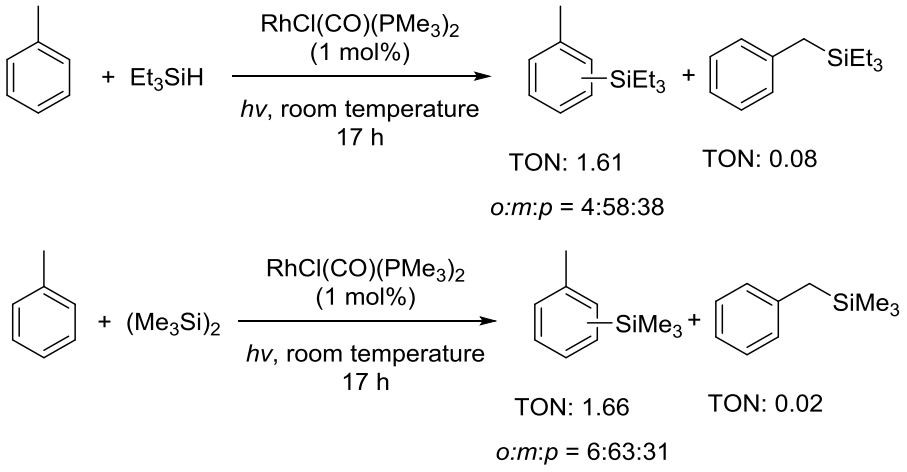
Tanaka and co-workers reported a method for the Rh-catalyzed silylation of arenes with $HSiEt_3$ or $(Me_3Si)_2$ that is much more selective for the desired silylarenes over the products of silane redistribution.[37] When a solution of $HSiEt_3$ in benzene was irradiated with a mercury lamp at room temperature in the presence of 1% $RhCl(CO)(PMe_3)_2$ for 17 h, $PhSiEt_3$ (TON = 3.76) and biphenyl (TON = 0.92) formed (Scheme 2). The ratio of silylated arene to biaryls varied with the catalyst loading. For example, reducing the Si/Rh ratio to 100 led to the formation of more biphenyl ($PhSiEt_3$ TON = 1.77, biphenyl TON = 3.04). In addition, the reaction of benzene with $(Me_3Si)_2$ at room temperature under the same irradiation also led to $PhSiMe_3$ (TON = 3.23) and biphenyl (TON = 2.30).

Scheme 2. Rh-catalyzed arene silylation under photochemical conditions.[37]



The authors attributed the formation of biphenyl to the presence of radical species.[38] However, several pieces of data implied that the silylbenzene did not form by a radical pathway. First, the Si-Si bond cleavage did not occur in the reaction of $(Me_3Si)_2$ with phenyl radical.[39] Second, the silylation of toluene with $(Me_3Si)_2$ gave *ortho*-, *meta*-, and *para*-substituted products in a ratio of 6:63:31 (Scheme 3). If the mechanism involved the reaction of trimethylsilyl radicals with toluene (i.e. not via organometallic intermediates), the ratio of constitutional isomers should approach the statistical ratio (*ortho*:*meta*:*para* = 2:2:1).[40]

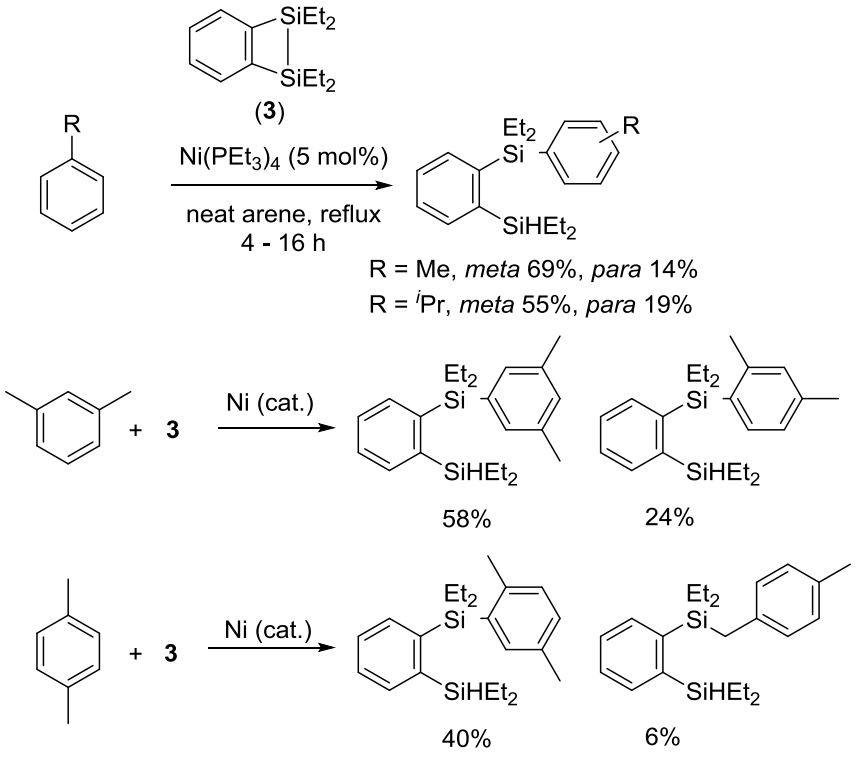
Scheme 3. Regioselectivity of the silylation of toluene.[37]



Ishikawa and co-workers have reported the silylation of neat arenes with 3,4-benzo-1,1,2,2-tetraethyl-1,2-disilacyclobutene (**3**) catalyzed by $Ni(PEt_3)_4$.[41-42] A mechanism involving insertion of Ni into the Si-Si bond, followed by cleavage of the aryl C-H bond and reductive elimination to form the C-Si bond of the product, was proposed. Reactions with toluene or

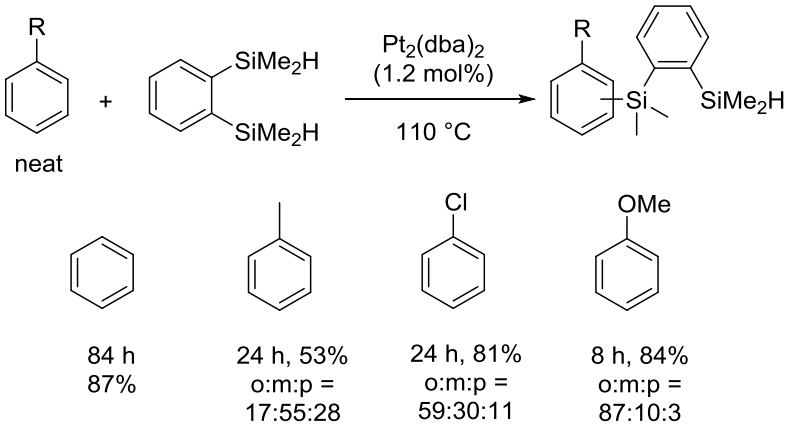
cumene afforded mixtures of products from silylation at the *meta*- and *para*-positions but not products from silylation at the *ortho*-position. The product distribution revealed a moderate level of steric influence of the substituent on the *ortho* C-H bonds (Scheme 4). However, reaction of *meta*-xylene afforded 24% of the product in which the silicon is installed *ortho* to the methyl substituent. Reaction with *para*-xylene also led to the 1,2,4-trisubstituted product, as well as 6% of the product from the silylation of a benzylic C-H bond. Reaction with 1,3,5-mesitylene afforded only the benzylic silylation product in 28% yield. In all cases, the second silicon atom in the starting disilane did not undergo C-Si coupling. Instead, it appeared to serve as the "hydrogen acceptor" to allow the regeneration of the Ni(0) catalyst.

Scheme 4. Ni-catalyzed silylation of arenes with a cyclic disilane.[41]



Tanaka and co-workers reported the platinum-catalyzed silylation of neat arenes with 1,2-bis(dimethylsilyl)benzene (Scheme 5).[43] The silicon reagent for this silylation resembles the one used by Ishikawa and co-workers,[41] but with two Si-H bonds instead of an Si-Si bond. Similar to the work by Ishikawa and co-workers, only one Si-H bond underwent arylation. The regioselectivity of the reaction depends on the nature of the arene: while reaction of toluene led to a mixture of products in a ratio of 17:55:28 (*o*:*m*:*p*), reactions of arenes containing both electron-donating and electron-withdrawing groups led to higher ratios of *ortho*-functionalized products to the other isomeric products.

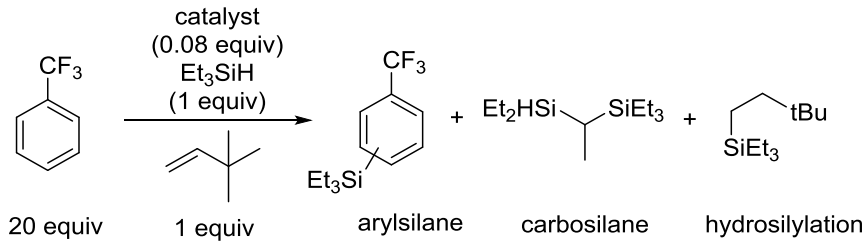
Scheme 5. Pt-catalyzed silylation of arenes with an *ortho*-bis(silyl)benzene.[43]



The authors investigated the possibility that the Pt-catalyzed silylation occurred by radical intermediates.[44] Although the reaction of toluene in the presence of di-*tert*-butyl peroxide and in the absence of the platinum catalyst gave a mixture of products in a ratio similar to that from the normal catalytic reaction, the total yield was only 0.9%. In addition, the reaction run with radical inhibitors, such as 2,6-di-*tert*-butyl-*p*-cresol (BHT) or galvinoxyl, did not lead to a significant change in the yield or regioselectivity. Furthermore, the reaction of trimethylsilyl radical with chlorobenzene is known to produce chlorotrimethylsilane,[45] and not the corresponding aryltrimethylsilane, whereas the platinum-catalyzed reaction formed the arylsilane. From these observations, the authors proposed that the reaction does not involve free silyl radicals; rather it involves cleavage of aryl C-H bonds by platinum complexes.[43]

Berry and co-workers reported dehydrogenative coupling of arenes with Et_3SiH as the silicon source and with *tert*-butylethylene (tbe) as the sacrificial hydrogen acceptor.[46] $Cp^*Rh(H)_2(SiEt_3)_2$ (**4a**) and (η^6-C_6Me_6)$Ru(H)_2(SiEt_3)_2$ (**5a**) were found be to active catalysts for the silylation of arene C-H bonds, although simple complexes such as $[Cp^*RhCl_2]_2$ (**4b**) and [(η^6-C_6Me_6)$RuCl_2$]$_2$ (**5b**) also can be used directly as catalyst precursors without the need to isolate the metal-silyl complexes. These silylation reactions led to a mixture of products containing the desired arylsilane, ^{t}BuCH$_2$CH$_2$SiEt$_3$ from hydrosilylation of the hydrogen acceptor tbe, and carbosilane dimer from silylation of the α C-H bond in Et_3SiH. The rate of the reaction and the distribution of products depended on the reaction temperature and the identity of the metal. In general, the ratio of arylsilane product versus carbosilane product was higher at higher temperature (150 ℃ versus 100 ℃). The product from hydrosilylation of tbe formed in amounts <10% of the products in all cases (Table 1). The rates of the reactions catalyzed by Ru catalysts were 20 times slower than those of reactions with Rh catalysts. In addition, at 50% conversion of Et_3SiH (the limiting reagent), the selectivity for arylsilane was much higher when the reaction was run with Ru catalysts than when it was run with Rh catalysts (**4a**/**b** vs **5a**/**b**). However, at >90% silane conversion, the absolute yields of the arylsilane for reactions run with Ru catalysts are lower despite the higher ratio of arylsilane to carbosilane; the remainder of the silicon material was not accounted for.

Table 1. Distribution of products from the Rh- and Ru-catalyzed silylation of trifluoromethylbenzene with Et_3SiH at 50% conversion of the silane.[46]

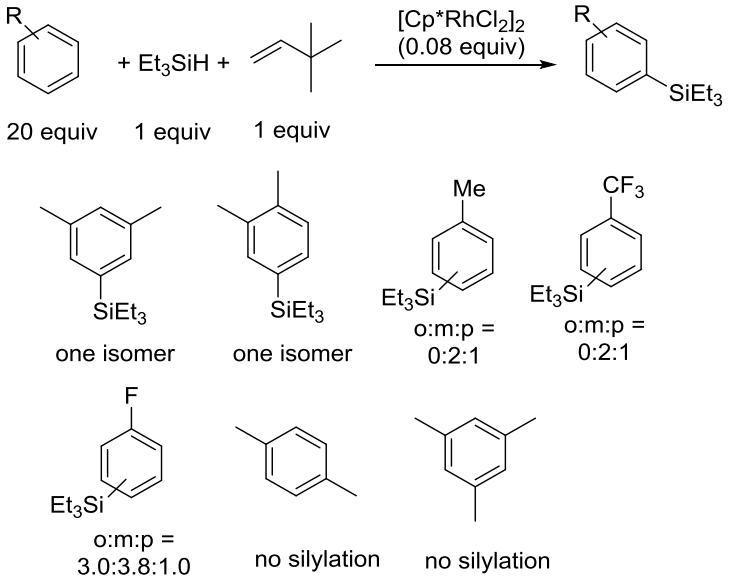


catalyst	T (℃)	product selectivity (%)		
		arylsilane	carbosilane	hydrosilylation
4a	150	45	50	5
4a	100	18	74	8
4b	150	40	56	4
4b	100	20	74	6
5a	150	90	5	5
5b	150	88	3	9
4b[a]	150	51	23	4
5b[a]	150	38	2	3

[a] At 90% silane conversion. Yields instead of selectivity reported.

The authors found that the reaction exhibited some level of steric control, as evidenced by the lack of *ortho*-silylation products when the substituent is larger than a fluorine. Thus, *p*-xylene and mesitylene were not silylated under these conditions, and *m*-xylene and *o*-xylene both gave a single isomeric arylsilane (Scheme 6). In contrast, the silylation of fluorobenzene led to a mixture of products in a ratio of 3.0:3.8:1.0 (*o*:*m*:*p*). In addition, the regioselectivity seemed to be independent of the electronic properties of the arenes. Both reactions of toluene and of trifluoromethylbenzene yielded the *meta*- and *para*-silyl products in a statistical ratio (2:1).

Scheme 6. Silylation of arenes catalyzed by $[Cp^*RhCl_2]_2$.[46]

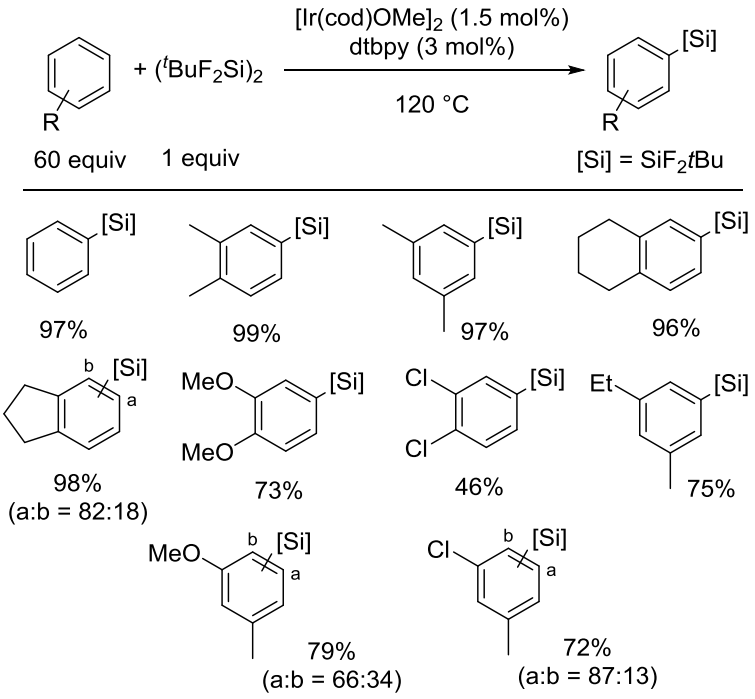


The relative rate of reactions with electronically distinct arenes was measured by conducting reactions with a mixture of the substituted arene and benzene. The ratios of substituted silylarenes to silylbenzene followed the trend CF_3 (2.8) > F (1.4) > H (1.0) > CH_3 (0.32). The faster rates of reactions with more electron-deficient arenes suggest that a transfer of electron density from the metal to the arene occurred during C-H bond cleavage. Finally, silylation catalyzed by $[Cp^*RhCl_2]_2$ was incompatible with heavy halogen substituents, such as Cl or Br. Reaction of PhCl led to a low yield (< 3.6%) of the desired $Et_3Si(C_6H_4Cl)$. The predominant products from this reaction were benzene and Et_3SiCl formed from protodehalogenation of PhCl. Similarly, reaction with PhBr gave benzene and Et_3SiBr as the primary products.

Ishiyama and co-workers reported the Ir-catalyzed silylation of aryl C-H bonds with a tetrafluorodisilane in neat arenes.[47] The combination of catalyst precursors, $[Ir(cod)OMe]_2$ and dtbpy, are the same as that used in the borylation of aryl C-H bonds.[3, 48] $[Ir(cod)Cl]_2$ and $Ir(cod)_2BF_4$ were also suitable pre-catalysts, but other metal precursors, including $[Ni(acac)_2]$-^{n}BuLi, $[Rh(cod)Cl]_2$, $Ru_3(CO)_{12}$, and $Pt(dba)_2$ did not lead to an active catalyst for the silylation of aryl C-H bonds with this disilane.

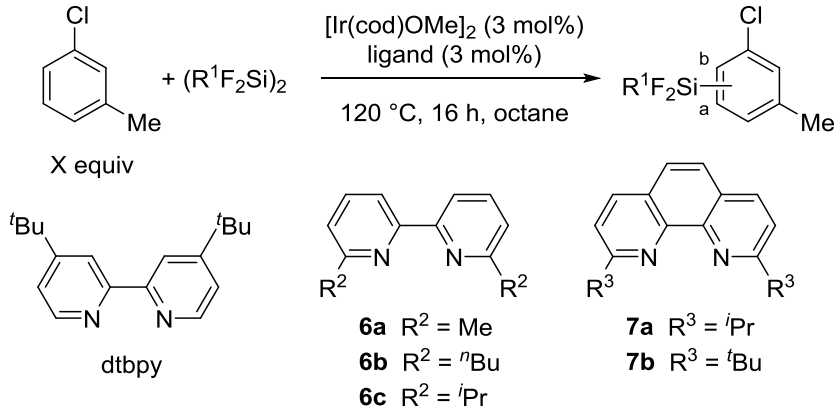
The reactions of benzene derivatives containing various simple substituents with the disilane in a ratio of 60:1 at 120 ℃ led to silylarene products in good yields (Scheme 7). A good level of sterically controlled regioselectivity was observed. For example, reaction of *m*-xylene and various symmetrically 1,2-disubstituted arenes gave products as single isomers. However, reactions of unsymmetrically 1,3-disubstituted arenes in which one of the substituents is a small group, such as OMe or Cl, afforded mixtures of 1,3,5- and 1,3,4-trisubstituted products. In contrast to the Rh-catalyzed silylation of aryl C-H bonds reported by Berry and co-workers,[46] protodehalogenation of aryl chlorides was not observed. It appears that only one of the silyl units in the disilane coupled to the arene; the other led to the unreactive byproduct $HSiF_2{}^t$Bu.

Scheme 7. Ir-catalyzed silylation of aryl C-H bonds with a tetrafluorodisilane.[47]



To reduce the amount of excess arene and to increase the regioselectivity of silylation of unsymmetrically 1,3-disubstituted arenes, Ishiyama and co-workers investigated alternative ligands and disilane sources.[49] Simple methyl substitutions at the 6,6'-positions of bipyridine ligands significantly increased the steric bulk of the active catalyst and led to almost exclusive formation of the 1,3,5-trisubstituted arylsilane products (Table 2). Larger substituents such as *n*-Bu or *i*-Pr impeded the reaction, presumably because the active catalysts are too sterically hindered. Similarly, reaction run with 2,9-di-*iso*-propylphenanthroline as the ligand gave the desired product in 42% yield, whereas reaction with 2,9-di-*tert*-butylphenanthroline gave no desired product. In addition, the authors varied the steric properties of disilane reagent and found that reaction with (^{s}BuF$_2$Si)$_2$ gave the arylsilane product in the highest yield. Even with only 5 equiv of 3-chlorotoluene, the product was obtained in 74% yield as a single isomer.

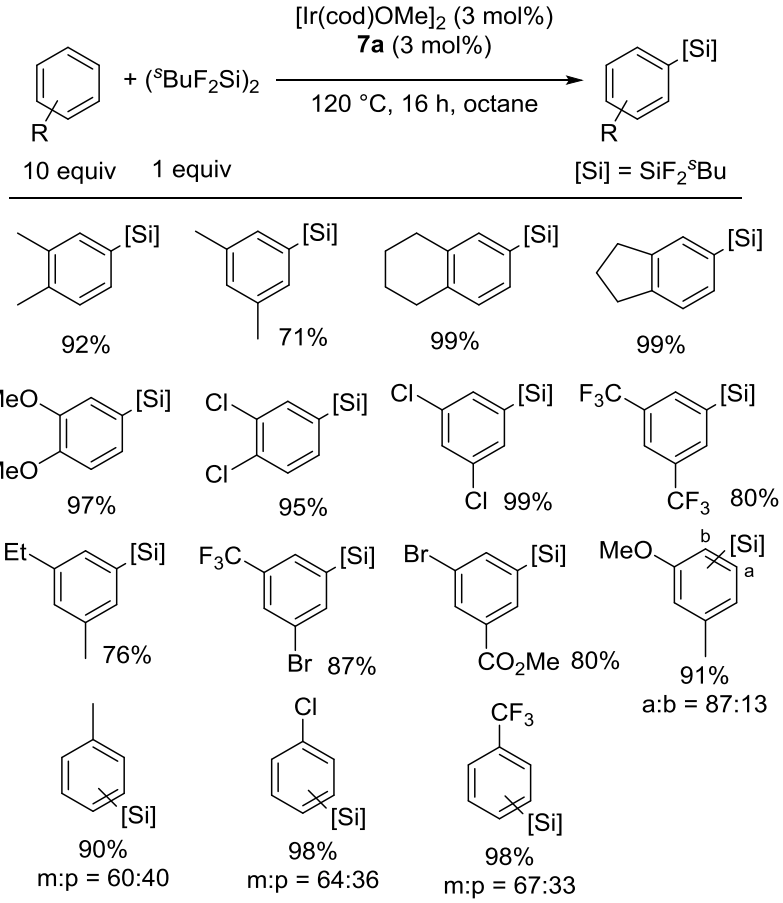
Table 2. Evaluation of the effect of ligand and disilane on the yield and regioselectivity of the silylation of aryl C-H bonds.[49]



R^1	X	ligand	yield	a:b
^{t}Bu	60	dtbpy	72	87:13
^{t}Bu	60	**6a**	60	99:1
^{t}Bu	60	**6b**	56	99:1
^{t}Bu	60	**6c**	20	>99:1
^{t}Bu	60	**7a**	42	>99:1
^{t}Bu	60	**7b**	0	-
^{t}Bu	10	**7a**	28	>99:1
^{n}Bu	10	**7a**	32	>99:1
^{s}Bu	10	**7a**	99	>99:1
^{s}Bu	5	**7a**	74	>99:1

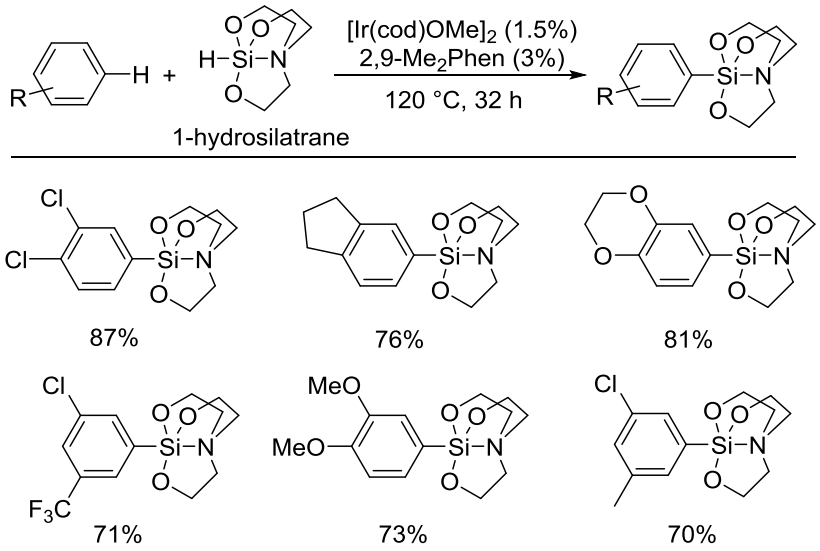
With the improved ligand and disilane, the authors re-evaluated the substrate scope and the regioselectivity of this reaction (Scheme 8). The yields of the products were generally higher than they were in the earlier report,[47] even with a smaller excess of the arene. More significantly, 3-chlorotoluene and indane gave single products with the new system. Only the reaction with 3-methylanisole still afforded a mixture of products (87:13, versus 66:34 in the earlier report). The reactions of mono-substituted arenes led to statistical mixtures of *meta*- and *para*-disubstituted products. The electronic property of the substituent did not seem to influence the product distribution, a trend which is similar to the silylation reaction reported by Berry and co-workers.[46] However, the relative rate of the reaction was also independent of the electronic nature of the arene, as shown by a competition experiment between toluene and trifluoromethylbenzene, in which the products from the two arenes were obtained in a 1:1 ratio.

Scheme 8. Ir-catalyzed silylation of arenes with improved regioselectivity.[49]



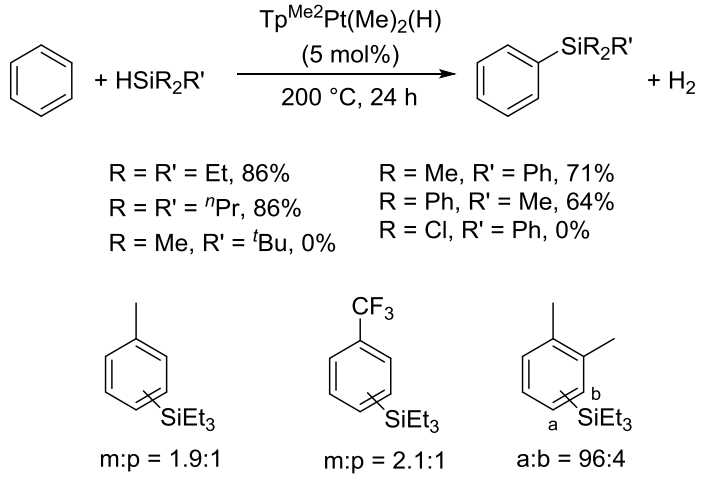
Because the preparation of the fluorodisilanes requires multiple steps and is low-yielding,[50] Miyaura and co-workers sought to substitute fluorosilanes with alkoxysilanes, which are more synthetically accessible and should allow the organosilane products to be reactive at the C-Si bond. Reaction with several representative alkoxysilanes, such as $HSiMe_2(OEt)$, $HSiMe(OEt)_2$, and $HSi(OEt)_3$, did not form any desired product. However, reaction of 1-hydrosilatrane, which is air- and moisture-stable and is prepared in one step by reaction of $HSi(OEt)_3$ with boratrane,[51] occurred (Scheme 9).[52] The silylation reactions with 1-hydrosilatrane were conducted in neat arenes catalyzed by an Ir complex ligated with 2,9-dimethylphenanthroline (2,9-Me_2Phen). The reaction was shown to be selective for the most sterically accessible C-H bonds.

Scheme 9. Silylation of arenes with 1-hydrosilatrene.[52]



Hartwig and co-workers reported a protocol for the silylation of arenes with a platinum catalyst.[53] The reaction occurred with several silicon sources, including the synthetically relevant $HSiMe_2Ph$ (Scheme 10). However, the reaction required very high temperatures (200 ℃) and did not tolerate many functional groups, such as a halogen. The regioselectivity of the reaction was controlled by the steric properties of the substituents on the arenes. Little product from silylation *ortho* to a methyl or trifluoromethyl group was observed (Scheme 10).

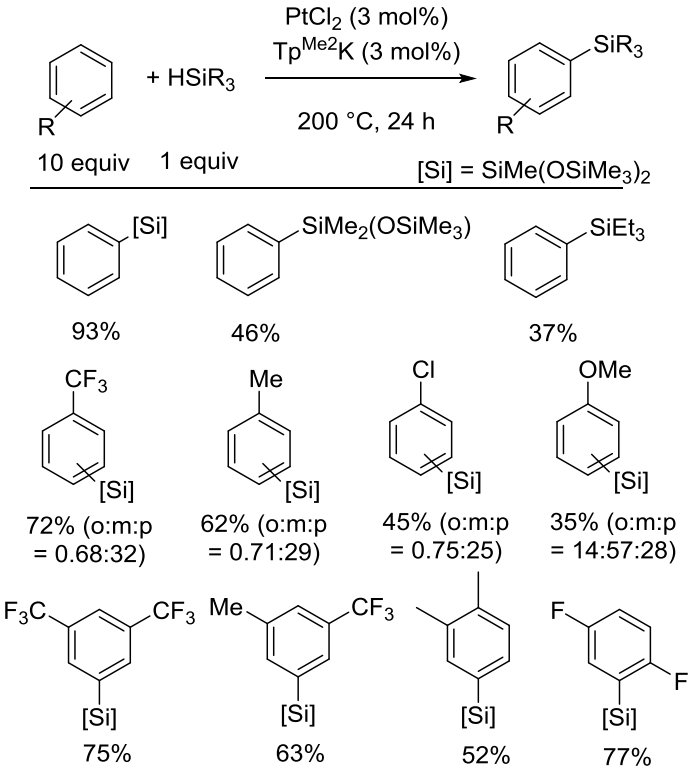
Scheme 10. Pt-catalyzed, intermolecular silylation of aryl C-H bonds.[53]



With a catalyst similar to the one used by Hartwig and co-workers,[53] Murata and co-workers reported a platinum-catalyzed silylation of aryl C-H bonds with neat arenes and the commercially available $HSiMe(OSiMe_3)_2$.[54] The catalyst was generated *in situ* from $PtCl_2$ and $Tp^{Me2}K$. The reactions of benzene with $(Me_3SiO)Me_2SiH$ and Et_3SiH also led to the corresponding arylsilane products, albeit in lower yields than did the reactions with $HSiMe(OSiMe_3)_2$. The reaction occurred with sterically controlled regioselectivity: silylation *ortho* to a methyl or trifluoromethyl group was not observed, but silylation *ortho* to the smaller

OMe group in anisole did occur (Scheme 11). The reaction with chlorobenzene gave only a trace amount of product from protodehalogenation.

Scheme 11. Pt-catalyzed, intermolecular silylation of aryl C-H bonds with $HSiMe(OSiMe_3)_2$.[54]



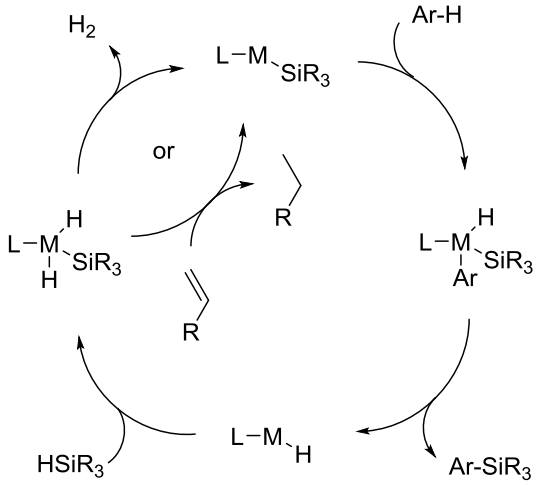
We reported in Chapter 3 the first undirected, intermolecular silylation of aryl C-H bonds that occurs with arene as the limiting reagent and under mild conditions (45 ℃).[34] This is especially important for synthetic applications because the arene is usually the more valuable reaction component. In addition, the reaction exhibits very high sterically derived regioselectivity, which the authors attributed to both the steric bulk of the bisphosphine ligands and of the silane reagent. The reaction occurred with $HSiMe(OSiMe_3)_2$ as the silane. Because the silyl group is activated by the two oxygen atoms attached to the silicon, the arylsilane products can be subjected to further transformations, such as cross-coupling, oxidation, halogenation, or amination.

1.3 Mechanistic Studies on C-H Silylation

A reasonable general mechanism for the silylation of C-H bonds catalyzed by complexes of group 8 and 9 metals is shown in Scheme 12: cleavage of the C-H bonds of the substrate by a metal-silyl fragment, followed by C-Si bond-forming reductive elimination furnishes the product. Addition of the H-Si bond (or Si-Si bond when a disilane is the silicon source) to the metal

regenerates the metal-silyl species. The hydrogen byproduct of the reaction (or $HSiR_3$ when a disilane is used) is either eliminated directly from the metal center or transferred to a sacrificial hydrogen acceptor. The exact sequence of the events and the oxidation state of the metal during each event can vary. When a directing group is present, the catalyst could bind to the directing group before or after oxidative addition of the Si-H bond to the metal center.

Scheme 12. A general mechanism for silylation of C-H bonds.



Although many catalytic cycles for the silylation of C-H bonds have been proposed, little mechanistic data to support these proposals have been gained in most cases. Simple kinetic experiments, such as the measurement of KIE's, have been conducted to probe whether arene C-H activation is the overall rate-limiting step (RLS) of the catalytic cycle. For example, Takai and co-workers observed a large KIE of 6.8 from the competition between protiated vs deuterated substrates.[55] However, this result only suggests that the C-H bond cleavage is irreversible; it does not require that C-H bond cleavage is the overall RLS. On the other hand, Chatani and co-workers measured the KIE of a pyridine-directed silylation in separate flasks and obtained a small inverse KIE, suggesting that C-H bond cleavage is not the overall RLS.[56] Similarly, Murai and co-workers observed incorporation of deuterium into the arene prior to oxazoline-directed silylation of aryl C-H bonds, suggesting that the C-H bond cleavage step is reversible.[57]

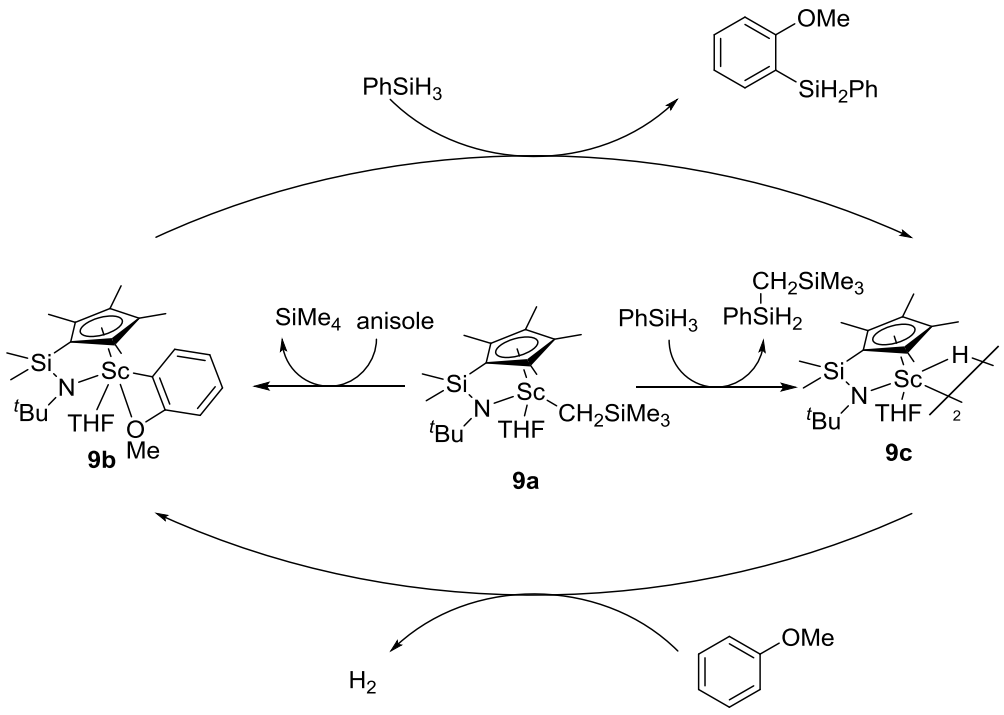
Case 1: Sc-catalyzed directed silylation of arenes. The proposed mechanism for the Sc-catalyzed directed silylation of anisole reported by Hou and co-workers is shown in Scheme 13.[58] The pre-catalyst **9a** undergoes σ-bond metathesis with $PhSiH_3$ to generate a dimeric Sc(II) complex **9c** and $PhSiH_2(CH_2SiMe_3)$ byproduct. Complex **9c** then undergoes σ-bond metathesis with the substrate to form **9b**. Complex **9b** undergoes σ-bond metathesis with $PhSiH_3$ to generate the silylarene product and regenerates the Sc dimer **9c**.

The key intermediates, **9b** and **9c**, were synthesized independently, characterized by X-ray diffraction, and tested for their kinetic relevance. Specifically, reaction of **9a** with $PhSiH_3$ at 40 ℃ in the absence of arene generated the dimeric **9c** in a quantitative yield. Subjecting **9c** to an excess amount of anisole yielded **9b**, accompanied by the release of hydrogen. Alternatively, **9b**

was generated in 69% yield by allowing **9a** to react with excess anisole at 80 ℃. Finally, the reaction of **9b** with 1.5 equiv of $PhSiH_3$ at 30 ℃ gave the arylsilane product in 79% yield, and the catalyst resting state **9c** in 76% yield. Thus, it appeared that **9b** and **9c** are actual intermediates in the catalytic cycle.

The activation parameters of the reaction were measured, and a large negative $\Delta S^{\ddagger}$ (-80.2 J mol^{-1} K^{-1}) was obtained. In addition, silylation of 4-methylanisole and 2-D-4-methylanisole exhibited a KIE of 1.0. These results suggest that the RLS is the coordination of the substrate to the metal center and not cleavage of the C-H bond.

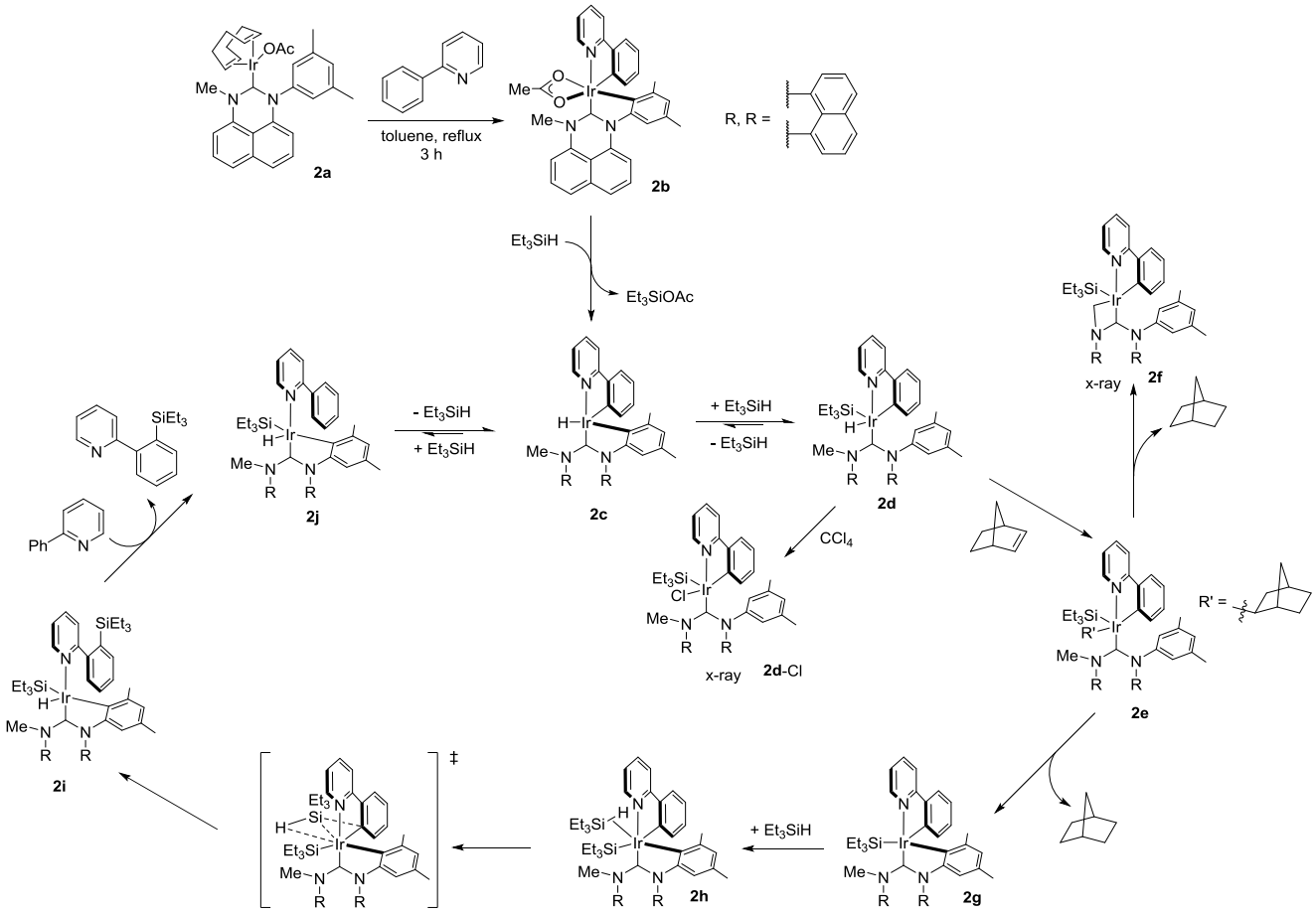
Scheme 13. Proposed mechanism of the Sc-catalyzed silylation of aryl C-H bonds.[58]



Case 2: Ir-catalyzed directed silylation of arenes. The catalytic cycle proposed for the Ir-catalyzed silylation of 2-phenylpyridine reported by Mashima and co-workers is shown in Scheme 14.[59] The reaction is proposed to occur with the participation of the ligand during C-H bond cleavage of 2-phenylpyridine. In the proposed catalytic cycle, 2-phenylpyridine first displaces COD on **2a**. Then, cleavage of the C-H bonds of the substrate and of the xylyl group on the carbene ligand both occur. Removal of the acetate by Et_3SiH and addition of a second equivalent of Et_3SiH generate intermediate **2d**. The formation of **2b** from **2a** was observed independently by heating **2a** in refluxing toluene with 2-phenylpyridine; **2b** was produced by this reaction in 94% yield. Intermediate **2d** could not be isolated from the reaction of **2b** with $HSiEt_3$ because of facile decomposition during the purification process, but the authors converted **2d** to the corresponding chloride complex **2d**-Cl by treating **2d** with CCl_4. Complex **2d**-Cl was characterized by x-ray crystallography.

Subjecting **2d** generated *in situ* with norbornene resulted in a decrease in the NMR hydride signal of **2d** at room temperature. In the absence of additional Et_3SiH, a bis-cyclometalated $Ir(SiEt_3)$ complex **2f** formed and was isolated in 54% yield. Complex **2f** was proposed to form by insertion of norbornene into the Ir-H bond, oxidative addition of the C-H bond of a methyl group of a carbene ligand, and reductive elimination of norbornane. In the productive pathway, however, the same hydrogenation of norbornene was accompanied by oxidative addition of the C-H bond of the xylyl group on the ligand to generate intermediate **2g**. Oxidative addition of the C-H bond on the xylyl group and C-H bond-forming reductive elimination to generate norbornane are proposed to occur, and this process could proceed either step-wise via a Ir(V) intermediate[60-61] or through σ-bond metathesis between an Ir-norbornyl bond and the *ortho* C-H bond of the xylyl group.[62-63] Addition of $HSiEt_3$ to **2g** led to the six-coordinate species **2h**. The C-Si bond forming event is proposed to occur via σ-complex-assisted metathesis (σ-CAM).[64] The C-Si bond formation occurred selectively between the carbon of phenylpyridine and the Et_3Si group over C-Si bond formation between the carbon of the xylyl group on the ligand and the Et_3Si group because of the steric hindrance of the xylyl group.

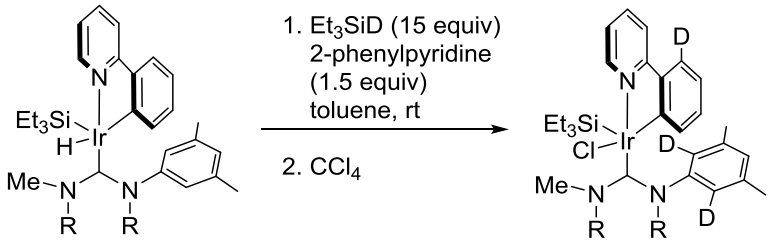
Scheme 14. Proposed mechanism of the Ir-catalyzed, directed silylation of aryl C-H bonds.[61]



The equilibrium among **2j**, **2c**, and **2d** was established by allowing **2d** generated *in situ* to react with $DSiEt_3$ (

Scheme 15). Incorporation of deuterium into the *ortho*-positions of the xylyl group and the 2'-position of phenylpyridine was observed, implying that cleavage of the C-H bonds of both the substrate and of the xylyl group on the ligand is reversible.

Scheme 15. Incorporation of deuterium into 2d.[59]



2d

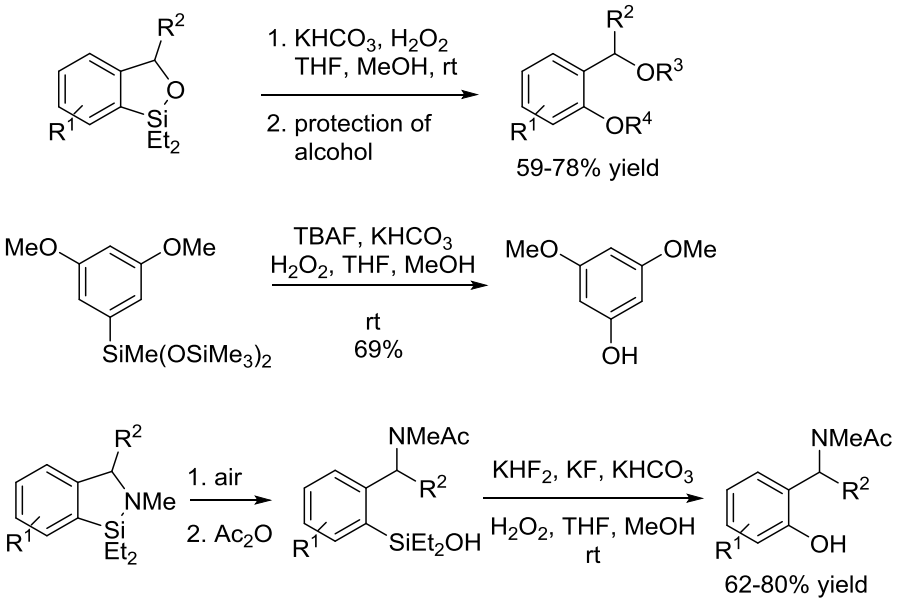
1.4 Applications of C-H Silylation

An important of application of the silylation of C-H bonds is to install a temporary functional group (silyl group) that can be further functionalized. In this regard, the applications of the silylation and the borylation of C-H bonds to synthetic organic chemistry are related. However, the silylation of C-H bonds can occur with regioselectivity that is distinct from that of the borylation of C-H bonds (e.g. the remote regioselectivity of the Rh-catalyzed intermolecular silylation[34]). In addition, some transformations, such as halogenation, are more facile for arylsilanes[34, 65] than for arylboronate esters.[19, 66] However, cross-coupling of arylsilicon reagents with aryl electrophiles (Hiyama coupling[13-14]) is less developed than cross-coupling of boron reagents (Suzuki-Miyaura coupling). Furthermore, certain functionalizations of C-H bonds, such as the alcohol- and amine-directed silylation of alkyl C-H bonds,[67-69] occur only with silicon reagents because the boron intermediates that would be analogous to the silyl ethers and silylamines are unstable. Finally, some of the silanes derived from silylation of a C-H bond are desired because of their properties. For example, silafluorene derivatives that have been generated by intramolecular arene silylation[55] are useful electroluminescent materials.[70-71]

Oxidation: the oxidation of aryl- and alkylsilanes to form phenols or alkyl alcohols, also known as the Tamao-Fleming oxidation, requires the presence of an electronegative heteroatom, such as O, Cl, or F atom (Tamao oxidation),[16, 72] or a phenyl or benzyl group (Fleming oxidation)[15] attached to the silicon atom. Thus, many of the more recent examples of the silylation of C-H bonds generate products suitable for this transformation.

Arylsilanes prepared by intramolecular silylation or intermolecular silylation also have been transformed to phenols via oxidation. The silyl group in the Rh-catalyzed intermolecular silylation is significantly more sterically hindered than the diethylsilyl group in the alcohol-directed intramolecular silylation of arenes[73] and required TBAF as the activator for the oxidation.[34] In addition, products from the alkylamine-directed intramolecular arene silylation could not be subjected directly to oxidation because of competing oxidation of the amino group.[74] Thus, the alkyl amine was first acylated, and the arylsilane was then subjected to the conditions for oxidation to afford the corresponding phenols.

Scheme 16. Oxidation of arylsilanes.

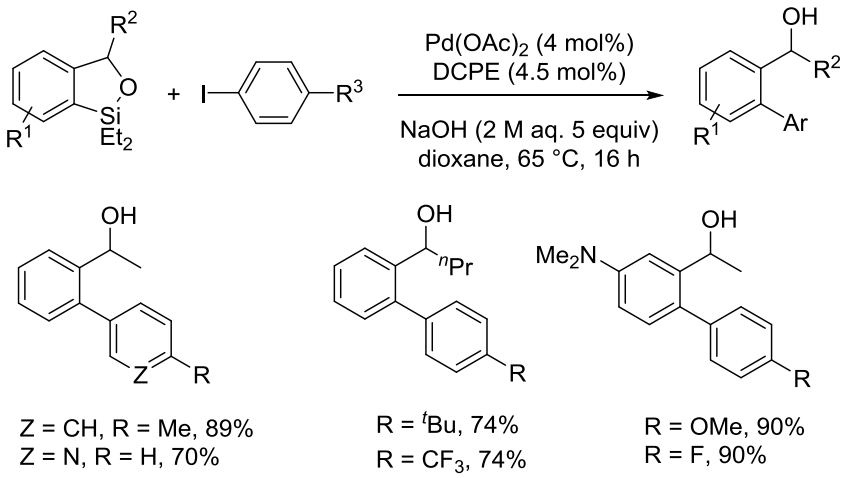


Cross-coupling: the cross-coupling of organosilicon reagents with aryl electrophiles[13, 75] (Hiyama coupling) allows the construction of vinylarene or biaryl motifs and could constitute an alternative to the Suzuki-Miyaura cross coupling in the synthesis of complex molecules. However, cross-coupling with organosilicon reagents has been less developed than cross-coupling with organoboron reagents because of the lower reactivity of organosilanes.[14] Fluoride activators were found to enhance the reactivity of organosilanes toward transmetallation by the formation of pentavalent siliconates.[76] However, the widespread use of silanol-based protecting groups and the cost and corrosive nature of superstoichiometric, soluble fluoride sources render the use of fluoride as activator undesirable.

As an alternative, Denmark and co-workers have developed methods for the fluoride-free Hiyama coupling reactions by using organodimethylsilanols or the corresponding silanoates.[31-32, 77] Deprotonation of the organodimethylsilanols by an added strong base, such as $KOSiMe_3$, *in situ* generates the organosilanoates. Displacement of the halide in a Pd(Ar)(X) intermediate by an organosilanolate generates a Pd(Ar)($OSiR_2Ar$') species, which undergoes transmetallation to form Pd(Ar)(Ar').[31] The rate of this transfer of the aryl group from the silanolate to palladium is accelerated by added silanolate, presumably by binding of the external silanolate to the silicon of the bound silanolate.[78]

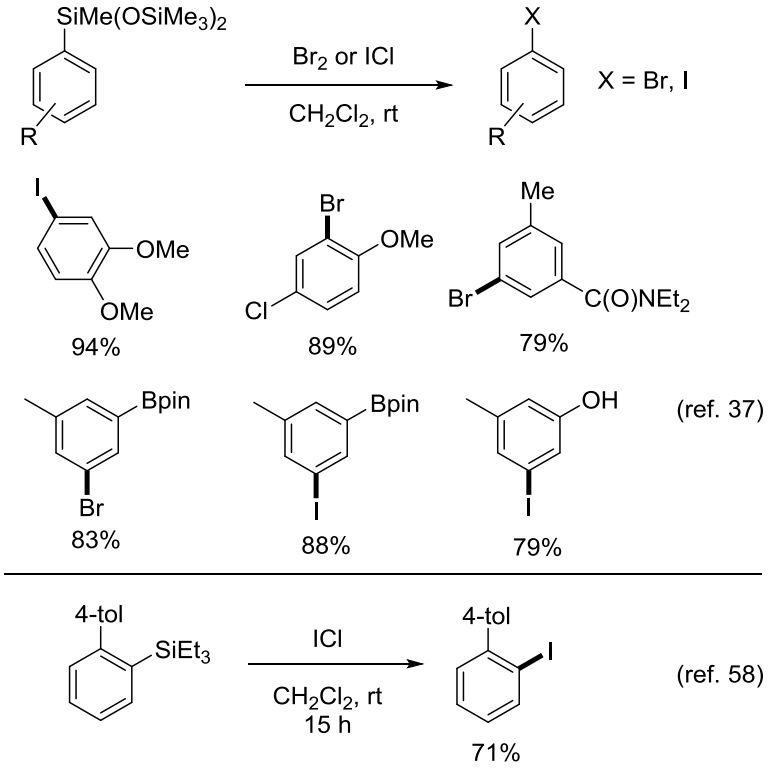
Based on the reactivity of organodimethylsilanols, Hartwig and co-workers developed a protocol for the cross-coupling of benzoxasiloles with aryl halides (Scheme 17).[73] Aqueous NaOH was added to activate the silicon, presumably through cleavage of the Si-O bond in the substrate to form an aryldiethylsilonate intermediate that is analogous to the organodimethylsilonate proposed by Denmark and co-workers.[31]

Scheme 17. Cross-coupling of arylsilanes derived from intramolecular silylation of aryl C-H bonds.[73]



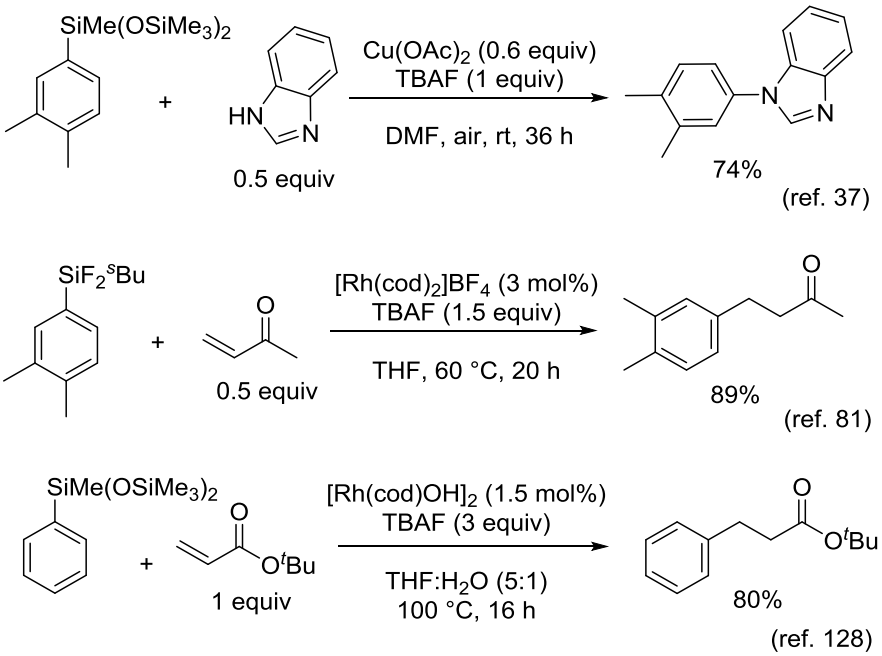
Halogenation: Because the silylation of aryl C-H bonds can occur with sterically-derived regioselectivity, the sequence comprising silylation of a C-H bond and subsequent bromination or iodination can afford products unattainable by direct electrophilic aromatic halogenation. For example, $ArSiMe(OSiMe_3)_2$ compounds undergo bromination with Br_2 and iodination with ICl (Scheme 18).[34] These conditions under which the transformations take place are milder and do not require stoichiometric or catalytic amounts of copper reagents as do the halogenations of arylboronates.[19, 66] In contrast to oxidation or cross-coupling, *ipso*-halogenation of arylsilanes occurs even with aryltrialkylsilanes (Scheme 18).[65]

Scheme 18. Halogenation of arylsilanes.



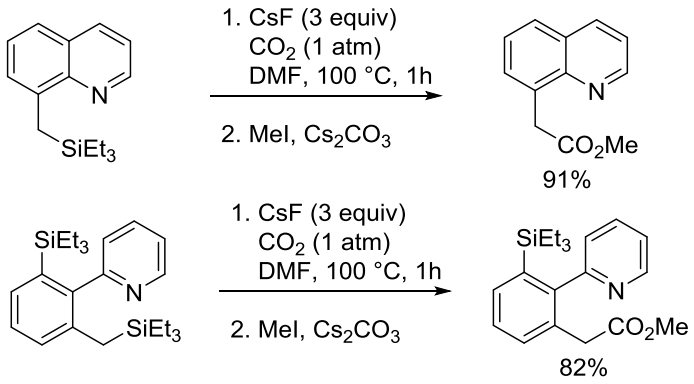
Other Transformations: Organosilanes derived from the Rh-catalyzed intermolecular silylation of arenes undergo copper-mediated amination in the presence of TBAF as the activator[34] (Scheme 19) under conditions similar to the ones described by Lam and co-workers for the amination of Ar-Si(OMe)$_3$.[22] In addition, arylsilanes undergo 1,4-addition to enones and acrylates (Scheme 19).[49, 79]

Scheme 19. Amination and conjugate addition involving arylsilanes.



Furthermore, benzyltrialkylsilanes have been shown to be cleaved at the benzyl-silicon bond by addition of CsF in DMF. The benzyl group subsequently underwent carboxylation with CO_2 (Scheme 20).[80] Methylation of resulting carboxylate forms the corresponding methyl esters. This transformation is selective for benzylsilanes and does not affect aryl C-Si bonds.

Scheme 20. Carboxylation of benzylsilanes.[80]



1.5 References

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Cheng, C.; Hartwig J. F.. *Chem. Rev*. **2015**, *115*, 8946-8975

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Chapter 2: Silylation of Alkenyl C-H Bonds

2.1 Introduction

Vinylsilanes and vinylboranes are versatile synthetic intermediates that can be constructed through catalytic functionalization of C-H bonds with boron and silicon reagents.[1,2] Because the majority of borylations of alkenes to form vinylboronates as the major product require cyclic alkenes, vinylarenes, or specific substituted alkenes (vinyl ethers and allyltrimethylsilane),[3] methods for the alternative dehydrogenative silylation of terminal alkenyl C-H bonds are desirable. Current methods for the preparation of vinylsilanes include the silyl-Heck reaction,[4] alkyne hydrosilylation,[5] direct dehydrogenative silylation of alkenes,[6] and manipulation of compounds with existing C-Si bonds;[7] each of these methods suffer from a number of drawbacks including the requirement of an excess of the alkene, limitation to vinylarenes, or the production of the more readily-accessible *E*-vinylsilane isomer as the major product.

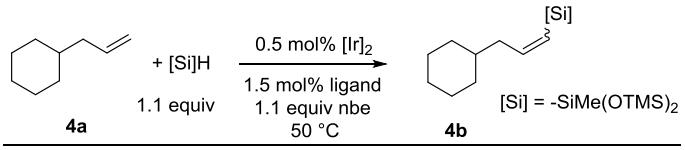
Recently, Lu and Falck reported the *Z*-selective silylation of terminal alkenes with Et_3SiH in the presence of the iridium-di-*tert*-butylbipyridine catalyst we had developed for the borylation of arenes.[8] However, the lack of electronegative atoms attached to the silicon atom prevents the products from being substrates for Tamao oxidation or Hiyama-Denmark coupling reactions.[9] Unfortunately, silylation reactions often occur in lower yields with silanes, such as alkoxysilanes, bearing electronegative atoms than with trialkylsilanes. Because the alkoxysilyl group is electron withdrawing, the hydride is less hydridic.[10] In addition, the rates of side reactions, such as hydrosilylation, silane dehydrocoupling, and silane redistribution, are affected by the identity of the substituents on the silanes.[6b,11] Therefore, reactions with a silane containing a silicon-heteroatom bond are unlikely to parallel directly the reactions of trialkylsilanes. We hypothesized that the dehydrogenative silylation could be made more practical by conducting the reactions with a tertiary hydrosilanes containing bulky siloxy groups and that the catalysts Hartwig and co-workers recently developed for the silylation of aliphatic C-H bonds[2f] could make the dehydrogenative silylation faster than the redistribution reactions of a hydrosilane containing one or more electronegative groups.

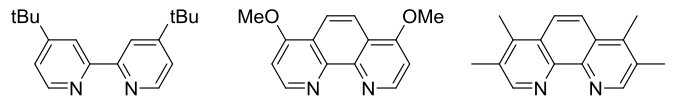
We report here the dehydrogenative silylation of terminal alkenes with $(TMSO)_2MeSiH$, a silane that is commercially available in bulk quantities, catalyzed by iridium complexes of 3,4,7,8-tetramethyl-1,10-phenanthroline (Me_4Phen), along with subsequent cross coupling and oxidation of the vinylsilane products. The reaction is highly selective for the *Z*-vinylsilane product. Isotope labelling suggests that the reaction occurs by insertion of the alkene, rather than direct C-H activation, and the stereoselectivity of the process can be reversed by conducting the reaction with a hindered, chelating nitrogen ligand.

2.2 Results and Discussion

To begin to develop the dehydrogenative silylation with a silane suitable for synthetic purposes, we surveyed the reactions of allylcyclohexane (**4a**) with several inexpensive and readily available siloxysilanes, such as a trisiloxane $(TMSO)_2MeSiH$,[12] in the presence of norbornene (nbe) as hydrogen acceptor and a series of catalysts. The reaction of this silane with **4a** catalyzed by $[Ir(cod)OMe]_2$ and Me_4Phen formed the *Z*-vinylsilane **4b** in 82% yield with a *Z*/*E* isomer ratio of 90:10 (Table 1, entry 6). The alkene geometry was assigned based on the *J*-coupling value of the vinylic protons (14.3 Hz for **4b** vs 18.6 Hz for the independently prepared *E*-isomer **4c**, *vide infra*). Reaction with the more sterically-hindered silane $(TMSO)_3SiH$ occurred with slightly higher diastereoselectivity but required a higher temperature (100 ℃, entry 7) and longer time, while reactions with smaller silanes such as $(TMSO)Me_2SiH$ or Et_3SiH exhibited higher turnover rates but lower diastereoselectivity (entries 8 and 9).

Table 1. Survey of conditions for terminal alkene silylation.[a]





dtbpy $(MeO)_2Phen$ Me_4Phen

entry	ligand	[Ir]	solvent	silane	yield[b]	Z/E[b]
1	Phen	**1**[c]	THF	$(TMSO)_2MeSiH$	58%	85:15
2	bpy	**1**	THF	$(TMSO)_2MeSiH$	-	-
3	dtbpy[d]	**1**	THF	$(TMSO)_2MeSiH$	78%	85:15
4	$(MeO)_2Phen$[e]	**1**	THF	$(TMSO)_2MeSiH$	19%	83:17
5	4-MePhen	**1**	THF	$(TMSO)_2MeSiH$	82%	86:14
6	Me_4Phen[f]	**1**	THF	$(TMSO)_2MeSiH$	82%	90:10
7[g]	Me_4Phen	**1**	THF	$(TMSO)_3SiH$	83%	92:8
8	Me_4Phen	**1**	THF	$(TMSO)Me_2SiH$	75%	82:18
9	Me_4Phen	**1**	THF	Et_3SiH	85%	79:21
10	Me_4Phen	**1**	heptane	$(TMSO)_2MeSiH$	86%	86:14
11	Me_4Phen	**1**	MeTHF	$(TMSO)_2MeSiH$	74%	90:10
12	Me_4Phen	**1**	CH_2Cl_2	$(TMSO)_2MeSiH$	19%	91:9
13	Me_4Phen	**2**[h]	THF	$(TMSO)_2MeSiH$	77%	88:12
14[i]	**Me_4Phen**	**3**[j]	**THF**	**$(TMSO)_2MeSiH$**	**83%**	**90:10**
15[k]	Me_4Phen	**1**	THF	$(TMSO)_2MeSiH$	49%	82:18

[a] For detailed reaction conditions, see the supporting information (SI). [b] Determined by GC. [c] $[Ir(cod)OMe]_2$. [d] 4,4′-*di-tert-butyl*-2,2′-bipyridine. [e] 4,7-dimethoxy-1,10-phenanthroline.

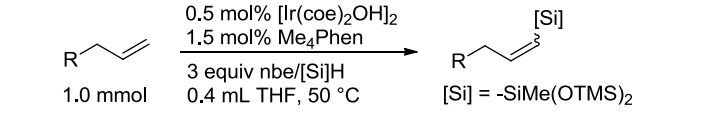
[f] 3,4,7,8-tetramethyl-1,10-phenanthroline. [g] Reaction conducted at 100 ℃ for 7 d. Reaction at 50 ℃ gave no product. [h] $[Ir(coe)_2Cl]_2$. [i] Reaction run for 8 h. [j] $[Ir(coe)_2OH]_2$. [k] No nbe was added.

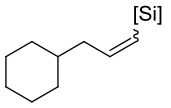
Among the ligands examined, 3,4,7,8-tetramethyl-1,10-phenathroline (Me_4Phen) generated the catalyst that reacted with the highest activity and diastereoselectivity.[13] Reactions conducted with phosphine or nitrogen-based ligands, other than phenanthroline or bipyridine derivatives, resulted in poor yields of the vinylsilane (see SI for data). Reactions conducted with the hydroxy-bridged binuclear dimer $[Ir(coe)_2OH]_2$[14] as the catalyst precursor (entry 14) occurred faster than those conducted with the related complexes $[Ir(coe)_2Cl]_2$ (entry 13) and $[Ir(cod)OMe]_2$ (entry 6), presumably because of the lack of strongly coordinating ligands and thus faster generation of the catalytically active species.[15] Furthermore, the choice of solvent influenced the yield, but not the diastereoselectivity (entries 10-12 and SI). Finally, the same reaction conducted without the sacrificial hydrogen acceptor nbe gave the vinylsilane product in 49% yield, along with 50% propylcyclohexane (Table 1, entry 15), showing that nbe is critical for inhibiting substrate hydrogenation (*vide infra*).

With certain alkenes, the reactions in the presence of 1.1 equiv of silane and nbe led to substantial substrate hydrogenation that lowered the yields of the desired vinylsilane products. One substrate especially prone to hydrogenation is 4-phenyl-1-butene (**5a**). At full conversion, the desired product **5b** was produced in only 68% yield (Table S2, entry 1). However, conducting the reaction at higher concentration of nbe (3 equiv) greatly reduced hydrogenation of the starting alkene and increased the yield of the vinylsilane product to 84% (entry 5).

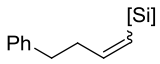
Under the conditions developed for the reaction of **5a** (Table S2, entry 5), reactions with various terminal alkenes afforded the corresponding vinylsilanes in good yields with high diastereoselectivity favoring the *Z*-product (Table 2). A variety of functional groups were tolerated, such as epoxide (**7b**), ketone (**9b**), ester (**6b**), amide (**17b**, **18b**), alcohol (**11b**), aryl iodide (**15b**), and internal alkene (**10b**). Higher catalyst loading or higher temperature was needed for substrates containing coordinating groups, such as a tertiary amine or nitrile, but the corresponding vinylsilanes were obtained in good yields. This reaction system does not lead to the conversion of internal alkenes, 1,1-disubstituted alkenes, or terminal alkenes with substitutions on the α-carbon, such as 2-methyl-1-pentene or 3-methyl-1-pentene. This limitation in scope is likely due to the steric demand at the metal center.

Table 2. Scope of alkene silylation with $(TMSO)_2MeSiH$.[a]

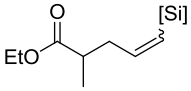




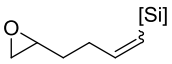
4b
93% (90:10 Z/E)



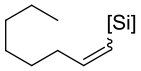
5b
80% (92:8 Z/E)



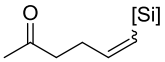
6b
77% (89:11 Z/E)



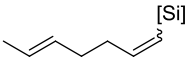
7b
83% (90:10 Z/E)



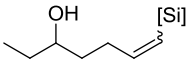
8b
85% (92:8 Z/E)



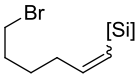
9b
71% (90:10 Z/E)



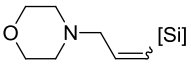
10b
71% (91:9 Z/E)



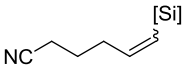
11b
85% (89:11 Z/E)



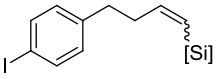
12b
78% (91:9 Z/E)



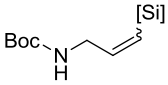
13b
60% (85:15 Z/E)[b],[c]



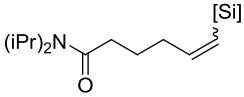
14b
64% (85:15 Z/E)[b],[d]



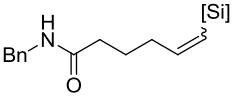
15b
(81%)[b],[e] (93:7 Z/E)



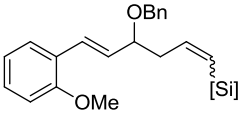
16b
60% (88:12 Z/E)[b],[d]



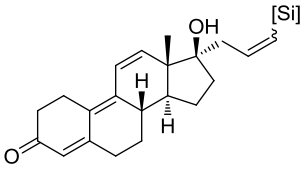
17b
76% (88:12 Z/E)[b]



18b
76% (85:15 Z/E)[b],[d]



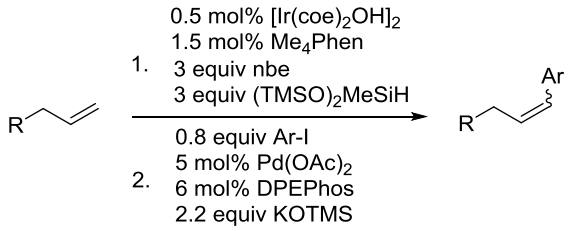
19b
(86%)[e] (91:9 Z/E)

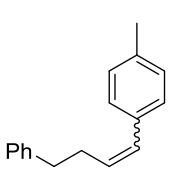


20b
61%[b] (90:10 Z/E)

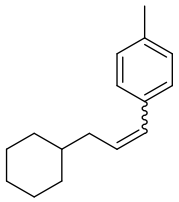
[a] Yields refer to isolated yields. Z/E ratios were determined by NMR spectroscopy. [b] 1 mol% of $[Ir(coe)_2OH]_2$ and 3 mol% of ligand were used. [c] Reaction was heated at 65 ℃. [d] 4-MePhen was used instead of Me_4Phen as ligand. [e] GC yield. The crude product was directly subjected to oxidation (*vide infra*).

Table 3. One-pot synthesis of vinylarenes from alkenes.[a]

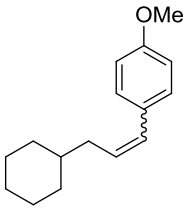




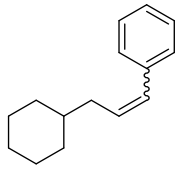
5e
74% (93:7 Z/E)



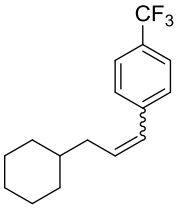
4e
75% (90:10 Z/E)



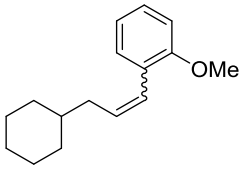
4f
69% (88:12 Z/E)



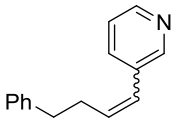
4i
59%[b] (88:12 Z/E)



4g
85% (87:13 Z/E)



4h
81% (86:14 Z/E)



5f
76% (93:7 Z/E)

[a] Yields refer to isolated yields based on 0.8 equiv of Ar-I. E/Z ratios were determined by GC or NMR spectroscopy. [b] Bromobenzene (1.1 equiv) was used instead of an aryl iodide. Yield is based on the starting alkene.

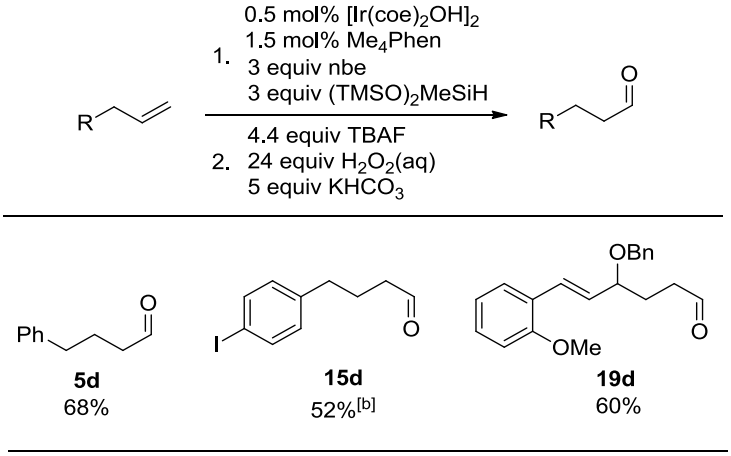
Cross-coupling reactions of aryl electrophiles with vinylsilanes in which the silyl group is -SiMe(OTMS)$_2$ are rare or unknown. However, the presence of two heteroatoms on the silicon atom made it possible for these materials to undergo Hiyama-Denmark cross-coupling in the absence of a fluoride activator.[9c] Indeed, we found that reactions conducted with catalytic amounts of Pd(OAc)$_2$ and chelating phosphine ligand DPEPhos and KOTMS as activator in THF gave vinylarene products in good yields with retention of the diastereomeric ratio. Although vinylarenes can be accessed from terminal alkenes through the Heck reaction[16] or direct arene vinylation,[17] the method we report here produces the *Z*-isomer as the major product, while the Heck reaction produces the *E*-isomer. Alternative routes by Suzuki coupling require the *Z*-vinyl halide or vinylboronate, which are difficult to access.[16e]

As shown in Table 3, the Ir-catalyzed silylation of terminal alkenes with (TMSO)$_2$MeSiH provides an alternative method for the arylation of vinyl C-H bonds by a one-pot procedure involving silylation and coupling. Under these conditions, various aryl iodides and an aryl bromide are all suitable electrophilic coupling partners.

In addition to the cross-coupling with aryl iodide electrophiles, we developed conditions for the oxidation of the vinylsilanes in the presence of aqueous H_2O_2 and 4.4 equiv of TBAF in a

mixture of THF and methanol to give the corresponding aldehydes. The reaction requires 4 equiv of TBAF, presumably due to the presence of 4 Si-O bonds in the starting material.[18] Table 4 shows a series of aldehydes prepared through a one-pot silylation and oxidation sequence starting with terminal alkenes. This protocol leads to the formation of aldehyde products with regioselectivity complementing the Wacker oxidation of alkenes and avoids the need for two oxidation steps to convert an alkylborane to the aldehyde.

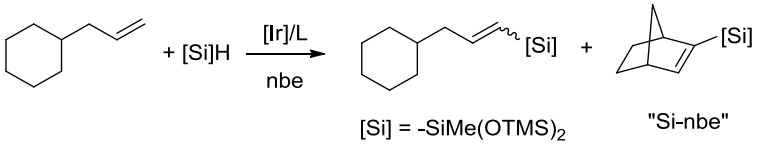
Table 4. One-pot aldehyde synthesis from alkenes.[a]



[a] Yields refer to isolated yields over two steps. [b] 1 mol% of $[Ir(coe)_2OH]_2$ and 3 mol% ligand was used for the silylation.

While studying the effects of ligands on the diastereoselectivity of alkene silylation, we discovered that the reaction conducted with 2-methyl-1,10-phenanthroline[19] (2-MePhen) as the ligand gave the *E*-vinylsilane as the major product (*Z/E* = 7:93, Table 5, entry 1). The yield of the *E*-vinylsilane was lower than the yield of the *Z*-vinylsilane obtained from reactions with Me_4Phen as ligand; the major side-products are hydrogenated starting material and silylated nbe ("Si-nbe", Table 6, *m/z* = 299.1, M-CH_3). However, the yields were good and the selectivity for the *E* isomer was high. Reactions conducted with other 2 or 2,9-substituted phenanthrolines (Table 5) showed that reactions conducted with phenanthrolines containing substituents larger than a methyl group on the 2-position occurred more slowly (entries 2 and 4) than those with 2-MePhen, while reactions conducted with 2,9-dialkyl-1,10-phenanthrolines gave predominantly the *Z*-vinylsilane in poor yields (entry 6 and SI). Reactions run with higher concentrations of nbe led to increased production of Si-nbe, but the yields of the desired product did not increase (entries 7 and 8).

Table 5. Surveying conditions for E-selective alkene silylation.[a]

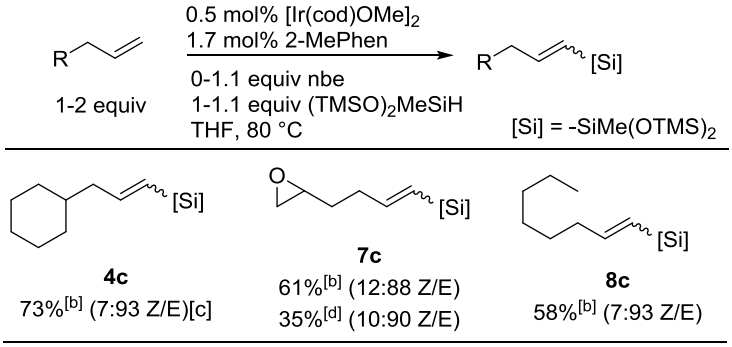


entry	ligand	equiv nbe	equiv silane	yield[b]	Z/E[b]
1	**2-MePhen**	**1.1**	**1.1**	**70%**	**7:93**
2	2-EtPhen	1.1	1.1	27%	11:89
3	2-MeOPhen	1.1	1.1	nd	nd
4	2-PhPhen	1.1	1.1	5%	nd
5	2-ClPhen	1.1	1.1	15%	82:18
6	2,9-Me_2Phen	1.1	1.1	11%	89:11
7	2-MePhen	2.0	2.0	64%	9:91
8	2-MePhen	3.8	3.8	54%	12:88

[a] For reaction conditions, see SI. [b] Determined by GC.

The reactions of several alkenes to form *E*-vinylsilanes with high diastereoselectivity are summarized in Table 6. For the reactions of non-polar alkenes (**4** and **8**), 2 equiv of alkenes were used. One equiv of the alkene serves as the hydrogen acceptor under these conditions to facilitate product purification.[20] High ratios of *E* to *Z* isomers were observed, and the reaction tolerated electrophilic functionality.

Table 6. Scope of E-selective alkene silylation.[a]



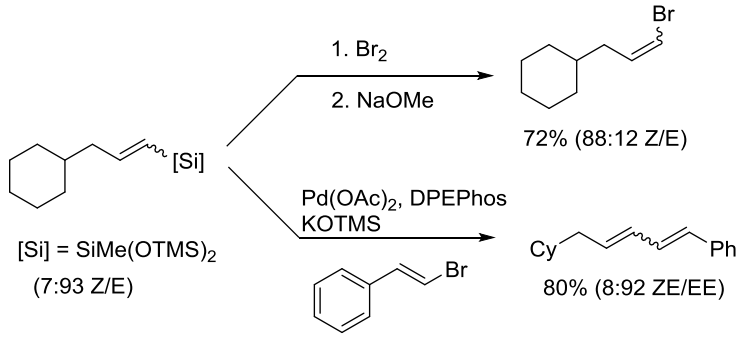
[a] Reaction conditions: Method A: $[Ir(cod)OMe]_2$ (0.5 mol%), 2-MePhen (1.7 mol%), alkene (2.0 mmol), and silane (1.0 mmol) in 0.4 mL THF. Method B: $[Ir(cod)OMe]_2$ (0.5 mol%), 2-MePhen (1.7 mol%), alkene (1.0 mmol), nbe (1.1 mmol), and silane (1.1 mmol) in 0.4 mL THF. [b] Isolated yield using Method A based on silane. [c] Z/E ratios were determined by NMR spectroscopy. [d] Isolated yield using Method B based on alkene.

The resulting *E*-vinylsilanes can be transformed to *Z*-vinylbromides (Scheme 1). Addition of bromine to the alkene forms the 1,2-dibromoalkylsilane; reaction of the dibromide generated *in situ* with base gives the *Z*-vinyl bromide.

The vinylsilanes also can be converted to stereochemically defined dienes. We used the *E*-vinylsilane to identify conditions for the conversion of the C-H functionalization product to dienes. Reaction of the *E*-vinylsiane with an *E*-vinyl bromide in the presence of $Pd(OAc)_2$ and DPEphos with KOTMS as base generated the diene stereospecifically. Analogous procedures are

suitable for the conversion of *Z*-vinylsilanes to *Z,E*-dienes.[21] Such dienes that lack steric or electronic deactivation of one of the two alkenes are difficult to produce by cross metathesis.[22,23]

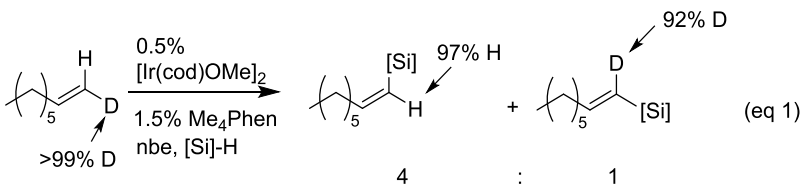
Scheme 1. Transformation of E-vinyl silanes.

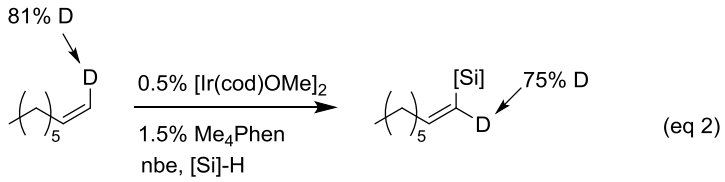


Mechanistic studies suggest that the dehydrogenative silylation of alkenes occurs by a pathway distinct from arene silylation and does not occur by direct insertion of iridium into the vinyl C-H bond. First, the reactions that give predominately the *Z*-vinylsilane proceeds without nbe as the acceptor (Table 1, entry 15), while reaction with 2-MePhen as ligand strongly favors the *E*-vinylsilane product even in the presence of nbe (Table 6, entry 1). This observation contrasts the published results with triethylsilane in which no catalytic reaction was observed in the absence of nbe, and nbe was proposed to promote the selectivity for the *Z*-isomer.[8,24] Our data suggest that the diastereoselectivity of the reactions with the siloxysilane is influenced more by the ligand than by the hydrogen acceptor.

Second, the ratios of the rates for separate reactions of 1-octene and 1,1-d_2-1-octene conducted with Me_4Phen or 2-MePhen as ligand are 1.7 and 1.5, respectively. This small kinetic isotope effect suggests that the reaction does not occur by initial, irreversible oxidative addition of the vinyl C-H bond and that the C-H bond cleavage step is similar for reactions catalyzed by the two systems.

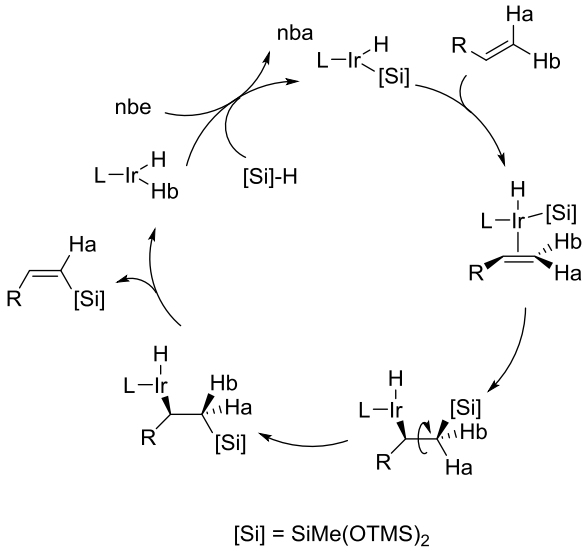
Finally, and most definitively, the reaction of *trans*-1-d_1-1-octene under the conditions that favor formation of the *Z*-vinylsilane gave the major *Z*-product containing hydrogen at the vinylic position (eq 1). Similarly, the reaction of *cis*-1-d_1-1-octene led to the vinylsilane product containing deuterium at the *trans* position (eq 2). These labeling studies support a mechanism involving syn-insertion of the alkene into the iridium-silyl bond, followed by ß-hydrogen elimination from a syn coplanar conformation of the silylalkyl intermediate (Scheme 2)





(eq 2)

Scheme 2. Proposed catalytic cycle for dehydrogenative silylation.



[Si] = $SiMe(OTMS)_2$

2.3 Conclusions

In summary, we discovered a diastereoselective intermolecular silylation of terminal alkenes with a siloxysilane to give either *E*- or *Z*-vinylsilanes depending on the ligand employed. These vinylsilane products are suitable for further functionalization, including cross-coupling and oxidation. The one-pot silylation and Hiyama coupling sequence provides an alternative strategy to the Wittig olefination and Heck reaction for the synthesis of *cis*-1,2-substituted alkenes, while the silylation/oxidation sequence complements the regioselectivity of the Wacker process and is shorter than the combination of hydroboration, oxidation to the alcohol, and further oxidation to the aldehyde. The nature of the active silylating species and the origin of difference in diastereoselectivity between 2-MePhen and Me_4Phen ligands are currently under investigation.

2.4 Experimental

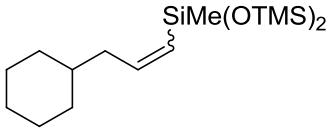
General Comments

All air-sensitive manipulations were conducted under an inert atmosphere in a nitrogen-filled glovebox or by standard Schlenk techniques. Toluene, tetrahydrofuran, and dichloromethane were dried with an Innovative Technology Pure-Solv solvent purification system. Reagents were purchased from commercial sources unless otherwise indicated and degassed prior to use. $[Ir(cod)OMe]_2$ was obtained from Johnson-Matthey. $[Ir(coe)_2Cl]_2$[25] and $[Ir(coe)_2OH]_2$[26] were prepared according to the literature procedures.

GC analyses were conducted on an Agilent 6890 GC equipped with an HP-5 column (25 m x 0.20 mm ID x 0.33 m film) and an FID detector. GC yields were calculated using dodecane as the internal standard. High-resolution mass spectra were obtained via the Micro-Mass/Analytical Facility operated by the College of Chemistry, University of California, Berkeley. NMR spectra were acquired on Bruker AVQ-400, AVB-400, DRX 500, and AV-600 spectrometers. Chemical shifts were reported in ppm relative to residual solvent peaks ($CDCl_3$ = 7.26 ppm for ^1H and 77.16 ppm for ^{13}C). Coupling constants were reported in Hz. Flash column chromatography was performed on a Teledyne ISCO CombiFlash® Rf system. Products were visualized on TLC plates under 254 nm UV light or by staining with I_2.

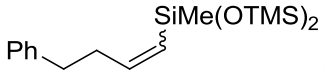
General Procedure for the Ir-Catalyzed Silylation of Alkenes

In a nitrogen-atmosphere glovebox, THF (0.4 mL) was added to a 4-mL vial containing $[Ir(coe)_2OH]_2$ (4.3 mg, 5.0 μmol) and Me_4Phen (3.5 mg, 0.015 mmol), and the mixture was stirred at room temperature for 5 min. To the dark brown suspension was added $(TMSO)_2MeSiH$ (670 mg, 3.0 mmol), and the resulting solution was stirred at room temperature for 5 min. Norbornene (280 mg, 3.0 mmol) and the alkene substrate (1.0 mmol) were added subsequently, the vial was sealed, and the solution was stirred at room temperature for 30 min and then heated at 50 ℃. The reaction progress was monitored by GC. After complete conversion of the starting material, the volatile materials were removed *in vacuo*, and the residue was purified by flash column chromatography to give the vinylsilane product.



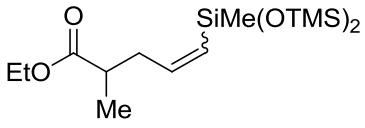
4b

The general procedure was followed with allylcyclohexane. The crude mixture was purified by flash column chromatography (hexanes) to give **4b** as a colorless oil (320 mg, 93% yield, Z/E = 90:10). ^1H NMR (500 MHz, $CDCl_3$) δ 6.35 – 6.27 (m, 1H), 5.35 (d, *J* = 14.3 Hz, 1H), 2.11 (t, *J* = 7.1 Hz, 2H), 1.76 – 1.62 (m, 5H), 1.38 – 1.28 (m, 1H), 1.28 – 1.09 (m, 3H), 0.98 – 0.84 (m, 2H), 0.14 – 0.07 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.14 (s), 127.74 (s), 41.10 (s), 38.37 (s), 33.38 (s), 26.76 (s), 26.55 (s), 2.25 (s), 2.05 (s). HRMS (EI+) calcd for $[C_{15}H_{33}O_2Si_3]^+$ (M-CH_3): 329.1788, found: 329.1793.



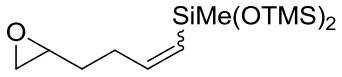
5b

The general procedure was followed with 4-phenyl-1-butene. The crude mixture was purified by flash column chromatography (hexanes) to give **5b** as a colorless oil (283 mg, 80% yield, Z/E = 92:8). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.29 (t, *J* = 7.5 Hz, 2H), 7.20 (d, *J* = 7.5 Hz, 3H), 6.32 (dt, *J* = 14.4, 7.3 Hz, 1H), 5.39 (d, *J* = 14.3 Hz, 1H), 2.70 (t, *J* = 7.4 Hz, 2H), 2.54 (dd, *J* = 15.5, 7.5 Hz, 2H), 0.13 – 0.04 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.05 (s), 141.92 (s), 128.59 (s), 128.46 (s), 128.08 (s), 125.98 (s), 36.05 (s), 35.10 (s), 2.13 (s), 2.04 (s). HRMS (EI+) calcd for $[C_{17}H_{32}O_2Si_3]^+$: 352.1710, found: 352.1710.



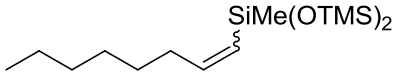
6b

The general procedure was followed with ethyl 2-methyl-4-pentenoate. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 8:2) to give **6b** as a colorless oil (278 mg, 77% yield, Z/E = 89:11). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.26 – 6.14 (m, 1H), 5.41 (d, *J* = 14.3 Hz, 1H), 4.16 – 4.09 (m, 2H), 2.57 – 2.50 (m, 1H), 2.47 (dd, *J* = 13.6, 6.7 Hz, 1H), 2.43 – 2.35 (m, 1H), 1.24 (t, *J* = 7.1 Hz, 3H), 1.14 (d, *J* = 6.7 Hz, 3H), 0.12 – 0.05 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 176.23 (s), 146.37 (s), 129.55 (s), 60.36 (s), 39.67 (s), 36.75 (s), 16.62 (s), 14.39 (s), 2.03 (s), 1.98 (s). HRMS (EI+) calcd for $[C_{15}H_{34}O_4Si_3]^+$: 362.1765, found: 362.1767.



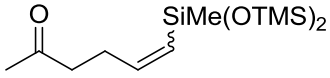
7b

The general procedure was followed with 5,6-epoxy-1-hexene. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 9:1) to give **7b** as a colorless oil (264 mg, 83% yield, Z/E = 90:10). ^{1}H NMR (499 MHz, $CDCl_3$) δ 6.28 (dt, *J* = 14.4, 7.4 Hz, 1H), 5.38 (dt, *J* = 14.2, 1.2 Hz, 1H), 2.95 – 2.89 (m, 1H), 2.74 (dd, *J* = 4.7, 4.2 Hz, 1H), 2.47 (dt, *J* = 5.0, 2.4 Hz, 1H), 2.41 – 2.34 (m, 2H), 1.69 – 1.55 (m, 2H), 0.14 – 0.03 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.47 (s), 128.35 (d, *J* = 4.4 Hz), 51.99 (s), 47.22 (s), 32.60 (s), 29.77 (s), 2.07 (s), 1.99 (s). HRMS (ESI+) calcd for $[C_{13}H_{30}NaO_3Si_3]^+$ (M+Na): 341.1395, found: 341.1396.



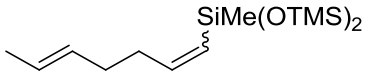
8b

The general procedure was followed with 1-octene. The crude mixture was purified by flash column chromatography (hexanes) to give **8b** as a colorless oil (284 mg, 85% yield, Z/E = 92:8). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.30 (dt, *J* = 14.5, 7.4 Hz, 1H), 5.34 (d, *J* = 14.2 Hz, 1H), 2.21 (q, *J* = 7.2 Hz, 2H), 1.47 – 1.24 (m, 8H), 0.90 (t, *J* = 6.8 Hz, 3H), 0.16 – 0.06 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 150.51 (s), 127.13 (s), 33.70 (s), 32.09 (s), 29.84 (s), 29.34 (s), 22.85 (s), 14.26 (s), 2.19 (s, *J* = 19.0 Hz), 2.02 (s). HRMS (EI+) calcd for $[C_{14}H_{33}O_2Si_3]^+$ (M-CH_3): 317.1788, found: 317.1795.



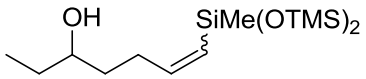
9b

The general procedure was followed with 5-hexen-2-one. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 9:1) to give **9b** as a colorless oil (227 mg, 71% yield, Z/E = 90:10). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.18 (ddd, *J* = 7.3, 6.9, 4.2 Hz, 1H), 5.33 (d, *J* = 14.2 Hz, 1H), 2.51 – 2.39 (m, 4H), 2.09 (s, 3H), 0.09 – 0.03 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 207.70 (s), 147.78 (s), 128.57 (s), 43.50 (s), 29.89 (s), 27.49 (s), 1.93 (s), 1.88 (s). HRMS (EI+) calcd for $[C_{13}H_{30}O_3Si_3]^+$: 318.1503, found: 318.1506.



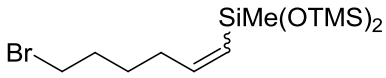
10b

The general procedure was followed with 1,5-heptadiene. The crude mixture was purified by flash column chromatography (hexanes) to give **10b** as a colorless oil (226 mg, 71% yield, Z/E = 91:9). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.20 (dt, *J* = 14.6, 7.4 Hz, 1H), 5.38 – 5.33 (m, 2H), 5.27 (d, *J* = 14.2 Hz, 1H), 2.19 (qd, J = 7.7, 1.1 Hz, 2H), 2.03 – 1.96 (m, 2H), 1.56 (dd, *J* = 3.4, 1.2 Hz, 3H), 0.06 – 0.01 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.69 (s), 130.82 (s), 127.60 (s), 125.31 (s), 33.49 (s), 32.77 (s), 18.06 (s), 2.13 (s), 2.02 (s). HRMS (EI+) calcd for $[C_{13}H_{29}O_2Si_3]^+$ (M-CH_3): 301.1475, found: 301.1477.



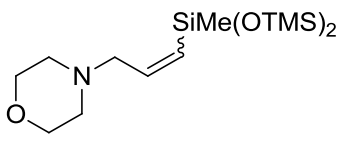
11b

The general procedure was followed with 6-hepten-3-ol. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 9:1) to give **11b** as a colorless oil (285 mg, 85% yield, Z/E = 89:11). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.32 – 6.22 (m, 1H), 5.34 (d, *J* = 14.2 Hz, 1H), 3.54 – 3.48 (m, 1H), 2.30 (q, *J* = 7.5 Hz, 2H), 1.91 (bs, 1H), 1.57 – 1.37 (m, 4H), 0.92 (t, *J* = 7.4 Hz, 3H), 0.12 – 0.04 (m, 21H). 13C NMR (126 MHz, CDCl3) δ 149.83 (s), 127.61 (s), 72.65 (s), 36.62 (s), 30.20 (s), 29.81 (s), 10.09 (s), 2.11 (s), 1.94 (s). HRMS (EI+) calcd for $[C_{13}H_{31}O_3Si_3]^+$ (M-CH_3): 319.1581, found: 319.1582.



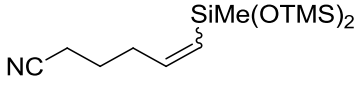
12b

The general procedure was followed with 6-bromo-1-hexene. The crude mixture was purified by flash column chromatography (hexanes) to give **12b** as a colorless oil (298 mg, 78% yield, Z/E = 91:9). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.25 (dt, *J* = 14.5, 7.4 Hz, 1H), 5.37 (d, *J* = 14.2 Hz, 1H), 3.41 (t, *J* = 6.8 Hz, 2H), 2.28 – 2.22 (m, 2H), 1.91 – 1.85 (m, 2H), 1.58 – 1.50 (m, 2H), 0.14 – 0.07 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.01 (s), 127.92 (s), 33.55 (s), 32.39 (s), 32.31 (s), 28.04 (s), 2.00 (s), 1.88 (s). HRMS (EI+) calcd for $[C_{12}H_{28}BrO_2Si_3]^+$ (M-CH_3): 367.0580, found: 367.0582.



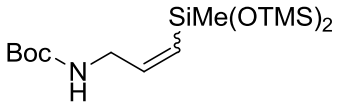
13b

The general procedure was followed with allylmorpholine and 2× normal catalyst loading at 65 ℃. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 9:1 to 7:3) to give **13b** as an orange oil (207 mg, 60% yield, Z/E = 85:15). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.41 – 6.20 (m, 1H), 5.49 (d, *J* = 14.5 Hz, 1H), 3.67 (s, 4H), 3.12 (d, *J* = 6.5 Hz, 2H), 2.42 (s, 4H), 0.09 – 0.03 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.62 (s), 130.50 (s), 66.95 (s), 60.45 (s), 53.64 (s), 1.88 (s), 1.82 (s). HRMS (EI+) calcd for $[C_{14}H_{33}NO_3Si_3]^+$: 347.1768, found: 347.1772.



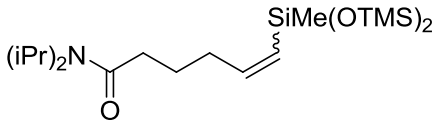
14b

The general procedure was followed with 6-hexenenitrile and 2× normal catalyst loading with 4-MePhen as the ligand. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 9:1) to give **14b** as a colorless oil (203 mg, 64% yield, Z/E = 85:15). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.19 (dt, *J* = 14.5, 7.4 Hz, 1H), 5.43 (d, *J* = 14.3 Hz, 1H), 2.37 – 2.29 (m, 4H), 1.79 – 1.72 (m, 2H), 0.12 – 0.05 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.66 (s), 129.80 (s), 119.61 (s), 31.97 (s), 25.41 (s), 16.59 (s), 1.96 (s), 1.90 (s). HRMS (EI+) calcd for $[C_{13}H_{29}NO_2Si_3]^+$: 315.1506, found: 315.1512.



16b

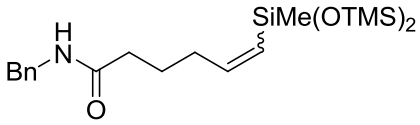
The general procedure was followed with *N*-Boc-allylamine and 2× normal catalyst loading with 4-MePhen as the ligand. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 9:1 to 6:4) to give **16b** as a colorless oil (225 mg, 60% yield, Z/E = 88:12). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.30 – 6.19 (m, 1H), 5.47 (d, *J* = 14.3 Hz, 1H), 4.67 (bs, 1H), 3.83 (t, *J* = 5.7 Hz, 2H), 1.41 (s, 9H), 0.12 – 0.02 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 155.76 (s), 145.33 (s), 130.30 (s), 79.26 (s), 42.25 (s), 28.48 (s), 1.89 (s), 1.81 (s). HRMS (ESI+) calcd for $[C_{15}H_{35}NNaO_4Si_3]^+$ (M+Na): 400.1766, found: 400.1767.



17b

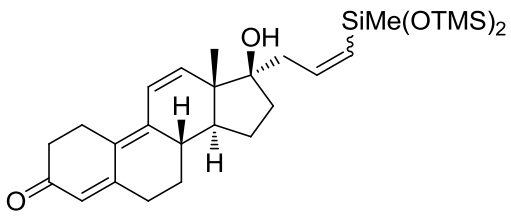
The general procedure was followed with *N*,*N*-bis(1-methylethyl)-5-hexenamide[27] and 2× normal catalyst loading on a 0.25 mmol scale. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 7:3) to give **17b** as a yellow oil (79 mg, 76% yield,

Z/E = 88:12). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.25 (dt, *J* = 14.4, 7.3 Hz, 1H), 5.34 (d, *J* = 14.3 Hz, 1H), 4.00 – 3.86 (m, 1H), 3.45 (bs, 1H), 2.32 – 2.19 (m, 4H), 1.77 – 1.63 (m, 2H), 1.35 (d, *J* = 6.4 Hz, 6H), 1.17 (d, *J* = 6.5 Hz, 6H), 0.12 – 0.01 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 171.70 (s), 149.44 (s), 127.89 (s), 45.62 (s), 34.85 (s), 33.01 (s), 25.24 (s), 21.13 (s), 20.81 (s), 2.14 (s), 1.97 (s). HRMS (ESI+) calcd for $[C_{19}H_{44}NO_3Si_3]^+$ (M+H): 418.2624, found: 418.2624.



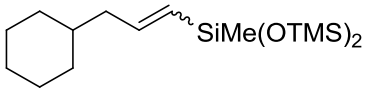
18b

The general procedure was followed with *N*-phenylmethyl-5-hexenamide[28] and 2× normal catalyst loading with 4-MePhen as ligand. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 8:2) to give **18b** as a yellow oil (322 mg, 76% yield, Z/E = 85:15). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.32 – 7.27 (m, 2H), 7.23 (t, *J* = 7.4 Hz, 3H), 6.34 (bs, 1H), 6.23 (dt, *J* = 14.5, 7.4 Hz, 1H), 5.37 (d, *J* = 14.3 Hz, 1H), 4.36 (d, *J* = 5.6 Hz, 2H), 2.28 – 2.15 (m, 4H), 1.77 – 1.69 (m, 2H), 0.17 – 0.06 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 172.79 (s), 148.82 (s), 138.51 (s), 128.62 (s), 128.15 (s), 127.72 (s), 127.36 (s), 43.47 (s), 36.06 (s), 32.79 (s), 25.52 (s), 2.05 (s), 1.90 (s). HRMS (ESI+) calcd for $[C_{20}H_{37}NNaO_3Si_3]^+$ (M+Na): 446.1974, found: 446.1974.



20b

The general procedure was followed with Altrenogest (Santa Cruz Biotechnology, Inc.) and 2× normal catalyst loading on a 0.2 mmol scale. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 7:3) to give **20b** as an off-white wax (65 mg, 61% yield, Z/E = 90:10). ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.53 – 6.44 (m, 2H), 6.32 (d, *J* = 10.0 Hz, 1H), 5.76 (s, 1H), 5.59 (d, *J* = 14.3 Hz, 1H), 2.87 – 2.73 (m, 2H), 2.61 – 2.51 (m, 2H), 2.48 – 2.40 (m, 4H), 2.36 (dd, *J* = 14.4, 7.4 Hz, 1H), 2.10 – 2.02 (m, 1H), 1.93 – 1.84 (m, 1H), 1.75 – 1.60 (m, 3H), 1.54 – 1.44 (m, 1H), 1.33 – 1.19 (m, 2H), 1.01 (s, 3H), 0.12 – 0.05 (m, 21H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 199.25 (s), 156.61 (s), 145.02 (s), 142.08 (s), 141.70 (s), 131.65 (s), 127.13 (s), 124.06 (s), 123.68 (s), 81.72 (s), 49.39 (s), 48.05 (s), 41.62 (s), 38.43 (s), 36.80 (s), 34.69 (s), 31.61 (s), 27.21 (s), 24.43 (s), 23.22 (s), 16.69 (s), 2.06 (s), 2.02 (s), 2.01 (s), 2.00 (s). HRMS (ESI+) calcd for [$C_{28}H_{47}O_4Si_3^+$] (M+H): 531.2777, found: 531.2793.

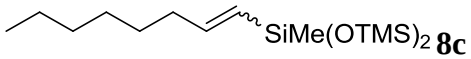


4c

The general procedure was followed with 2 mmol of allylcyclohexane, no nbe, 1 mmol of silane, and 2-MePhen as ligand. The crude mixture was purified by flash column chromatography (hexanes) to give **4c** as a colorless oil (250 mg, 73% yield [based on silane], Z/E = 7:93). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.13 (dt, *J* = 18.6, 6.8 Hz, 1H), 5.47 (dt, *J* = 18.6, 1.3 Hz, 1H), 2.02 (td, *J* = 6.8, 1.2 Hz, 2H), 1.71 (d, *J* = 10.9 Hz, 5H), 1.43 – 1.31 (m, 1H), 1.30 – 1.13 (m, 3H), 0.98 – 0.85 (m, 2H), 0.17 – 0.06 (m, 21H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.88 (s), 129.26 (s), 44.91 (s), 37.76 (s), 33.37 (s), 26.79 (s), 26.54 (s), 2.04 (s), 0.15 (s). HRMS (EI+) calcd for [$C_{15}H_{33}O_2Si_3$]$^+$ (M-CH_3): 329.1788, found: 329.1792.

7c

The general procedure was followed with 2 mmol of 5,6-epoxy-1-hexene, no nbe, 1 mmol of silane, and 2-MePhen as ligand. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 9:1) to give **7c** as a colorless oil (194 mg, 61% yield, Z/E = 11:89). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.14 (dt, *J* = 18.3, 5.7 Hz, 1H), 5.52 (d, *J* = 18.6 Hz, 1H), 2.90 (s, 1H), 2.73 (d, *J* = 3.4 Hz, 1H), 2.46 (t, *J* = 2.3 Hz, 1H), 2.25 (ddt, *J* = 21.6, 14.6, 7.3 Hz, 2H), 1.63 (d, *J* = 6.7 Hz, 2H), 0.16 – -0.01 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.29 (s), 128.81 (s), 51.89 (s), 47.26 (s), 32.61 (s), 31.50 (s), 1.96 (s), 0.01 (s). HRMS (EI+) calcd for $[C_{12}H_{27}O_3Si_3]^+$ (M-CH_3): 303.1268, found: 303.1264.

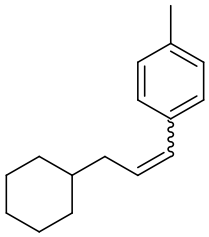


8c

The general procedure was followed with 2 mmol of 1-octene, no nbe, 1 mmol of silane, and 2-MePhen as ligand. The crude mixture was purified by flash column chromatography (hexanes) to give **8c** as a colorless oil (192 mg, 58% yield, Z/E = 7:93). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.15 (dt, *J* = 18.6, 6.3 Hz, 1H), 5.49 (d, *J* = 18.7 Hz, 1H), 2.11 (td, *J* = 7.6, 1.2 Hz, 2H), 1.44 – 1.35 (m, 2H), 1.34 – 1.21 (m, 7H), 0.90 (t, *J* = 6.8 Hz, 3H), 0.14 – 0.06 (m, 21H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.32 (s), 127.81 (s), 36.62 (s), 31.96 (s), 29.07 (s), 28.67 (s), 22.84 (s), 14.27 (s), 2.04 (s), 0.11 (s). HRMS (EI+) calcd for $[C_{14}H_{33}O_2Si_3]^+$ (M-CH_3): 317.1788, found: 317.1790.

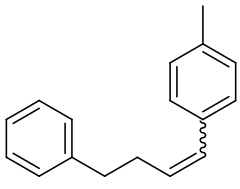
General Procedure for the One-pot Synthesis of Vinylarenes from Alkenes

The general procedure for alkene silylation on a 1.0 mmol scale was followed with allylcyclohexene or 4-phenyl-1-butene. The volatile materials were evaporated from the crude reaction mixture containing the vinylsilane **4b** or **5b** *in vacuo*. In a nitrogen-atmosphere glovebox, a solution of $Pd(OAc)_2$ (11.2 mg) in THF (1 mL) was added to a solution of DPEPhos (32 mg) in THF (1 mL), and the mixture was stirred at room temperature for 3 min. The yellow suspension was then transferred to the 20-mL glass vial containing the crude vinylsilane. Aryl iodide (0.80 mmol) and KOTMS (2.2 mmol) were then added. The mixture was heated at 50 ℃ for 15 h, after which time the volatile materials were removed *in vacuo*, and the crude mixture was purified by flash column chromatography to give the vinylarene product.



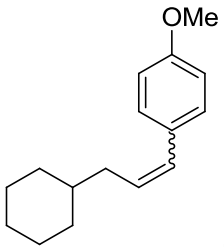
4e

The general procedure was followed with allylcyclohexane and 4-iodotoluene. The crude mixture was purified by flash column chromatography (hexanes) to give **4e** as a colorless oil (128 mg, 75% yield, Z/E = 90:10). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.18 (d, *J* = 8.0 Hz, 2H), 7.14 (d, *J* = 8.0 Hz, 2H), 6.41 (d, *J* = 11.7 Hz, 1H), 5.65 (dt, *J* = 11.7, 7.3 Hz, 1H), 2.35 (s, 3H), 2.22 (td, *J* = 7.1, 1.6 Hz, 2H), 1.76 (d, *J* = 13.1 Hz, 2H), 1.73 – 1.61 (m, 3H), 1.43 – 1.32 (m, 1H), 1.30 – 1.07 (m, 3H), 0.92 (ddd, *J* = 24.5, 12.5, 2.9 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 136.14 (s), 135.16 (s), 131.37 (s), 129.18 (s), 128.91 (s), 128.86 (s), 38.87 (s), 36.46 (s), 33.38 (s), 26.69 (s), 26.53 (s), 21.31 (s). HRMS (EI+) calcd for $[C_{16}H_{22}]^{+}$: 214.1722, found: 214.1719.



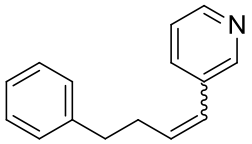
5e

The general procedure was followed with 4-phenyl-1-butene and 4-iodotoluene. The crude mixture was purified by flash column chromatography (hexanes) to give **5e** as a colorless oil (132 mg, 74% yield, Z/E = 93:7). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 (t, *J* = 7.5 Hz, 2H), 7.28 – 7.24 (m, 3H), 7.20 (q, *J* = 8.1 Hz, 4H), 6.48 (d, *J* = 11.6 Hz, 1H), 5.73 (dt, *J* = 11.7, 7.0 Hz, 1H), 2.86 – 2.80 (m, 2H), 2.73 (dd, *J* = 15.2, 7.1 Hz, 2H), 2.40 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.87 (s), 136.38 (s), 134.80 (s), 131.23 (s), 129.38 (s), 128.98 (s), 128.77 (s), 128.59 (s), 128.47 (s), 126.02 (s), 36.25 (s), 30.62 (s), 21.29 (s). HRMS (EI+) calcd for $[C_{17}H_{18}]^{+}$: 222.1409, found: 222.1409.



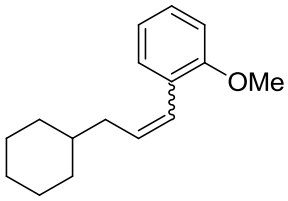
4f

The general procedure was followed with allylcyclohexane and 4-iodoanisole on a 0.5 mmol scale. The crude mixture was purified by flash column chromatography (hexanes) to give **4f** as a colorless oil (64 mg, 69% yield, Z/E = 85:15). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.24 (d, *J* = 8.6 Hz, 2H), 6.89 (d, *J* = 8.7 Hz, 2H), 6.39 (d, *J* = 11.7 Hz, 1H), 5.62 (dt, *J* = 11.7, 7.2 Hz, 1H), 3.82 (s, 3H), 2.23 (td, *J* = 7.1, 1.5 Hz, 2H), 1.78 (d, *J* = 13.1 Hz, 2H), 1.75 – 1.63 (m, 3H), 1.45 – 1.33 (m, 1H), 1.31 – 1.10 (m, 3H), 0.93 (ddd, *J* = 24.5, 12.5, 2.9 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.18 (s), 130.69 (s), 130.48 (s), 130.09 (s), 128.70 (s), 113.59 (s), 55.34 (s), 38.87 (s), 36.43 (s), 33.38 (s), 26.68 (s), 26.52 (s). HRMS (EI+) calcd for $[C_{16}H_{22}O]^+$: 230.1671, found: 230.1667.



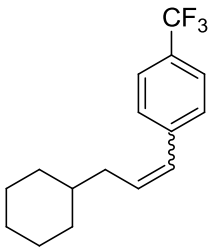
5f

The general procedure was followed with 4-phenyl-1-butene and 3-iodopyridine. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 9:1 to 5:5) to give **5f** as a colorless oil (128 mg, 76% yield, Z/E = 93:7). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.48 (s, 1H), 8.45 (d, *J* = 4.6 Hz, 1H), 7.48 (d, *J* = 7.8 Hz, 1H), 7.29 (t, *J* = 7.5 Hz, 2H), 7.24 – 7.14 (m, 4H), 6.39 (d, *J* = 11.6 Hz, 1H), 5.84 (dt, *J* = 11.7, 7.3 Hz, 1H), 2.78 (t, *J* = 7.6 Hz, 2H), 2.63 (q, *J* = 7.4 Hz, 2H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 149.94 (s), 147.73 (s), 141.29 (s), 135.68 (s), 134.23 (s), 133.18 (s), 128.53 (s), 128.49 (s), 126.14 (s), 126.01 (s), 123.11 (s), 35.90 (s), 30.44 (s). HRMS (EI+) calcd for $[C_{15}H_{15}N]^+$: 209.1204, found: 209.1204.



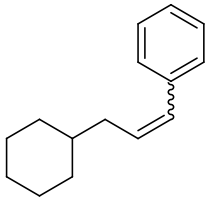
4h

The general procedure was followed with allylcyclohexane and 2-iodoanisole. The crude mixture was purified by flash column chromatography (hexanes) to give **4h** as a colorless oil (149 mg, 81% yield, Z/E = 86:14). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 – 7.23 (m, 2H), 6.96 (t, *J* = 7.4 Hz, 1H), 6.91 (d, *J* = 8.2 Hz, 1H), 6.57 (d, *J* = 11.7 Hz, 1H), 5.80 (dt, *J* = 11.7, 7.4 Hz, 1H), 3.86 (s, *J* = 3.6 Hz, 3H), 2.18 (td, *J* = 7.1, 1.6 Hz, 2H), 1.84 – 1.64 (m, 4H), 1.46 – 1.35 (m, 1H), 1.32 – 1.12 (m, 4H), 0.93 (ddd, *J* = 24.2, 12.4, 2.7 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.15 (s), 131.81 (s), 130.20 (s), 128.00 (s), 126.79 (s), 124.73 (s), 120.08 (s), 110.49 (s), 55.57 (s), 38.72 (s), 36.39 (s), 33.38 (s), 26.69 (s), 26.53 (s). HRMS (EI+) calcd for $[C_{16}H_{22}O]^+$: 230.1671, found: 230.1674.



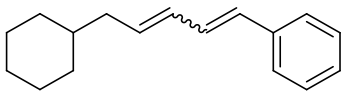
4g

The general procedure was followed with allylcyclohexane and 4-iodobenzotrifluoride. The crude mixture was purified by flash column chromatography (hexanes) to give **4g** as a colorless oil (183 mg, 85% yield, Z/E = 87:13). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.60 (d, *J* = 8.1 Hz, 2H), 7.38 (d, *J* = 8.0 Hz, 2H), 6.48 (d, *J* = 11.8 Hz, 1H), 5.83 (dt, *J* = 11.8, 7.4 Hz, 1H), 2.23 (dd, *J* = 10.0, 4.2 Hz, 2H), 1.82 – 1.64 (m, 4H), 1.47 – 1.36 (m, 1H), 1.33 – 1.12 (m, 4H), 0.99 – 0.89 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.58 (q, *J* = 1.1 Hz), 134.27 (s), 129.10 (s), 128.47 (q, *J* = 32.2 Hz), 128.22 (s), 125.15 (q, *J* = 3.8 Hz), 124.48 (q, *J* = 271.8 Hz), 38.76 (s), 36.43 (s), 33.34 (s), 26.61 (s), 26.48 (s). HRMS (EI+) calcd for $[C_{16}H_{19}F_3]^+$: 268.1439, found: 268.1440.



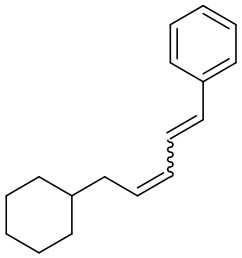
4i

The general procedure was followed with allylcyclohexane and bromobenzene. The crude mixture was purified by flash column chromatography (hexanes) to give **4i** as a colorless oil (119 mg, 59% yield, Z/E = 88:12). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.41 – 7.32 (m, 4H), 7.29 – 7.21 (m, 1H), 6.50 (d, *J* = 11.7 Hz, 1H), 5.76 (dt, *J* = 11.8, 7.3 Hz, 1H), 2.29 (t, *J* = 7.0 Hz, 2H), 1.86 – 1.68 (m, 5H), 1.49 – 1.39 (m, 1H), 1.36 – 1.25 (m, 2H), 1.25 – 1.15 (m, 1H), 1.03 – 0.92 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 138.02 (s), 132.02 (s), 129.37 (s), 128.93 (s), 128.18 (s), 126.47 (s), 38.84 (s), 36.40 (s), 33.36 (s), 26.68 (s), 26.52 (s). HRMS (EI+) calc for $[C_{15}H_{20}]^+$: 200.1565, found: 200.1563.



Isolated compound **4c** (Z/E = 7:93, 68 mg, 0.20 mmol) was subjected to the cross-coupling conditions with *E*-β-bromostyrene (38 mg, 0.21 mmol), and the crude mixture was purified by flash column chromatography (hexanes) to give the product as a colorless oil (36 mg, 80% yield,

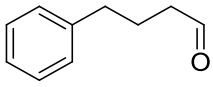
Z/E = 8:92). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39 (d, *J* = 7.5 Hz, 2H), 7.34 – 7.30 (m, 2H), 7.21 (t, *J* = 7.3 Hz, 1H), 6.78 (dd, *J* = 15.6, 10.4 Hz, 1H), 6.45 (d, *J* = 15.7 Hz, 1H), 6.20 (dd, *J* = 15.1, 10.5 Hz, 1H), 5.84 (dt, *J* = 15.0, 7.5 Hz, 1H), 2.06 (t, *J* = 7.1 Hz, 2H), 1.78 – 1.64 (m, 5H), 1.41 – 1.33 (m, 1H), 1.30 – 1.13 (m, 3H), 1.00 – 0.90 (m, 2H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 137.82 (s), 134.78 (s), 131.61 (s), 130.01 (s), 129.57 (s), 128.67 (s), 127.17 (s), 126.24 (s), 41.07 (s), 38.32 (s), 33.32 (s), 26.69 (s), 26.49 (s). HRMS (EI+) calc for $[C_{17}H_{22}]^{+}$: 226.1722, found: 226.1723.



Isolated compound **4b** (Z/E = 90:10, 63 mg, 0.19 mmol) was subjected to the cross-coupling conditions with *E*-β-bromostyrene (38 mg, 0.21 mmol), and the crude mixture was purified by flash column chromatography (hexanes) to give the product as a colorless oil (33 mg, 79% yield, Z/E = 87:13). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.39 (m, 2H), 7.33 (t, *J* = 7.6 Hz, 2H), 7.27 – 7.20 (m, 1H), 7.08 (ddd, *J* = 15.6, 11.1, 1.0 Hz, 1H), 6.54 (d, *J* = 15.6 Hz, 1H), 6.22 (dd, *J* = 11.2, 10.8 Hz, 1H), 5.58 (dt, *J* = 10.8, 7.9 Hz, 1H), 2.23 – 2.17 (m, 2H), 1.81 – 1.65 (m, 5H), 1.43 – 1.35 (m, 1H), 1.30 – 1.17 (m, 3H), 1.03 – 0.95 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 137.87 (s), 132.13 (s), 132.04 (s), 129.50 (s), 128.70 (s), 127.43 (s), 126.45 (s), 124.81 (s), 38.56 (s), 35.94 (s), 33.38 (s), 26.69 (s), 26.52 (s). HRMS (EI+) calc for $[C_{17}H_{22}]^{+}$: 226.1722, found: 226.1722.

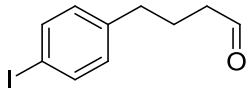
General Procedure for the One-pot Synthesis of Aldehydes from Alkenes

The general procedure for alkene silylation on a 1.0 mmol scale was followed, and the volatile materials were evaporated *in vacuo*. To the crude mixture was added THF (14 mL) and TBAF (4.4 mL of 1.0 M THF solution) at 0 ℃, and the reaction mixture was stirred at 0 ℃ for 15 min. At 0 ℃, 30% aqueous H_2O_2 (4.2 mL), MeOH (10 mL), and $KHCO_3$ (0.5 g) were added, and the solution was stirred at room temperature for 18 h. Then H_2O (40 mL) was added, and the stirring continued for 30 min at 23 ℃. The mixture was extracted with EtOAc (50 mL×2), and the organic layer was washed with $Na_2S_2O_3$ (30% aqueous solution, 15 mL×2). The organic layer was then washed with brine (15 mL), dried over $MgSO_4$, and the solvent was evaporated. The crude product was purified by flash column chromatography to give the aldehyde products.



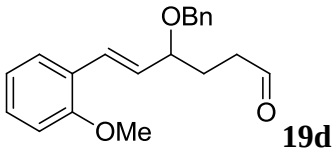
5d

The general procedure was followed starting from 4-phenyl-1-butene. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 9:1) to give **5d** as a colorless oil (101 mg, 68% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 9.76 (s, 1H), 7.30 (t, *J* = 7.2 Hz, 2H), 7.20 (dd, *J* = 18.7, 7.2 Hz, 3H), 2.67 (t, *J* = 7.4 Hz, 2H), 2.46 (t, *J* = 7.0 Hz, 2H), 2.05 – 1.92 (m, 2H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 202.37 (s), 141.32 (s), 128.56 (s), 126.20 (s), 43.24 (s), 35.11 (s), 23.75 (s). Two aromatic resonances overlap with each other at 128.6 ppm.[29] HRMS (EI+) calcd for $[C_{10}H_{12}O]^{+}$: 148.0888, found: 148.0889.



15d

The general procedure was followed starting from 4-(4-iodophenyl)-1-butene[30]. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 10:0 to 9:1) to give **15d** as a colorless oil (144 mg, 52% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 9.75 (s, 1H), 7.59 (d, *J* = 8.2 Hz, 2H), 6.92 (d, *J* = 8.1 Hz, 2H), 2.59 (t, *J* = 7.6 Hz, 2H), 2.44 (td, *J* = 7.3, 1.3 Hz, 2H), 1.95 – 1.89 (m, 2H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 202.09 (s), 140.96 (s), 137.56 (s), 130.65 (s), 91.27 (s), 43.06 (s), 34.54 (s), 23.47 (s).[31]



19d

The general procedure was followed starting from **19a**. The crude mixture was purified by flash column chromatography (hexanes:EtOAc, 9:1 to 8:2) to give **19d** as a colorless oil (187 mg, 60% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 9.76 (s, 1H), 7.47 (dd, *J* = 7.6, 1.2 Hz, 1H), 7.38 – 7.33 (m, 4H), 7.31 – 7.23 (m, 2H), 6.98 – 6.87 (m, 3H), 6.13 (dd, *J* = 16.1, 8.1 Hz, 1H), 4.64 (d, *J* = 11.8 Hz, 1H), 4.39 (d, *J* = 11.8 Hz, 1H), 3.97 (dt, *J* = 5.3, 7.8 Hz, 1H), 3.86 (s, 3H), 2.63 – 2.50 (m, 2H), 2.10 – 2.03 (m, 1H), 2.01 – 1.94 (m, 1H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 202.37 (s), 156.85 (s), 138.58 (s), 129.91 (s), 129.06 (s), 128.43 (s), 128.02 (s), 127.95 (s), 127.59 (s), 126.97 (s), 125.30 (s), 120.71 (s), 110.97 (s), 79.59 (s), 70.22 (s), 55.49 (s), 40.26 (s), 28.62 (s). HRMS (EI+) calcd for $[C_{20}H_{22}O_3]^{+}$: 310.1569, found: 310.1569.

Bromination of 4c

To a solution of **4c** (Z/E = 7:93, 172 mg, 0.500 mmol) in CH_2Cl_2 (2 mL) was added drop wise a solution of bromine (80 mg, 0.50 mmol) in CH_2Cl_2 (2 mL) at -23 ℃. The solution was stirred at -23 ℃ for 30 min and then allowed to warm to room temperature for 30 min. The solvent was evaporated, and the resulting oil was suspended in MeOH (3 mL) and treated with a slurry of NaOMe (135 mg, 2.50 mmol) in MeOH (3 mL) at 0 ℃. The solution was stirred at room temperature for 2 h, and the solvent was evaporated. The residue was extracted with a minimal amount of hexanes and filtered over a silica plug. The solvent was evaporated from the filtrate to give the product as a colorless oil (73 mg, 72% yield, Z/E = 12:88). ^{1}H NMR (600 MHz, $CDCl_3$) δ 6.18 (dt, *J* = 7.0, 1.2 Hz, 1H), 6.10 (dt, *J* = 7.1, 7.1 Hz, 1H), 2.10 (td, *J* = 7.0, 1.1 Hz, 2H), 1.75 – 1.59 (m, 5H), 1.44 – 1.35 (m, 1H), 1.27 – 1.10 (m, 3H), 1.01 – 0.93 (m, 2H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 133.87 (s), 108.28 (s), 37.47 (s), 37.42 (s), 33.15 (s), 26.55 (s), 26.39 (s). HRMS (EI+) calcd for $[C_9H_{15}Br]^+$: 202.0357, found: 202.0359.

2.5 References and Notes

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"Iridium-Catalyzed, Diastereoselective Dehydrogenative Silylation of Terminal Alkenes with $(TMSO)_2MeSiH$".
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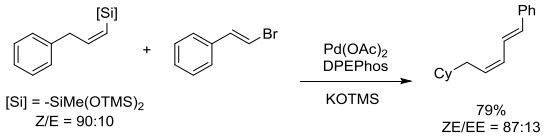

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Chapter 3: Rh-Catalyzed Silylation of Aryl C-H Bonds

3.1 Introduction

Methods for the selective functionalization of aromatic C-H bonds under mild, neutral conditions have synthetic applications in fields ranging from materials science to medicinal chemistry [1-6]. Perhaps most important for the utility of C-H bond functionalization is the control of site-selectivity. Regioselectivity in classical electrophilic aromatic substitution reactions is governed by the electronic properties of the substituents on the arene. In catalytic C-H functionalization of arenes, regiocontrol has been achieved in some cases by directing groups that bind to the catalyst and direct the reaction to an *ortho*- [2] or *meta*-C-H bond [7-9]. In other cases, such as in the widely used iridium-catalyzed borylation of arenes [3], the regioselectivity results from the steric properties of substituents *ortho* to a reacting C-H bond. However, reactions that occur with selectivity derived from the steric properties of groups distal to a potential site of reactivity on arenes have been challenging to develop. Groups in these positions are assumed to have minor steric effects on the reaction site, so much so that a classical method for perturbing the electronic effects of an aromatic ring on a chemical reaction is to introduce substituents *meta* or *para* to a site of reactivity.

We describe here a catalytic silylation of arenes that occurs with the highest levels of remote steric control of any reported aromatic C-H bond functionalization. The formation of arene-silicon bonds by C-H silylation could be a valuable route toward arylsilane monomers for silicone polymers and arylsilane intermediates in the synthesis of complex molecules [10-11]. Compared to the borylation of C-H bonds, our silylation of C-H bonds occurs with a simpler and more accessible class of main group reagent, and the arylsilane products are more stable to many of the conditions of typical organic transformations.

Much effort has been spent to develop protocols for the silylation of arenes, but the scope and efficiency of the reactions are limited. Intermolecular arene silylations with hydrosilanes have been conducted only at high temperatures (>100 ℃) or under photochemical conditions [12-17], with a large excess of arene relative to the silane. This stoichiometry is a limitation for synthetic applications because the arene is usually the more valuable reaction component. Furthermore, most silylation reactions have been conducted with trialkylsilanes [12, 16, 18], and the arylsilane products of these reactions have limited synthetic utility. To address this limitation, the silylation of arenes has been conducted with disilanes containing Si-F bonds, but these reactions also require high temperatures and excess arenes, and access to the disilane reagents requires multi-step syntheses [13-14]. Silylation of arenes assisted by a directing group has been reported more frequently, but these reactions are limited to functionalization *ortho* to the directing group [19-27].

Thus, practical silylations of arenes should be conducted with a readily available silane, under mild conditions, and with arenes as the limiting reagent. We report a combination of a rhodium catalyst, a simple hydrogen acceptor, and a readily available hydrosilane that generates arylsilanes in high yields with exceptional steric control, with arene as the limiting reagent, and

with substituents on silicon that render the arylsilane products synthetically valuable. The arylsilane products undergo cross coupling, oxidation, and halogenation; yet in the absence of fluoride or strong bases as activators, the silyl moiety is stable toward many common organic transformations. These studies show the value of C-H bond silylation for synthetic applications, the importance of rhodium catalysts for this class of transformation, and the capacity of catalysts to achieve C-H bond functionalization with remote steric control.

3.2 Results and Discussion

The regioselectivity of the silylation of arenes results from a high level of steric control by substituents *ortho* and *meta* to the reacting C-H bond. Studies on regioselectivity were conducted with rhodium catalysts derived from biphenylphosphine derivatives **L1** and **L2** because reactions with these ligands afforded the product in highest yields (Table 1, entries 9 and 10), and the two ligands possess different steric properties. Because the silane and cyclohexene are commercially available and inexpensive, we conducted reactions with two equivalents of the silane and acceptor to maximize the conversion of the arene [28] (Table 1, entry 11).

Under these conditions, the silylation of various 1,3-disubstitued arenes occurred at the mutually *meta* positions with >95:5 selectivities (Fig. 1) [29]. Even reaction with **6a** bearing a potentially *ortho*-directing amide group gave the 1,3,5-trisubstituted arene **6b** as the sole product. The reactions of symmetrically 1,2-disubstituted arenes gave the 1,2,4-trisubstituted arylsilanes with >99:1 selectivities. These regioselectivities parallel those of the iridium-catalyzed borylation of arenes, but with a more stable and less expensive reagent to form a linkage that undergoes transformations under conditions orthogonal to those of arylboronates (*vida infra*). Similar to prior borylation [30] and silylation [18] reactions, the silylation of an indole derivative (**16a**) and of benzofuran (**17a**) occurred at the 2-position of the heteroarenes with ≥97:3 selectivities [31].

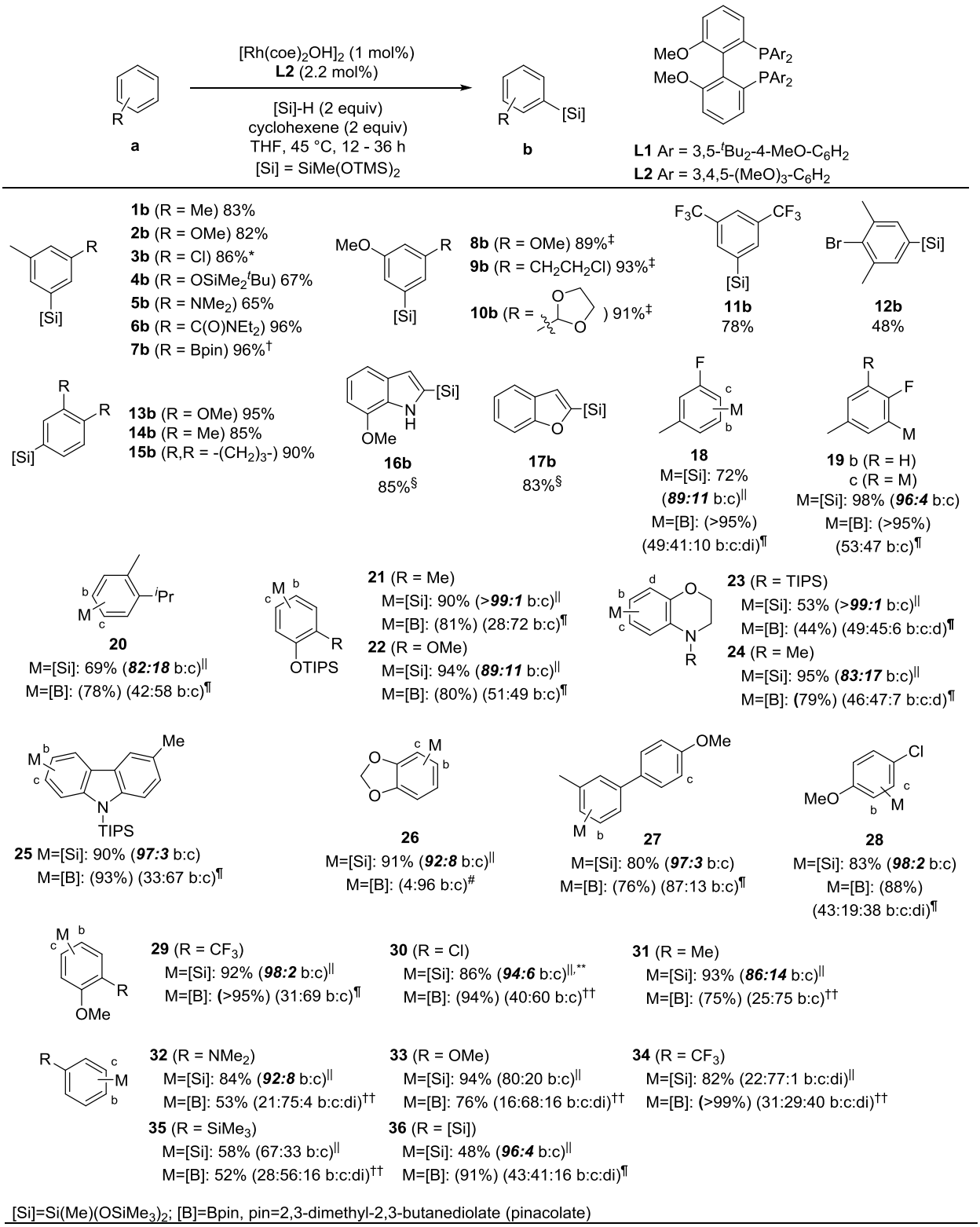


Fig. 1. The regioselective silylation of arenes. Reactions were conducted on a 0.3 mmol scale unless otherwise stated. Reported yields are for isolated materials. Yields in parentheses were determined by GC analysis for borylation reactions run on a 0.05 mmol scale. "di" denotes diborylation or disilylation products. *Dechloronated product was obtained in 4% yield.

[†]Reaction run on a 2.0 mmol scale. [‡]See footnote (*33*). [§]See footnote (*35*). [‖]Silylation carried out with **L1** as the ligand. [¶]Results of C-H borylation carried out following the literature procedure [32]. [#]Results from reference [33]. See footnote [34]. [**]Dechloronated product was obtained in 9% yield. [††]Results of borylation of the substrates obtained from reference [35].

Selective functionalization of fluoroarenes can provide synthetically valuable intermediates, but high sterically derived selectivity is often difficult to achieve because of the small size of fluorine. For example, the regioselective reaction of 3-fluorotoluene (**18a**) at the mutually *meta* position requires the catalyst to distinguish between the steric environment of a C-H bond *ortho* to a hydrogen atom and *ortho* to a fluorine atom. Silylation of **18a** occurred with an 89:11 selectivity favoring functionalization at the mutually *meta* position and without the formation of disilylation products. In contrast, the borylation of this substrate was unselective toward the C-H bonds *ortho* and *meta* to the fluorine (*ortho*:*meta* ~ 1:1).

The selective functionalization of unsymmetrically 1,2-disubstituted arenes is particularly challenging to achieve because the steric effects that control the site selectivity must be transmitted remotely. A catalytic system that addresses these problems must have exquisite sensitivity to steric differences at sites beyond the *ortho* positions. The borylation of arenes is only sensitive to substituents at the *ortho*-positions. Therefore, the borylation of unsymmetrically 1,2-disubstituted arenes occurs with poor regioselectivity. A recently-reported gold-catalyzed direct arylation occurs with high regioselectivity for unsymmetrically 1,2-disubstituted arenes [36]. However, the regioselectivity of this system is derived from the electronic properties of the substituents and is similar to that of electrophilic aromatic substitution.

The silylation of arenes reported here addresses the challenge of achieving site selectivity from remote steric effects. The following examples provide a comparison of the product distributions for the rhodium-catalyzed silylation and the iridium-catalyzed borylation of the same arenes (Fig. 1). In short, the silylation of arenes leads to products resulting from steric effects of substituents located *meta* to the site of reactivity. Higher regioselectivity was obtained from reactions run with the ligand **L1** bearing more sterically demanding *tert*-butyl groups than with ligand **L2** bearing less sterically demanding methoxy groups.

The silylation of *o*-cymene (**20a**) containing one large and one small alkyl group illustrates the sensitivity of the reaction to the substituents *meta* to the potentially reactive C-H bonds. The reaction of **20a** with **L1** as the ligand occurred with a selectivity of 82:18 in favor of the product containing the silyl group *para* to the larger of the two alkyl groups. In contrast, the borylation of this substrate occurred roughly equally at the two C-H bonds located *para* to the methyl and isopropyl groups. A similar remote steric sensitivity is illustrated by the reaction of 2-tri(isopropyl)siloxyanisole (**22a**), containing two electronically similar oxygen-based substituents of different sizes. The reaction of this arene catalyzed by the complex containing **L1** as ligand

occurred selectively *para* to the larger substituent to give the products in an 89:11 ratio. In contrast, the borylation of this substrate gave two products in a ratio of 51:49.

This sensitivity to the size of the *meta* substituent allows the size of a substituent on nitrogen in a heterocycle to modulate the regioselectivity of the C-H bond functionalization remotely. The size of the TIPS group in *N*-TIPS benzomorpholine (**23a**, TIPS = tri(isopropyl)silyl)) causes the silylation reaction to occur at the C-H bond *para* to the nitrogen atom with >99:1 regioselectivity; the reaction of *N*-methyl benzomorpholine (**24a**) occurred with a much lower (albeit significant) regioselectivity of 83:17. This effect of the *N*-TIPS group is also illustrated by the regioselective silylation of carbazole. The silylation of the *N*-TIPS-carbazole **25a** occurred with 97:3 selectivity for the position *para* to the *N*-TIPS group over the position *meta* to this group.

The silylation of benzodioxole (**26a**) is an example in which the steric effects override a propensity for metalation *ortho* to a substituent. The borylation of **26a** is reported to occur primarily at the *ortho*-position because of the small size of the dioxole unit and the higher acidity of the C-H bonds *ortho* to the oxygen-based substituents than *meta* to these substituents [33-34]. In contrast, the silylation of this arene gave the 1,2,4-substituted arylsilane as the predominant product from functionalization at the more sterically accessible C-H bond.

The rhodium-catalyzed silylation reaction can also selectively functionalize biaryls in which the two aryl groups have different steric properties. For example, silylation of 4'-methoxy-3-methyl-1,1'-biphenyl (**27a**) occurred preferentially on one aryl ring with a selectivity of 97:3 because of the 1,4-substitution pattern of the other aryl ring. In comparison, the selectivity for the borylation of this substrate is lower (87:13).

The electronic properties of the substituents do have a secondary influence on the regioselectivities. Silylation occurs at the more electron-rich position of the arene. This electronic effect can be gleaned from the reactions of 4-chloroanisole (**28a**) and some 1,2-disubstituted arenes (**29**-**31**). Reaction of **28a** occurred with a selectivity of 98:2 favoring silylation *ortho* to the methoxy group, whereas borylation of this substrate occurred at the two positions in a ratio of 2:1 [37]. Because a methoxy group (cyclohexane A value = 0.55-0.75) is usually considered to be slightly larger than a chlorine (A value = 0.53-0.64) [38], we attribute the regioselectivity of the silylation of **28a** to the electronic activation of the 2-position by the methoxy group. Likewise, silylation of a series of 2-substituted anisoles (**29**-**31**) catalyzed by the rhodium complex containing **L1** predominantly occurred *para* to the methoxy substituent.

The reactions of monosubstituted arenes are less selective than those of disubstituted arenes, but they reveal the combination of electronic and steric effects on the silylation reaction (**32**-**34**). The silylation of *N*,*N*-dimethylaminobenzene (**32**) occurred predominantly at the more electron-rich *para*-position (*para*:*meta* = 92:8, statistical ratio = 1:2), and the silylation of trifluoromethylbenzene (**34**) occurred preferentially at the less electron-deficient *meta*-positions (*para*:*meta* = 22:78), indicating that silylation is favored at the C-H bond on the more electron-

rich position of the ring. Disilylation occurred to a minimum extent, even during the reaction with **34**. One might expect to observe disilylation at both C-H bonds *meta* to the CF_3 group, but the large size of the $SiMe(OTMS)_2$ group hinders silylation at a position *meta* to it. Consistent with this assertion, the silylation of $PhSiMe(OTMS)_2$ (**36**) formed the disiylbenzene products with a *para*- to *meta*- ratio of 96:4.

Derivatization of the Silylarene Products

The silyl-substituted arenes generated from this catalytic process underwent a series of transformations made possible by the presence of the Si-O bonds (Fig. 2A). For example, the silylarenes underwent cross coupling with aryl halides to form biaryls and oxidation to form phenols. These silylarenes also underwent bromination and iodination, and these halogenation reactions were more facile and were conducted with simpler reagents than the copper-mediated halogenation of arylboronates [39]. In addition, rhodium-catalyzed 1,4-addition of silylarenes to acrylates and copper-mediated amination with benzimidazole occurred with good yields.

The arylsilanes and arylboronate esters react under conditions that are orthogonal to each other, and the difference between these conditions enables the sequential diversification of polysubstituted arenes. With a silyl-substituted arylboronate ester (**7b**), oxidation, cross coupling, and halogenation can be conducted at the site of the C-Si or C-B bond depending on the conditions and reagents chosen (Fig. 2B). For example, cross-coupling was conducted at the C-B bond before oxidation at the C-Si bond by using a weak base for the coupling process (sequence I). The C-B bond underwent oxidation with a basic solution of hydrogen peroxide prior to halogenation at the C-Si bond (sequence II). Furthermore, the halogenations at the C-Si bond were conducted in the presence of the C-B bond before oxidative functionalizations at the C-B bond (sequences III and IV).

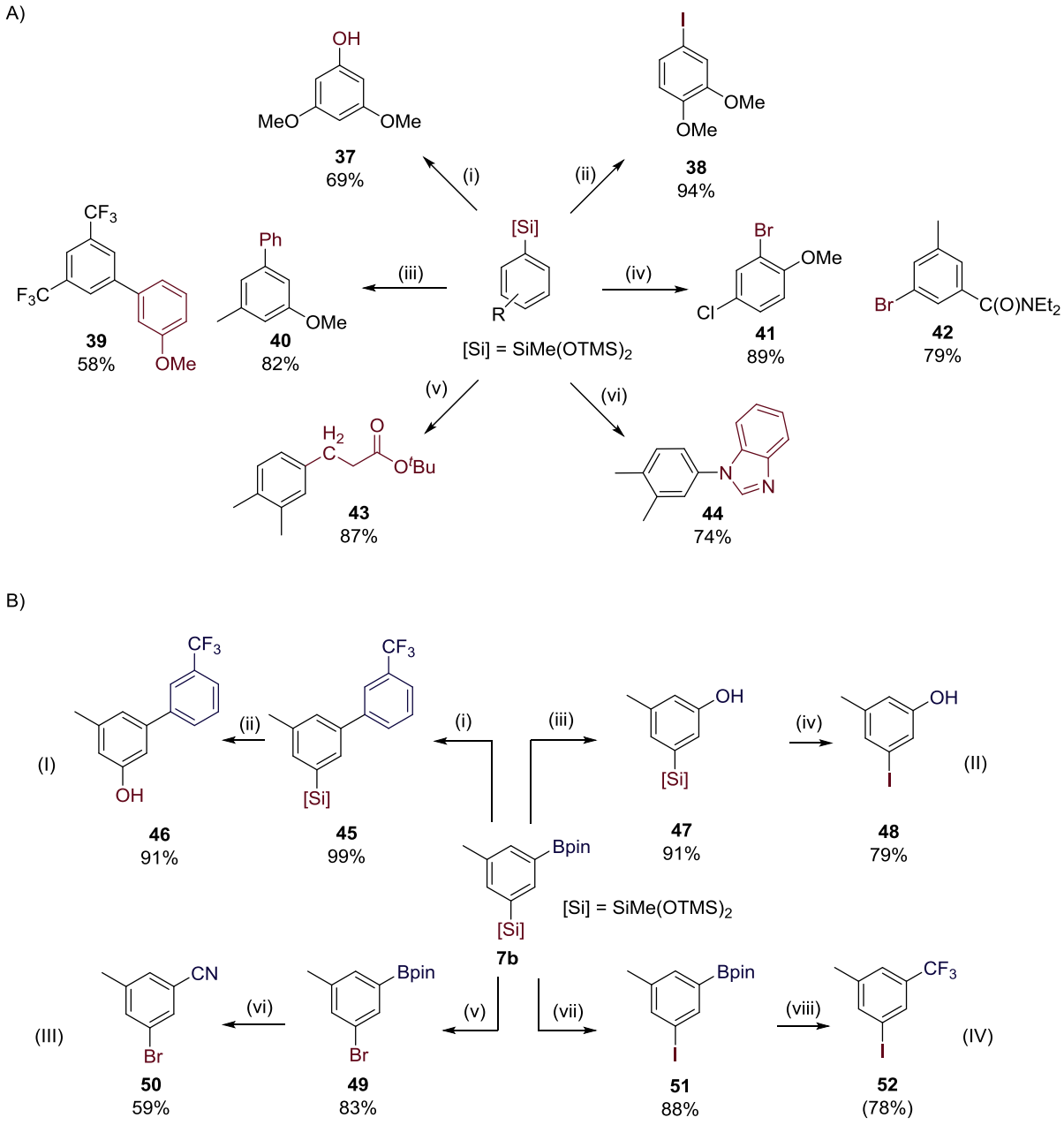


Fig. 2. Functionalization of the arylsilane products. Yields reported are for isolated materials. A) Silyl substitution. Reaction conditions: (i) TBAF (4 equiv), H_2O_2 (20 equiv), $KHCO_3$ (5 equiv), THF, MeOH, 23 ℃, 18 h; (ii) ICl (1.1 equiv), CH_2Cl_2, 23 ℃, 3 h; (iii) PhBr or 3-iodoanisole (0.7-1.5 equiv), KOTMS (3 equiv), $Pd(OAc)_2$ (0.05 equiv), DCPE (0.055 equiv), THF or toluene, 65-100 ℃, 5-14 h; (iv) Br_2 (1.5-8 equiv), CH_2Cl_2, 23 ℃, 1-24 h; (v) *tert*-butyl acrylate (0.5 equiv), $[Rh(cod)Cl]_2$ (0.02 equiv), TBAF (3 equiv), THF, H_2O, 100 ℃, 14 h; (vi) benzimidazole (0.5 equiv), $Cu(OAc)_2$ (0.6 equiv), TBAF (1 equiv), DMF, 23 ℃, 36 h. B) Orthogonality of silyl and boronate substituents. Reaction conditions: (i) $Pd(dppf)Cl_2$ (0.04 equiv), 3-CF_3-C_6H_4Br (1.5 equiv), K_2CO_3 (3 equiv), THF, H_2O, 70 ℃, 12 h; (ii) TBAF (4 equiv), H_2O_2 (20 equiv), $KHCO_3$ (5 equiv), THF, MeOH, 23 ℃, 18 h; (iii) NaOH (2 equiv), H_2O_2 (2 equiv), THF, H_2O, 23 ℃, 3 h;

(iv) ICl (1.1 equiv), CH_2Cl_2, 23 ℃, 3 h; (v) Br_2 (2 equiv), CH_2Cl_2, 0 ℃, 1 h; (vi) $Cu(NO_3)_2 \cdot 3H_2O$ (2 equiv), $Zn(CN)_2$ (3 equiv), CsF (1 equiv), MeOH, H_2O, 100 ℃, 6 h; (vii) ICl (1.2 equiv), CH_2Cl_2, 0 ℃, 1 h; (viii) (Phen)Cu(CF_3) (1.2 equiv), KF (1 equiv), air, DMF, 50 ℃, 16 h, yield determined by ^{19}F NMR spectroscopy analysis.

The methyl- and siloxy-substituted silyl group is stable to a range of classical organic transformations (Fig. 3). For example, an aldehyde unit underwent alkylation, reduction, Wittig alkenylation, aldol addition, and Takai alkenylation without affecting the silyl group. The C-Si bond is also stable to the conditions of a catalytic Heck reaction, a Sonogashira coupling (see Fig. S3), and olefin cross metathesis. Likewise, the silylarenes are stable to many transformations of arylboronate esters (*vide supra*). The reactions in this scheme encompass a large fraction of the transformations conducted by medicinal and process chemists in the preparation of complex molecules [40]. Thus, the silyl group can be installed by C-H bond functionalization and transformed at a later stage of a synthesis.

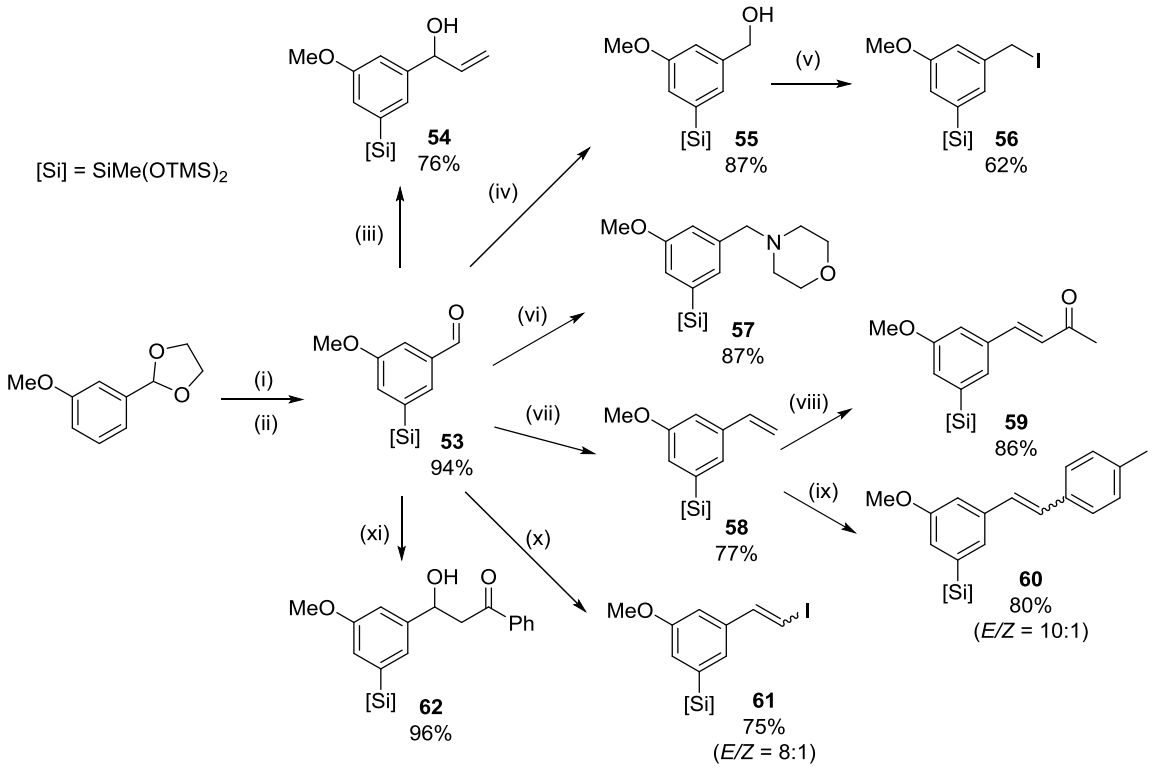


Fig. 3. Silylarenes as useful building blocks. Yields reported are for isolated material. Reaction conditions: (i) $[Rh(coe)_2OH]_2$ (0.01 equiv), **L2** (0.022 equiv), $(TMSO)_2MeSiH$ (2 equiv), cyclohexene (2 equiv), THF, 45 ℃, 36 h; (ii) $Pd(MeCN)_2Cl_2$ (0.06 equiv), acetone, 23 ℃, 16 h; (iii) vinylmagnesium bromide (1.2 equiv), THF, 0 ℃, 0.5 h; (iv) $NaBH_4$ (3 equiv), THF, MeOH, 0→23 ℃, 2 h; (v) Ph_3P (1.5 equiv), I_2 (1.5 equiv), imidazole (2 equiv), THF, 23 ℃, 2 h; (vi)

morpholine (1.2 equiv), $NaHB(OAc)_3$ (1.5 equiv), 1,2-dichloroethane, 23 °C, 20 h; (vii) ^{n}BuLi (1.1 equiv), Ph_3PMeI (1.3 equiv), THF, 0→23 °C, 4 h; (viii) Hoveyda-Grubbs Catalyst 2nd Generation (0.09 equiv), methyl vinyl ketone (6 equiv), CH_2Cl_2, 45 °C, 24 h; (ix) $Pd(OAc)_2$ (0.03 equiv), 4-bromotoluene (2 equiv), triethanolamine, THF, 100 °C, 16 h; (x) CHI_3 (2 equiv), $CrCl_2$ (6 equiv), dioxane, THF, 23 °C, 2 h; (xi) acetophenone (1.2 equiv), $MgBr_2$ (1.2 equiv), $(iPr)_2NEt$ (1.3 equiv), CH_2Cl_2, 23 °C, 2 h.

3.3 Conclusions

The intermolecular, rhodium-catalyzed silylation of arenes we report here occurs under mild conditions with arene as the limiting reagent and with regioselectivities that complement or surpass those of other arene functionalizations. Several factors lead to the selectivity and synthetic utility of the silylation reaction. First, the silicon reagent is sterically demanding. Assuming the intermediate that cleaves the C-H bond contains a silyl group on the metal, the size of the silane reagent, along with the size of the ancillary ligands on the metal, control the degree of stereoselectivity. Second, two of the substituents on the silane are bound to silicon through oxygen, an electronegative heteroatom, and this silicon-heteroatom bond is typically required for many of the transformations of arylsilanes at the C-Si bond. The origin of the remote selectivity remains to be defined. However, our results suggest that a wide scope of functionalization reactions with remote regiocontrol should be achievable through judicious choice of ancillary ligands and reagents with appropriate steric bulk.

3.4 Experimental

General Comments

All air-sensitive manipulations were conducted in a nitrogen-filled glovebox or using standard Schlenk technique. Tetrahydrofuran, benzene, and toluene were purified with an Innovative Technology Pure-Solv solvent purification system. Reagents were purchased from commercial sources unless otherwise indicated and degassed prior to use. $[Ir(cod)OMe]_2$ was obtained from Johnson-Matthey. 2-Methylphenanthroline (2-MePhen) [41], $[Rh(coe)_2Cl]_2$ [42], $[Rh(coe)_2OH]_2$ [43], *tert*-butyldimethyl(*m*-tolyloxy)silane (**4a**) [44], 4'-methoxy-3-methyl-1,1'-biphenyl (**27a**) [45], 2-(3-methoxyphenyl)-1,3-dioxolane (**10a**) [46], 2-triisopropylsiloxyanisole (**22a**) [47], and 3-bromo-9*H*-carbazole [48] were synthesized according to the published procedures.

GC analyses were conducted on an HP 6890 GC equipped with an HP-5 column (25 m x 0.20 mm ID x 0.33 m film) and an FID detector. GC yields were calculated using dodecane as

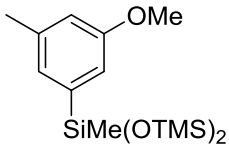
the internal standard. High-resolution mass spectra were obtained via the Micro-Mass/Analytical Facility operated by the College of Chemistry, University of California, Berkeley. NMR spectra were acquired on Bruker AVB-400, DRX-500, AV-500, and AV-600 spectrometers. Chemical shifts were reported in ppm relative to residual solvent peaks ($CDCl_3$ = 7.26 ppm for ^1H and 77.16 ppm for ^{13}C). Coupling constants were reported in Hz. For products isolated as mixtures of regioisomers, the NMR chemical shifts of the major isomers were reported. Flash column chromatography was performed on a Teledyne ISCO CombiFlash® Rf system on silica gel columns. Products were visualized on TLC plates under 254 nm UV light or by staining with I_2.

Typical Procedure for the Silylation of Arenes

In a nitrogen-atmosphere glovebox, $HSiMe(OTMS)_2$ (133 mg, 0.600 mmol) was added to a solution of $[Rh(coe)_2OH]_2$ (2.0 mg, 3.0 μmol) and **L2** (6.2 mg, 6.6 μmol) in THF (200 mg), and the mixture was stirred at 23 ℃ for 5 min. Cyclohexene (49 mg, 0.60 mmol) and the arene (0.30 mmol) were then added, and the reaction mixture was stirred at 23 ℃ for 10 min and then at 45 ℃. The reaction progress was monitor by GC analysis. After complete conversion of the silane (usually 16 h), the volatile materials were evaporated, and the residue was purified by flash column chromatography to afford the arylsilane product.

1b

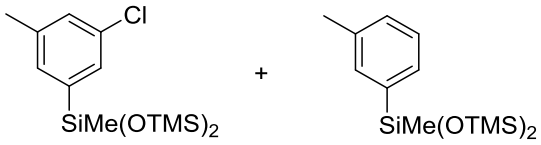
The general procedure was followed with 1,3-xylene (32.7 mg, 0.308 mmol) for 36 h. The product was obtained as a colorless liquid (83.3 mg, 83% yield). ^1H NMR (600 MHz, $CDCl_3$) δ 7.21 (s, 2H), 7.06 (s, 1H), 2.37 (s, 6H), 0.30 (s, 3H), 0.17 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 138.40 (s), 136.92 (s), 131.25 (s), 131.15 (s), 21.54 (s), 2.04 (s), 0.33 (s). HRMS (EI+) calcd for $[C_{15}H_{30}O_2Si_3]$: 326.1554, found: 326.1563.



2b

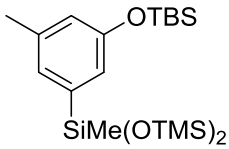
The general procedure was followed with 3-methylanisole (37.4 mg, 0.306 mmol). The product was obtained as a colorless liquid (86 mg, 82% yield). ^1H NMR (500 MHz, $CDCl_3$) δ 6.98 (s, 1H), 6.94 (s, 1H), 6.77 (s, 1H), 3.83 (s, 3H), 2.37 (s, 3H), 0.29 (s, 3H), 0.15 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.06 (s), 139.93 (s), 138.81 (s), 126.55 (s), 116.01 (s), 115.45 (s), 55.14

(s), 21.68 (s), 2.03 (s), 0.24 (s). HRMS (EI+) calcd for [$C_{15}H_{30}O_3Si_3$]: 342.1503, found: 342.1510.



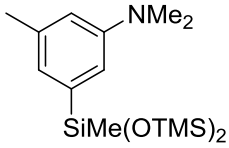
3b **3c**

The general procedure was followed with 3-chlorotoluene (38.2 mg, 0.302 mmol). The product was obtained as a colorless liquid (98.4 mg, 86% yield of b, 4% yield of c). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.31 (s, 1H), 7.22 (s, 1H), 7.19 (s, 1H), 2.35 (s, 3H), 0.28 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 140.94 (s), 139.20 (s), 133.95 (s), 132.11 (s), 130.24 (s, two peaks overlapping), 21.32 (s), 2.00 (s), 0.11 (s). HRMS (EI+) calcd for [$C_{14}H_{27}ClO_2Si_3$]: 346.1002, found: 346.1000.



4b

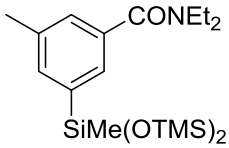
The general procedure was followed with *tert*-butyldimethyl(*m*-tolyloxy)silane (67.8 mg, 0.304 mmol), The product was obtained as a colorless liquid (91 mg, 67% yield, contains 6% inseparable starting material). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.97 (s, 1H), 6.86 (s, 1H), 6.71 (s, 1H), 2.33 (s, 3H), 1.02 (s, 9H), 0.27 (s, 3H), 0.22 (s, 6H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 155.12 (s), 139.80 (s), 138.76 (s), 127.10 (s), 122.27 (s), 121.68 (s), 25.88 (s), 21.53 (s), 18.37 (s), 2.03 (s), 0.18 (s), -4.22 (s). HRMS (EI+) calcd for [$C_{20}H_{42}O_3Si_4$]: 442.2211, found: 442.2207.



5b

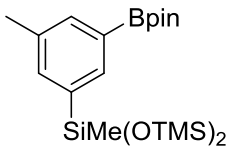
The general procedure was followed with *N*,*N*,3-trimethylaniline (43.3 mg, 0.320 mmol). The product was obtained as a colorless liquid (74 mg, 65% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.83 (s, 1H), 6.79 (s, 1H), 6.64 (s, 1H), 2.98 (s, 6H), 2.37 (s, 3H), 0.29 (s, 3H), 0.17 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 150.14 (s), 138.94 (s), 137.89 (s), 122.89 (s), 114.99 (s), 114.95 (s),

40.92 (s), 22.04 (s), 2.07 (s), 0.41 (s). HRMS (EI+) calcd for [$C_{16}H_{33}NO_2Si_3$]: 355.1819, found: 355.1823.



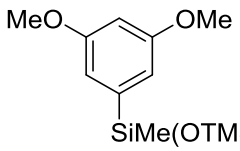
6b

The general procedure was followed with *N*,*N*-diethyl-3-methylbenzamide (58.8 mg, 0.307 mmol). The product was obtained as a colorless liquid (121 mg, 96% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.34 (s, 1H), 7.29 (s, 1H), 7.17 (s, 1H), 3.52 (bs, 2H), 3.21 (bs, 2H), 2.34 (s, 3H), 1.22 (bs, 3H), 1.07 (bs, 3H), 0.23 (s, 3H), 0.08 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 171.87 (s), 138.61 (s), 137.23 (s), 136.53 (s), 134.65 (s), 128.13 (s), 127.81 (s), 43.26 (s), 39.12 (s), 21.45 (s), 14.28 (s), 12.95 (s), 1.91 (s), 0.06 (s). HRMS (EI+) calcd for [$C_{19}H_{37}NO_3Si_3$]: 411.2081, found: 411.2065.



7b

The general procedure was followed with 4,4,5,5-tetramethyl-2-(*m*-tolyl)-1,3,2-dioxaborolane (442 mg, 2.03 mmol). After the reaction has completed, the solvent was evaporated, and the residue was suspended in hexanes. The mixture was filtered over celite, and filtrate was concentrated. The residue was then purified by flash column chromatography to give the product as a colorless liquid (851 mg, 96% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.86 (s, 1H), 7.68 (s, 1H), 7.49 (s, 1H), 2.39 (s, 3H), 1.37 (s, 12H), 0.31 (s, 3H), 0.15 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 137.63 (s), 137.20 (s), 137.03 (s), 136.56 (s), 136.08 (s), 83.72 (s), 25.00 (s), 21.49 (s), 2.03 (s), 0.35 (s). ^{11}B NMR (128 MHz, $CDCl_3$) δ 30.35 (bs). HRMS (EI+) calcd for [$C_{20}H_{39}BO_4Si_3$]: 438.2249, found: 438.2250.



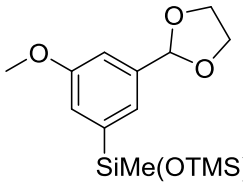
8b

The general procedure was followed with 1,3-dimethoxybenzene (68.1 mg, 0.493 mmol). The product was obtained as a colorless liquid (160 mg, 89% yield, isomeric purity: 95:5 by GC

analysis). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.75 (d, *J* = 2.2 Hz, 2H), 6.52 (t, *J* = 2.0 Hz, 1H), 3.83 (s, 6H), 0.30 (s, 3H), 0.17 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 160.44 (s), 140.90 (s), 110.76 (s), 101.67 (s), 55.26 (s), 1.99 (s), 0.12 (s). HRMS (EI+) calcd for [$C_{15}H_{30}O_4Si_3$]: 358.1452, found: 358.1461.

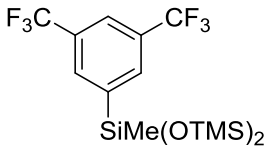
9b

The general procedure was followed with 1-(2-chloroethyl)-3-methoxybenzene (51.7 mg, 0.303 mmol). The product was obtained as a colorless liquid (110.0 mg, 93% yield, isomeric purity: 97:3 by GC analysis). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.04 – 6.98 (m, 2H), 6.82 – 6.79 (m, 1H), 3.84 (s, 3H), 3.73 (t, *J* = 7.6 Hz, 2H), 3.08 (t, *J* = 7.6 Hz, 2H), 0.30 (s, 3H), 0.15 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.20 (s), 140.53 (s), 139.01 (s), 126.12 (s), 116.79 (s), 115.83 (s), 55.19 (s), 45.01 (s), 39.48 (s), 2.02 (s), 0.16 (s). HRMS (EI+) calcd for [$C_{16}H_{31}ClO_3Si_3$]: 390.1270, found: 390.1272.



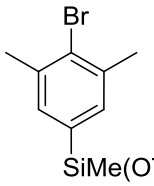
10b

The general procedure was followed with 2-(3-methoxyphenyl)-1,3-dioxolane (56.0 mg, 0.311 mmol) for 36 h. The product was obtained as a colorless liquid (114 mg, 91% yield, isomeric purity: 97:3 by GC analysis). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.26 (s, 1H), 7.12 (d, *J* = 2.5 Hz, 1H), 7.06 (s, 1H), 5.83 (s, 1H), 4.19 – 4.00 (m, 4H), 3.84 (s, 3H), 0.28 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.13 (s), 140.34 (s), 138.77 (s), 123.87 (s), 120.02 (s), 112.39 (s), 103.84 (s), 65.36 (s), 55.25 (s), 1.97 (s), 0.16 (s). HRMS (EI+) calcd for [$C_{17}H_{32}O_5Si_3$]: 400.1558, found: 400.1564.



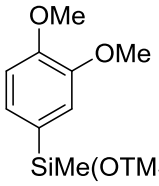
11b

The general procedure was followed with 1,3-bis(trifluoromethyl)benzene (64.3 mg, 0.300 mmol). The product was obtained as a colorless liquid (104 mg, 78% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (s, 2H), 7.88 (s, 1H), 0.33 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.93 (s), 133.26 (s), 130.83 (q, *J* = 32.8 Hz), 123.81 (q, *J* = 272.6 Hz), 123.55 – 123.00 (m), 1.88 (s), -0.02 (s). ^{19}F NMR (470 MHz, C_6D_6) δ -63.10 (s). HRMS (EI+) calcd for [$C_{14}H_{21}F_6O_2Si_3$] (M-CH3): 419.0754, found: 419.0764.



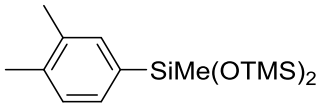
12b

The general procedure was followed with 2-bromo-1,3-dimethylbenzene (54.0 mg, 0.292 mmol) for 36 h. The product was obtained as a colorless liquid (56.8 mg, 48% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.24 (s, 2H), 2.44 (s, 6H), 0.27 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 137.51 (s), 137.01 (s), 133.17 (s), 129.64 (s), 24.06 (s), 2.03 (s), 0.26 (s). HRMS (EI+) calcd for [$C_{15}H_{29}BrO_2Si_3$]: 404.0659, found: 404.0669.



13b

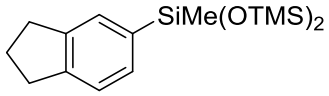
The general procedure was followed with 1,2-dimethoxybenzene (42.3 mg, 0.306 mmol). The product was obtained as a colorless liquid (104 mg, 95% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.13 (d, *J* = 7.8 Hz, 1H), 7.06 (s, 1H), 6.89 (d, *J* = 7.8 Hz, 1H), 3.91 (s, 3H), 3.89 (s, 3H), 0.27 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 150.22 (s), 148.36 (s), 130.25 (s), 126.58 (s), 115.56 (s), 110.74 (s), 55.76 (s), 55.70 (s), 1.97 (s), 0.25 (s). HRMS (EI+) calcd for [$C_{15}H_{30}O_4Si_3$]: 358.1452, found: 358.1450.



14b

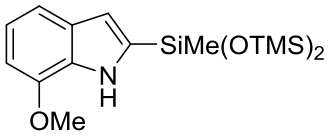
The general procedure was followed with 1,2-xylene (31.0 mg, 0.300 mmol). The product was obtained as a colorless liquid (82.8 mg, 85% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.36 (s, 1H),

7.34 (d, *J* = 7.6 Hz, 1H), 7.17 (d, *J* = 7.3 Hz, 1H), 2.32 (s, 3H), 2.31 (s, 3H), 0.30 (s, 3H), 0.16 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 138.09 (s), 135.74 (s, two peaks overlapping), 134.76 (s), 131.05 (s), 129.14 (s), 20.01 (s), 19.92 (s), 2.05 (s), 0.38 (s). HRMS (EI+) calcd for [$C_{15}H_{30}O_2Si_3$]: 326.1554, found: 326.1559.



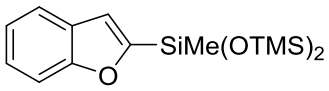
15b

The general procedure was followed with 2,3-dihydro-1*H*-indene (33.6 mg, 0.284 mmol). The product was obtained as a colorless liquid (87 mg, 90% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (s, 1H), 7.40 (d, *J* = 7.3 Hz, 1H), 7.29 (d, *J* = 7.3 Hz, 1H), 3.00 – 2.94 (m, 4H), 2.12 (p, *J* = 7.4 Hz, 2H), 0.32 (s, 3H), 0.18 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.83 (s), 143.49 (s), 135.98 (s), 131.32 (s), 129.37 (s), 123.95 (s), 33.13 (s), 32.89 (s), 25.33 (s), 2.07 (s), 0.48 (s). HRMS (EI+) calcd for [$C_{16}H_{30}O_2Si_3$]: 338.1554, found: 338.1558.



16b

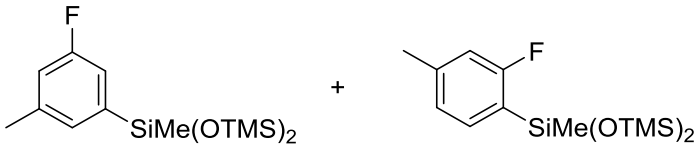
The general procedure was followed with 7-methoxyindole (44.7 mg, 0.304 mmol). The product was obtained as a colorless liquid (95.3 mg, 85% yield, isomeric purity: 98:2 by GC analysis). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.46 (bs, 1H), 7.34 (d, *J* = 8.0 Hz, 1H), 7.09 (t, *J* = 7.8 Hz, 1H), 6.82 (d, *J* = 2.2 Hz, 1H), 6.70 (d, *J* = 7.6 Hz, 1H), 4.04 (s, 3H), 0.43 (s, 3H), 0.23 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.33 (s), 135.83 (s), 129.99 (s), 128.98 (s), 120.12 (s), 113.69 (s), 111.82 (s), 102.03 (s), 55.37 (s), 1.99 (s), 0.87 (s). HRMS (EI+) calcd for [$C_{16}H_{29}NO_3Si_3$]: 367.1455, found: 367.1461.



17b

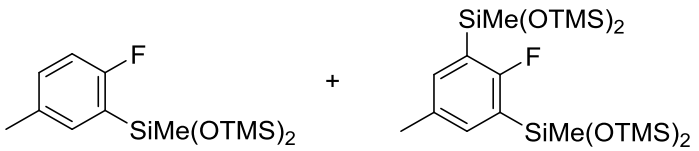
The general procedure was followed with benzofuran (37.4 mg, 0.317 mmol). The product was obtained as a colorless liquid (88.6 mg, 83% yield, isomeric purity: 97:3 by GC analysis). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.67 (d, *J* = 7.6 Hz, 1H), 7.59 (d, *J* = 8.2 Hz, 1H), 7.36 (td, *J* = 8.3, 1.2 Hz, 1H), 7.28 (dt, *J* = 7.2, 3.8 Hz, 1H), 7.09 (s, 1H), 0.44 (s, 3H), 0.22 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 160.79 (s), 157.85 (s), 127.82 (s), 124.77 (s), 122.51 (s), 121.50 (s), 116.54

(s), 111.62 (s), 1.88 (s), 0.12 (s). HRMS (EI+) calcd for [$C_{15}H_{26}O_3Si_3$]: 338.1190, found: 338.1198.



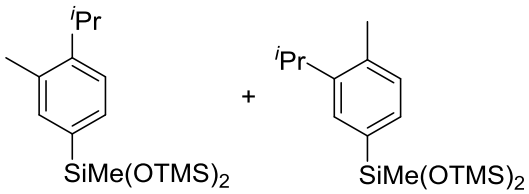
18b **18c**

The general procedure was followed with 3-fluorotoluene (32.2 mg, 0.292 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (70.0 mg, 72% yield, b:c = 89:11). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.13 (s, 1H), 7.04 (d, *J* = 8.2 Hz, 1H), 6.89 (d, *J* = 9.8 Hz, 1H), 2.37 (s, 3H), 0.28 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 162.74 (d, *J* = 247.2 Hz), 141.25 (d, *J* = 4.4 Hz), 139.83 (d, *J* = 6.6 Hz), 129.63 (d, *J* = 2.3 Hz), 117.11 (d, *J* = 21.0 Hz), 116.62 (d, *J* = 18.6 Hz), 21.41 (s), 1.98 (s), 0.08 (s). ^{19}F NMR (565 MHz, $CDCl_3$) δ -116.19 (t, *J* = 9.2 Hz). HRMS (EI+) calcd for [$C_{14}H_{27}FO_2Si_3$]: 330.1303, found: 330.1311.



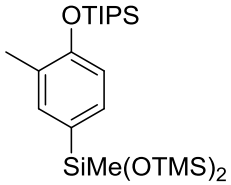
19b **19c**

The general procedure was followed with 4-fluorotoluene (32.6 mg, 0.296 mmol). The product was obtained as a colorless liquid (95.7 mg, 98% yield, b:c = 96:4). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30 (dd, *J* = 4.9, 2.0 Hz, 1H), 7.21 – 7.13 (m, 1H), 6.89 (t, *J* = 8.3 Hz, 1H), 2.34 (s, 3H), 0.35 (d, *J* = 0.8 Hz, 3H), 0.16 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 165.47 (d, *J* = 239.2 Hz), 135.87 (d, *J* = 10.7 Hz), 132.80 (d, *J* = 3.1 Hz), 132.34 (d, *J* = 8.1 Hz), 124.24 (d, *J* = 29.3 Hz), 114.47 (d, *J* = 25.5 Hz), 20.83 (s), 1.91 (s), 1.22 (s). ^{19}F NMR (470 MHz, C_6D_6) δ -107.04 (d, *J* = 4.2 Hz). HRMS (EI+) calcd for [$C_{14}H_{27}FO_2Si_3$]: 330.1303, found: 330.1306.



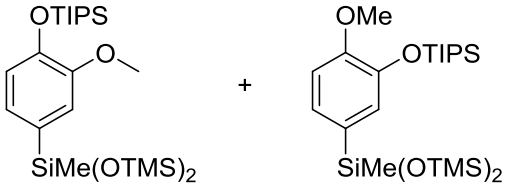
20b **20c**

The general procedure was followed with *o*-cymene (42.0 mg, 0.313 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (76.6 mg, 69% yield, b:c = 82:18). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.41 (d, *J* = 7.6 Hz, 1H), 7.34 (s, 1H), 7.27 (d, *J* = 7.6 Hz, 1H), 3.20 – 3.13 (m, 1H), 2.38 (s, 3H), 1.26 (d, *J* = 6.9 Hz, 6H), 0.29 (s, 3H), 0.16 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.25 (s), 135.42 (s), 135.27 (s), 134.14 (s), 131.42 (s), 124.09 (s), 29.46 (s), 23.27 (s), 19.53 (s), 2.06 (s), 0.47 (s). HRMS (EI+) calcd for [$C_{17}H_{34}O_2Si_3$]: 354.1867, found; 354.1872.



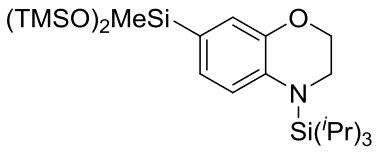
21b

The general procedure was followed with triisopropyl(*o*-tolyloxy)silane (81.3 mg, 0.307 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (135 mg, 90% yield, isomeric purity: >99:1 by GC analysis, contains 3% inseparable starting material). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.33 (s, 1H), 7.27 (d, *J* = 7.7 Hz, 1H), 6.81 (d, *J* = 7.8 Hz, 1H), 2.28 (s, 3H), 1.40 – 1.26 (m, 3H), 1.15 (d, *J* = 7.5 Hz, 18H), 0.28 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 155.79 (s), 136.33 (s), 132.20 (s), 129.93 (s), 127.81 (s), 117.56 (s), 18.22 (s), 17.22 (s), 13.23 (s), 2.04 (s), 0.34 (s). HRMS (EI+) calcd for [$C_{23}H_{48}O_3Si_4$]: 484.2681, found: 484.2678.



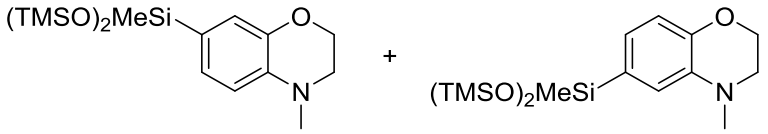
22b **22c**

The general procedure was followed with triisopropyl(2-methoxyphenoxy)silane (83.6 mg, 0.298 mmol) and with 1.3 mol% $[Rh(coe)_2OH]_2$, 2.9 mol% **L1**, and 3 equiv of $HSiMe(OTMS)_2$ and cyclohexene for 36 h. The product was obtained as a colorless liquid (140 mg, 94% yield, b:c = 89:11, contains 4% inseparable starting material). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.05 (s, 1H), 7.03 (d, *J* = 7.7 Hz, 1H), 6.90 (d, *J* = 7.7 Hz, 1H), 3.84 (s, 3H), 1.35 – 1.20 (m, 3H), 1.13 (d, *J* = 7.4 Hz, 18H), 0.29 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 150.47 (s), 147.03 (s), 131.08 (s), 126.50 (s), 120.28 (s), 116.87 (s), 55.51 (s), 18.06 (s), 13.04 (s), 1.99 (s), 0.18 (s). HRMS (EI+) calcd for [$C_{23}H_{48}O_4Si_4$]: 500.2630, found: 500.2635.



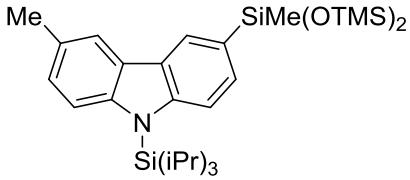
23b

The general procedure was followed with 4-(triisopropylsilyl)-3,4-dihydro-2H-benzo[b][1,4]oxazine (61.5 mg, 0.211 mmol), 3 equivalents of silane and cyclohexene, and with **L1** as the ligand for 36 h. The product was obtained as a colorless liquid (57.3 mg, 53% yield, isomeric purity: >99:1 by GC analysis, contains 2% inseparable starting material). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.95 (d, *J* = 1.4 Hz, 1H), 6.89 (dd, *J* = 7.9, 1.4 Hz, 1H), 6.82 (d, *J* = 8.0 Hz, 1H), 4.29 – 4.17 (m, 2H), 3.46 – 3.39 (m, 2H), 1.45 (dt, *J* = 10.9, 7.5 Hz, 3H), 1.13 (d, *J* = 7.5 Hz, 18H), 0.23 (s, 3H), 0.10 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.82 (s), 136.60 (s), 128.34 (s), 125.55 (s), 121.59 (s), 118.25 (s), 66.73 (s), 43.99 (s), 18.75 (s), 13.27 (s), 2.03 (s), 0.29 (s). HRMS (EI+) calcd for [$C_{24}H_{49}NO_3Si_4$]: 511.2790, found: 511.2794.



24b **24c**

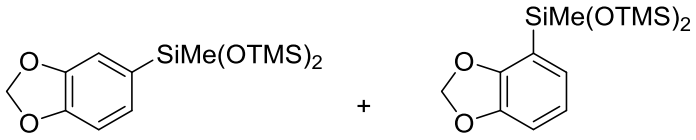
The general procedure was followed with 4-methyl-3,4-dihydro-2H-benzo[b][1,4]oxazine (46.0 mg, 0.308 mmol) and with **L1** as the ligand for 36 h. The product was obtained as a colorless liquid (108 mg, 95% yield, b:c = 83:17). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.05 (dd, *J* = 7.9, 1.4 Hz, 1H), 6.96 (d, *J* = 1.4 Hz, 1H), 6.69 (d, *J* = 7.9 Hz, 1H), 4.33 – 4.29 (m, 2H), 3.33 – 3.29 (m, 2H), 2.91 (s, 3H), 0.24 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 143.57 (s), 137.70 (s), 127.02 (s), 126.79 (s), 120.56 (s), 111.87 (s), 64.78 (s), 49.22 (s), 38.58 (s), 2.05 (s), 0.40 (s). HRMS (EI+) calcd for [$C_{16}H_{31}NO_3Si_3$]: 369.1612, found: 369.1614.



25b

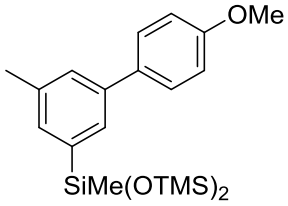
The general procedure was followed with 3-methyl-9-(triisopropylsilyl)-carbazole (95.6 mg, 0.283 mmol). The product was obtained as a viscous colorless liquid (142.5 mg, 90% yield, isomeric purity: 97:3 by GC and NMR spectroscopic analysis). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.44 (s, 1H), 8.06 (s, 1H), 7.84 (d, *J* = 8.4 Hz, 1H), 7.75 (d, *J* = 8.5 Hz, 1H), 7.72 (dd, *J* = 8.4, 1.1 Hz, 1H), 7.34 (dd, *J* = 8.5, 1.4 Hz, 1H), 2.69 (s, 3H), 2.16 (hept, *J* = 7.5 Hz, 3H), 1.36 (d, *J* =

7.6 Hz, 18H), 0.55 (s, 3H), 0.34 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 146.65 (s), 143.33 (s), 130.30 (s), 129.08 (s), 128.03 (s), 126.95 (s), 126.72 (s), 126.04 (s), 125.21 (s), 119.73 (s), 113.93 (s), 113.61 (s), 21.34 (s), 18.78 (s), 14.02 (s), 2.17 (s), 0.67 (s). HRMS (EI+) calcd for [$C_{29}H_{51}NO_2Si_4$]: 557.2997, found: 557.3002.



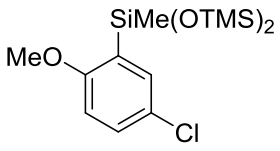
26b **26c**

The general procedure was followed with benzo[*d*][1,3]dioxole (35.9 mg, 0.294 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (91.7 mg, 91% yield, b:c = 92:8). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.09 (d, *J* = 7.6 Hz, 1H), 7.05 (s, 1H), 6.88 (d, *J* = 7.6 Hz, 1H), 5.97 (s, 2H), 0.29 (s, 3H), 0.15 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.76 (s), 147.25 (s), 131.96 (s), 127.59 (s), 112.79 (s), 108.52 (s), 100.60 (s), 2.00 (s), 0.25 (s). HRMS (EI+) calcd for [$C_{14}H_{26}O_4Si_3$]: 342.1139, found: 342.1138.



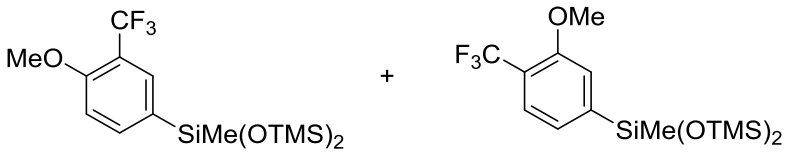
2**7b**

The general procedure was followed with 4'-methoxy-3-methyl-1,1'-biphenyl (58.5 mg, 0.295 mmol). The product was obtained as a colorless liquid (99.2 mg, 80% yield, isomeric purity: 97:3 by GC analysis, contains 7% inseparable disilylation product). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.62 (s, 1H), 7.59 (d, *J* = 8.0 Hz, 2H), 7.45 (s, 1H), 7.39 (s, 1H), 7.05 (d, *J* = 8.0 Hz, 2H), 3.90 (s, 3H), 2.48 (s, 3H), 0.37 (s, 3H), 0.21 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.15 (s), 140.07 (s), 138.97 (s), 137.41 (s), 134.36 (s), 132.53 (s), 128.96 (s), 128.95 (s), 128.31 (s), 114.29 (s), 55.42 (s), 21.74 (s), 2.09 (s), 0.35 (s). HRMS (EI+) calcd for [$C_{21}H_{34}O_3Si_3$]: 418.1816, found: 418.1825.



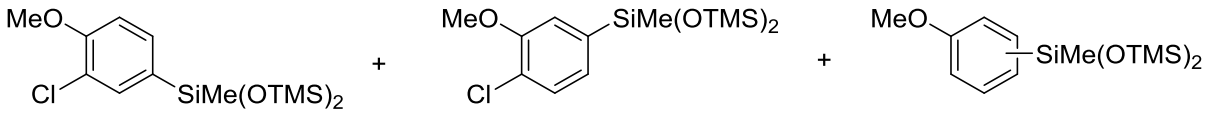
28b

The general procedure was followed with 4-chloroanisole (41.7 mg, 0.292 mmol). The product was obtained as a colorless liquid (87.6 mg, 83% yield, isomeric purity: 98:2 by GC analysis). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.43 (s, 1H), 7.30 (d, *J* = 8.6 Hz, 1H), 6.74 (d, *J* = 8.6 Hz, 1H), 3.78 (s, 3H), 0.29 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 162.55 (s), 135.27 (s), 130.86 (s), 128.59 (s), 125.66 (s), 110.77 (s), 55.14 (s), 1.91 (s), 1.00 (s). HRMS (EI+) calcd for [$C_{14}H_{27}ClO_3Si_3$]: 362.0957, found: 362.0963.



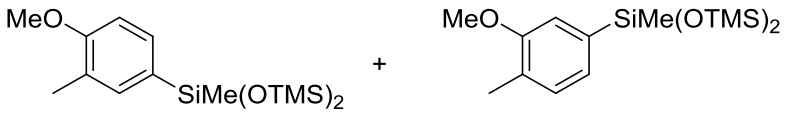
29b **29c**

The general procedure was followed with 2-trifluoromethylanisole (52.1 mg, 0.296 mmol) and with **L1** as the ligand. Following column chromatography, the mixture was distilled to give the product as a colorless liquid (108 mg, 92% yield, b:c = 98:2). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.76 (s, 1H), 7.70 (d, *J* = 8.2 Hz, 1H), 7.02 (d, *J* = 8.2 Hz, 1H), 3.92 (s, 3H), 0.29 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.63 (s), 138.71 (s), 132.10 (q, *J* = 5.1 Hz), 129.80 (s), 124.10 (q, *J* = 272.5 Hz), 118.15 (q, *J* = 30.4 Hz), 111.34 (s), 55.84 (s), 1.96 (s), 0.24 (s). ^{19}F NMR (565 MHz, $CDCl_3$) δ -63.38 (s). HRMS (EI+) calcd for [$C_{15}H_{27}F_3O_3Si_3$]: 396.1220, found: 396.1221.



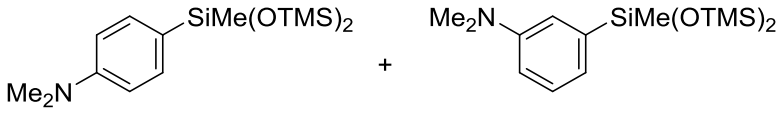
30b **30c** **30d**

The general procedure was followed with 2-chloroanisole (42.2 mg, 0.296 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (102 mg, 86% yield of b+c (b:c = 94:6), 9% yield of d). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.53 (s, 1H), 7.42 (d, *J* = 7.7 Hz, 1H), 6.94 (d, *J* = 7.9 Hz, 1H), 3.92 (s, 3H), 0.27 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 156.01 (s), 135.14 (s), 133.09 (s), 131.50 (s), 122.28 (s), 111.66 (s), 56.00 (s), 1.98 (s), 0.19 (s). HRMS (EI+) calcd for [$C_{14}H_{27}ClO_3Si_3$]: 362.0957, found: 362.0957.



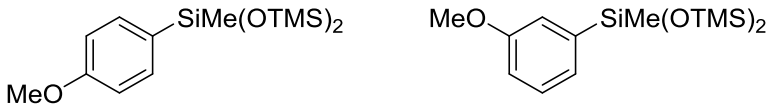
31a **31b**

The general procedure was followed with 2-methylanisole (38.4 mg, 0.314 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (100 mg, 93% yield, b:c = 86:14). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.43 (d, *J* = 7.8 Hz, 1H), 7.37 (s, 1H), 6.87 (d, *J* = 7.9 Hz, 1H), 3.88 (s, 3H), 2.29 (s, 3H), 0.31 (s, 3H), 0.17 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.08 (s), 135.87 (s), 132.56 (s), 129.45 (s), 125.82 (s), 109.33 (s), 55.16 (s), 16.43 (s), 2.05 (s), 0.42 (s). HRMS (EI+) calcd for [$C_{15}H_{30}O_3Si_3$]: 342.1503, found: 342.1499.



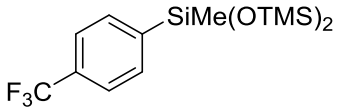
32b **32c**

The general procedure was followed with *N*,*N*-dimethylaniline (36.3 mg, 0.300 mmol) and with **L1** as the ligand. Following column chromatography, the mixture was distilled to give the product as a colorless liquid (85.9 mg, 84% yield, b:c = 92:8). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, *J* = 8.5 Hz, 2H), 6.77 (d, *J* = 8.4 Hz, 2H), 3.01 (s, 6H), 0.30 (s, 3H), 0.17 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 151.37 (s), 134.56 (s), 124.24 (s), 111.68 (s), 40.31 (s), 2.06 (s), 0.47 (s). HRMS (EI+) calcd for [$C_{15}H_{31}NO_2Si_3$]: 341.1663, found: 341.1664.

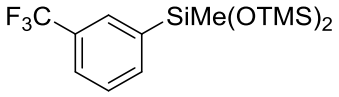


33b **33c**

The general procedure was followed with anisole (32.4 mg, 0.300 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (92.9 mg, 94% yield, b:c = 80:20). Major isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.53 (d, *J* = 8.2 Hz, 2H), 6.94 (d, *J* = 8.2 Hz, 2H), 3.85 (s, 3H), 0.30 (s, 3H), 0.16 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 160.85 (s), 134.92 (s), 129.95 (s), 113.44 (s), 55.06 (s), 2.02 (s), 0.32 (s). Minor isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.33 (t, *J* = 7.7 Hz, 1H), 7.19 (d, *J* = 7.1 Hz, 1H), 7.15 (d, *J* = 2.6 Hz, 1H), 6.96 (dd, *J* =7.1, 2.6 Hz, 1H), 3.85 (s, 3H), 0.32 (s, 3H), 0.17 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.02 (s), 140.25 (s), 129.03 (s), 125.71 (s), 118.57 (s), 115.12 (s), 55.15 (s), 2.02 (s), 0.17 (s). HRMS (EI+) calcd for [$C_{14}H_{28}O_3Si_3$]: 328.1346, found: 328.1345.

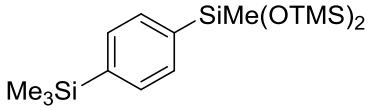


34b

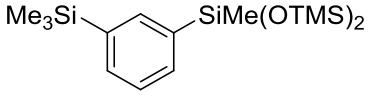


34c

The general procedure was followed with trifluoromethylbenzene (43.8 mg, 0.300 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (89.7 mg, 82% yield, b:c = 22:77, contains 1% disilylation product). Major isomer: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.82 (s, 1H), 7.74 (d, *J* = 7.3 Hz, 1H), 7.64 (d, *J* = 7.9 Hz, 1H), 7.48 (t, *J* = 7.6 Hz, 1H), 0.32 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 139.98 (s), 136.66 (d, *J* = 1.2 Hz), 130.06 (q, *J* = 20.6 Hz), 129.96 (q, *J* = 3.7 Hz), 128.07 (s), 126.23 (q, *J* = 3.7 Hz), 124.62 (q, *J* = 272.3 Hz), 1.94 (s), 0.05 (s). ^{19}F NMR (376 MHz, $CDCl_3$) δ -61.99 (s). Minor isomer: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.69 (d, *J* = 7.9 Hz, 2H), 7.62 (d, *J* = 7.9 Hz, 2H), 0.31 (s, 3H), 0.14 (s, 18H). ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.15 (s). HRMS (EI+) calcd for [$C_{13}H_{22}F_3O_2Si_3$•] (M-CH_3): 351.0880, found: 351.0883.

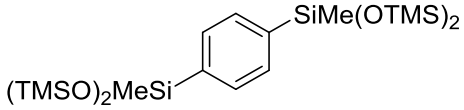


35b

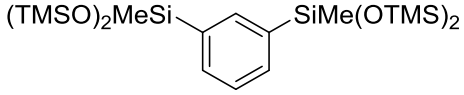


35c

The general procedure was followed with (trimethylsilyl)benzene (45.1 mg, 0.300 mmol) and with **L1** as the ligand. The product was obtained as a colorless liquid (65.0 mg, 58% yield, b:c = 67:33). Major isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.58 (d, *J* = 7.4 Hz, 2H), 7.55 (d, *J* = 7.4 Hz, 2H), 0.30 (s, 9H), 0.30 (s, 3H), 0.15 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 141.84 (s), 139.00 (s), 132.63 (s), 132.61 (s), 2.05 (s), 0.31 (s), -1.03 (s). Minor isomer: ^{13}C NMR (151 MHz, $CDCl_3$) δ 139.33 (s), 138.42 (s), 137.64 (s), 134.52 (s), 133.86 (s), 127.04 (s), 2.04 (s), 0.31 (s), -0.95 (s). HRMS (EI+) calcd for [$C_{16}H_{34}O_2Si_4$]: 370.1636, found: 370.1637.



36b

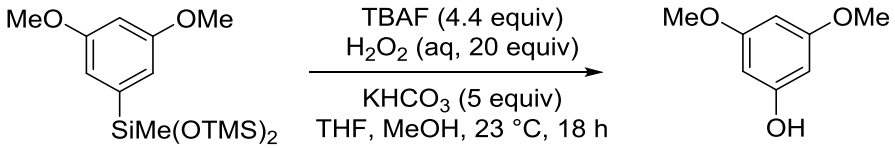


36c

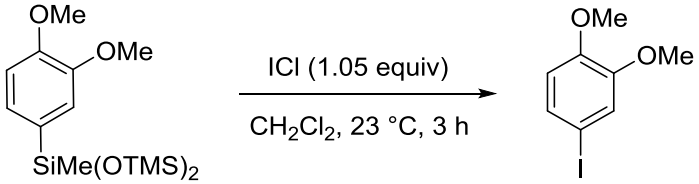
The general procedure was followed with 1,1,1,3,5,5,5-heptamethyl-3-phenyltrisiloxane (86.4 mg, 0.290 mmol) and with **L1** as the ligand. Following distillation, the product was obtained as a colorless liquid (72.0 mg, 48% yield, b:c = 96:4). Major isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ

7.55 (s, 4H), 0.28 (s, 6H), 0.12 (s, 36H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 139.75 (s), 132.48 (s), 2.01 (s), 0.14 (s). HRMS (EI+) calcd for [$C_{20}H_{46}O_4Si_6$]: 518.2012, found: 518.2017.

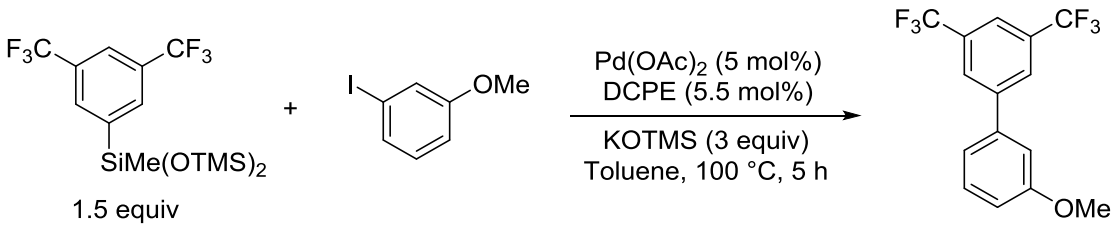
Derivatization of the Arylsilane Products



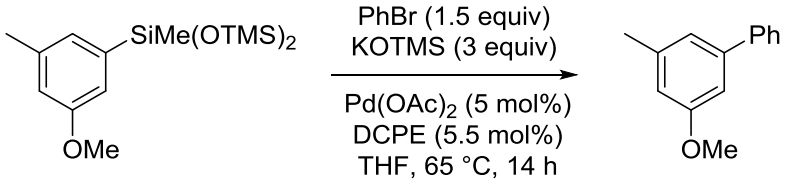
3,5-Dimethoxyphenol (**37**): To a solution of **8b** (73.1 mg, 0.204 mmol) in THF (2.8 mL) was added dropwise TBAF (1.0 M THF solution, 1.0 mL) at 0 ℃, and the mixture was stirred at 0 ℃ for 15 min. Methanol (1.0 mL), $KHCO_3$ (100 mg), and H_2O_2 (30% aqueous solution, 0.45 mL) were then added, and the reaction mixture was stirred at 23 ℃ for 18 h. The reaction mixture was diluted with ethyl acetate (10 mL) and quenched with $NaHSO_4$ (3 M aqueous solution, 2 mL) at 0 ℃. The aqueous phase was extracted with ethyl acetate (5 mL × 3), the combined organic layer was dried over Na_2SO_4, filtered, and the solvent was evaporated. The residue was purified by flash column chromatography (0→40% ethyl acetate in hexanes) to give the product as a colorless solid (21.7 mg, 69% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.08 (s, 1H), 6.03 (s, 2H), 5.32 (bs, 1H), 3.75 (s, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 161.74 (s), 157.53 (s), 94.36 (s), 93.26 (s), 55.48 (s). The NMR spectra agree with those of the authentic sample.



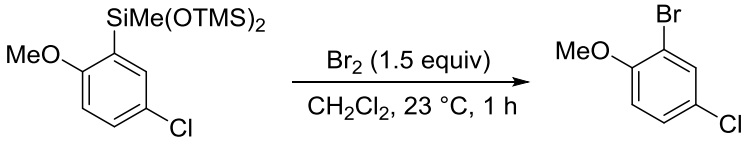
4-Iodo-1,2-dimethoxybenzene (**38**) [49]: To a solution of **13b** (97.6 mg, 0.272 mmol) in CH_2Cl_2 (1 mL) was added a solution of ICl (46.3 mg, 0.285 mmol) in CH_2Cl_2 (1 mL) at 0 ℃. The reaction mixture was stirred at 23 ℃ for 3 h. The volatile materials were evaporated, and the residue was purified by flash column chromatography (0→20% ethyl acetate in hexanes) to give the product as a colorless liquid that solidified at 23 ℃ (67.5 mg, 94% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.20 (d, J = 8.4 Hz, 1H), 7.10 (s, 1H), 6.60 (d, J = 8.4 Hz, 1H), 3.84 (s, 3H), 3.83 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 149.83 (s), 149.16 (s), 129.78 (s), 120.33 (s), 113.18 (s), 82.39 (s), 56.13 (s), 55.96 (s).



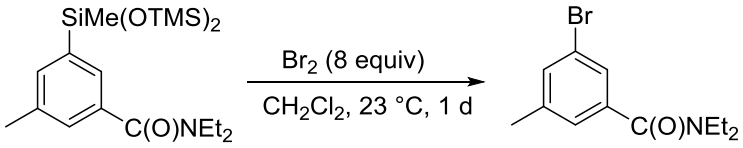
3'-Methoxy-3,5-bis(trifluoromethyl)-1,1'-biphenyl (39) [50]: To a solution of $Pd(OAc)_2$ (2.3 mg, 0.010 mmol) and 1,2-bis(dicyclohexylphosphino)ethane (DCPE, 4.7 mg, 0.011 mmol) in toluene (600 mg) was added **11b** (130 mg, 0.299 mmol), 3-iodoanisole (23.8 μL, 46.8 mg, 0.200 mmol), and KOTMS (76.8 mg, 0.600 mmol), and the reaction mixture was stirred at 100 ℃ for 5 h. The solvent was then evaporated, and the residue was purified by flash column chromatography (hexanes) to give the product as a colorless liquid (37.1 mg, 58% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.01 (s, 2H), 7.86 (s, 1H), 7.43 (t, *J* = 8.0 Hz, 1H), 7.19 (d, *J* = 7.7 Hz, 1H), 7.12 (t, *J* = 2.0 Hz, 1H), 7.00 (dd, *J* = 8.3, 2.5 Hz, 1H), 3.90 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 160.45 (s), 143.37 (s), 139.85 (s), 132.24 (q, *J* = 33.1 Hz), 130.51 (s), 127.44 (s), 123.54 (q, *J* = 272.9 Hz), 121.19 (dt, *J* = 7.8, 4.0 Hz), 119.80 (s), 114.24 (s), 113.31 (s), 55.59 (s). ^{19}F NMR (565 MHz, $CDCl_3$) δ -63.81 (s).



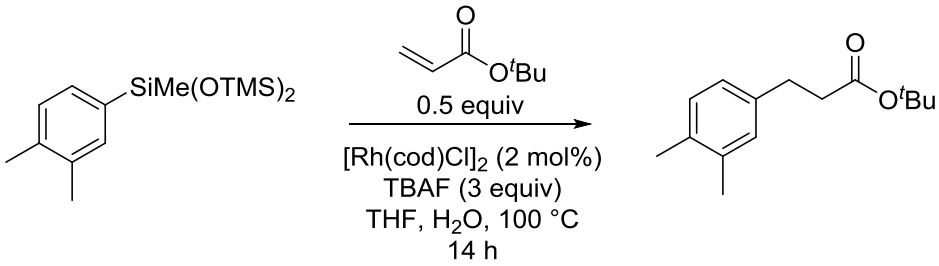
3-Methoxy-5-methyl-1,1'-biphenyl (**40**): To a solution of $Pd(OAc)_2$ (2.5 mg, 0.011 mmol) and 1,2-bis(dicyclohexylphosphino)ethane (DCPE, 5.2 mg, 0.012 mmol) in THF (660 mg) was added **2b** (76.9 mg, 0.224 mmol), bromobenzene (52 mg, 0.33 mmol), and KOTMS (85 mg, 0.66 mmol), and the reaction mixture was stirred at 65 ℃ for 14 h. The solvent was then evaporated, and the residue was purified by flash column chromatography (hexanes) to give the product as a colorless liquid (36.5 mg, 82% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.62 (d, *J* = 7.9 Hz, 2H), 7.46 (t, *J* = 7.6 Hz, 2H), 7.37 (t, *J* = 7.3 Hz, 1H), 7.05 (s, 1H), 6.98 (s, 1H), 6.76 (s, 1H), 3.88 (s, 3H), 2.43 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 160.09 (s), 142.71 (s), 141.39 (s), 139.88 (s), 128.80 (s), 127.45 (s), 127.33 (s), 120.76 (s), 113.69 (s), 110.08 (s), 55.39 (s), 21.80 (s). HRMS (EI+) calcd for [$C_{14}H_{14}O$]: 198.1045, found: 198.1048.



2-Bromo-4-chloro-1-methoxybenzene (**41**) [51]: To a solution of **28b** (151 mg, 0.416 mmol) in CH_2Cl_2 (5 mL) was added bromine (100 mg, 0.626 mmol) at 0 ℃, and the reaction mixture was stirred at 23 ℃ for 1 h. The reaction was then quenched with $Na_2S_2O_3$ (30% aqueous solution, 2 mL) at 0 ℃. The aqueous phase was extracted with ethyl acetate, the combined organic layer was dried over $MgSO_4$, filtered, and the solvent was evaporated. The residue was purified by flash column chromatography (0→10% ethyl acetate in hexanes) to give the product as a colorless liquid (81.6 mg, 89% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.53 (d, *J* = 2.4 Hz, 1H), 7.24 (dd, *J* = 8.8, 2.4 Hz, 1H), 6.81 (d, *J* = 8.8 Hz, 1H), 3.87 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 154.87 (s), 132.93 (s), 128.41 (s), 126.07 (s), 112.64 (s), 112.23 (s), 56.58 (s).

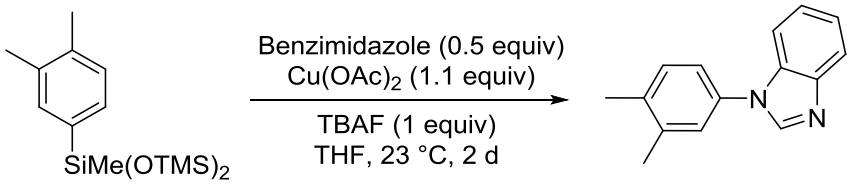


3-Bromo-*N*,*N*-diethyl-5-methylbenzamide (42): A procedure similar to the bromination of **28b** was followed with **6b** (116 mg, 0.282 mmol) with bromine (361 mg, 2.26 mmol) at 23 ℃ for 1 d. The product was obtained as a colorless viscous liquid (60.1 mg, 79% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.32 (s, 1H), 7.26 (s, 1H), 7.07 (s, 1H), 3.49 (bd, *J* = 5.1 Hz, 2H), 3.21 (bd, *J* = 4.5 Hz, 2H), 2.31 (s, 3H), 1.20 (bs, 3H), 1.08 (bs, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 169.76 (s), 140.60 (s), 138.98 (s), 132.76 (s), 126.25 (s), 125.66 (s), 122.28 (s), 43.34 (s), 39.33 (s), 21.18 (s), 14.26 (s), 12.91 (s). HRMS (EI+) calcd for [$C_{12}H_{16}BrNO$]: 269.0415, found: 269.0408.

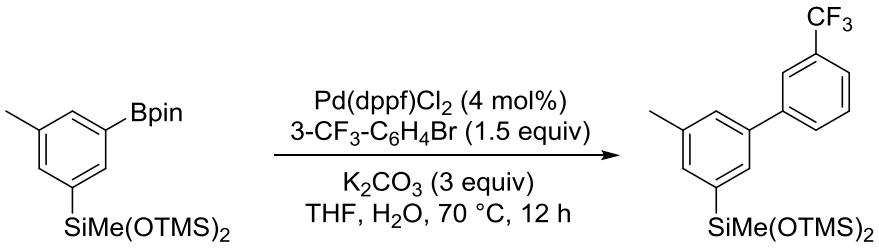


***tert*-Butyl 3-(3,4-dimethylphenyl)propanoate** (**43**): To a solution of $[Rh(cod)Cl]_2$ (2.0 mg, 4.0 μmol), **14b** (131 mg, 0.401 mmol), and *tert*-butylacrylate (26 mg, 0.20 mmol) in THF (800 mg) was added dropwise TBAF (1.0 M THF solution, 0.6 mL) at 0 ℃. Degassed water (0.3 mL) was then added, and the reaction mixture was stirred vigorously at 100 ℃ for 14 h. The organic layer was then separated and the aqueous phase was diluted with NH_4Cl (saturated aqueous solution, 2 mL). The aqueous phase was extracted with hexanes (3 mL × 3), the combined organic phase dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by flash column chromatography (0→10% ethyl acetate in hexanes) to give the product as a colorless

liquid (41.9 mg, 87% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.04 (d, *J* = 7.6 Hz, 1H), 6.98 (s, 1H), 6.93 (d, *J* = 7.6 Hz, 1H), 2.87 – 2.79 (m, 2H), 2.54 – 2.48 (m, 2H), 2.23 (s, 3H), 2.22 (s, 3H), 1.43 (s, 9H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 172.61 (s), 138.37 (s), 136.60 (s), 134.32 (s), 129.82 (s), 129.79 (s), 125.75 (s), 80.39 (s), 37.46 (s), 30.83 (s), 28.24 (s), 19.85 (s), 19.43 (s). HRMS (EI+) calcd for [$C_{15}H_{22}O_2$]: 234.1620, found: 234.1625.

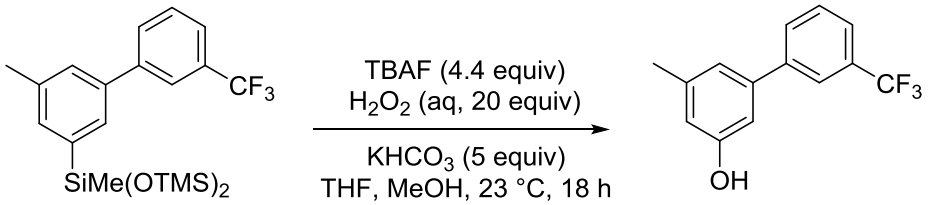


1-(3,4-Dimethylphenyl)-1H-benzo[d]imidazole (**44**) [52]: To a stirring mixture of **14b** (98.0 mg, 0.300 mmol), benzimidazole (17.6 mg, 0.149 mmol), and $Cu(OAc)_2$ (29.9 mg, 0.135 mmol) in DMF (1.5 mL) was added drop wise TBAF (0.3 mL of 1.0 M THF solution) at 23 ℃, and the reaction mixture was stirred at this temperature for 36 h. The mixture was then partitioned between a mixture of ethyl acetate (15 mL), hexanes (7 mL), and saturated aqueous $NaHCO_3$ (20 mL). The aqueous layer was extracted with a mixture of ethyl acetate and hexanes (2:1, 20 mL × 2), the combined organic layer washed with water (15 mL) and brine (15 mL), dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by flash column chromatography (0→70% ethyl acetate in hexanes) to afford the product as a colorless wax (24.6 mg, 74% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (s, 1H), 7.87 (dd, *J* = 5.5, 3.6 Hz, 1H), 7.52 (dd, *J* = 5.8, 3.4 Hz, 1H), 7.34 – 7.29 (m, 3H), 7.27 (s, 1H), 7.23 (dd, *J* = 7.9, 1.9 Hz, 1H), 2.36 (s, 3H), 2.36 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 144.04 (s), 142.54 (s), 138.74 (s), 136.88 (s), 134.11 (s), 133.99 (s), 131.05 (s), 125.28 (s), 123.60 (s), 122.70 (s), 121.53 (s), 120.60 (s), 110.67 (s), 20.07 (s), 19.60 (s).

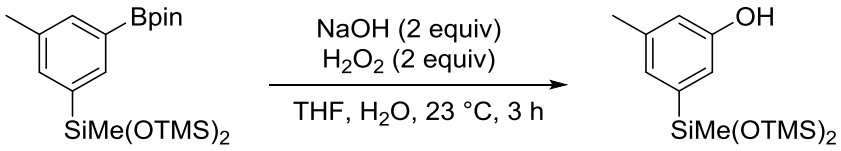


1,1,1,3,5,5,5-Heptamethyl-3-(5-methyl-3'-(trifluoromethyl)-[1,1'-biphenyl]-3-yl)trisiloxane (**45**): To a solution of $Pd(dppf)Cl_2$ CH_2Cl_2 (9.8 mg, 0.012 mmol), **7b** (135.1 mg, 0.308 mmol), and 1-bromo-3-(trifluoromethyl)benzene (101 mg, 0.449 mmol) in THF (2.4 g) was added K_2CO_3 (124 mg, 0.897 mmol). Water (0.2 mL) was then added, and the reaction mixture was stirred vigorously at 70 ℃ for 12 h. The solvents were evaporated, and the residue was purified

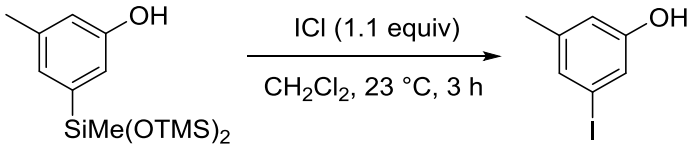
by flash column chromatography to give the product as a colorless liquid (139 mg, 99% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.93 (s, 1H), 7.83 (d, *J* = 7.6 Hz, 1H), 7.70 – 7.63 (m, 2H), 7.61 (t, *J* = 7.7 Hz, 1H), 7.50 (d, *J* = 3.1 Hz, 2H), 2.52 (s, 3H), 0.40 (s, 3H), 0.23 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 142.68 (s), 139.61 (s), 139.11 (s), 137.88 (s), 133.92 (s), 131.34 (q, *J* = 31.9 Hz), 130.55 (s), 129.42 (s), 129.34 (s), 129.25 (s), 124.46 (q, *J* = 272.3 Hz), 124.17 (q, *J* = 3.7 Hz), 123.89 (q, *J* = 3.5 Hz), 21.69 (s), 2.06 (s), 0.35 (s). ^{19}F NMR (376 MHz, $CDCl_3$) δ -61.82 (s). HRMS (EI+) calcd for [$C_{21}H_{31}F_3O_2Si_3$]: 456.1584, found: 456.1590.



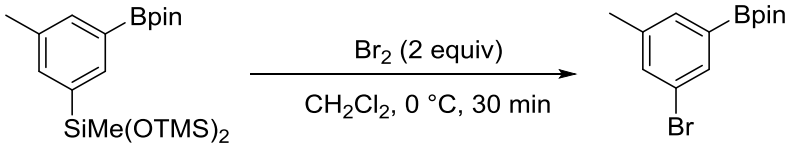
5-Methyl-3'-(trifluoromethyl)-[1,1'-biphenyl]-3-ol (**46**): A procedure similar to the oxidation of **8b** was followed with **45** (67.8 mg, 0.148 mmol). The product was obtained as a colorless solid (34.0 mg, 91% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.80 (s, 1H), 7.72 (d, *J* = 7.7 Hz, 1H), 7.60 (d, *J* = 7.7 Hz, 1H), 7.53 (t, *J* = 7.7 Hz, 1H), 6.99 (s, 1H), 6.88 (s, 1H), 6.71 (s, 1H), 5.09 (bs, 1H), 2.39 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 156.06 (s), 141.79 (s), 141.45 (s), 140.65 (s), 131.21 (q, *J* = 32.3 Hz), 130.50 (s), 129.29 (s), 124.32 (q, *J* = 272.5 Hz), 124.18 (q, *J* = 3.7 Hz), 124.03 (q, *J* = 3.9 Hz), 120.85 (s), 115.84 (s), 111.44 (s), 21.56 (s). ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.51 (s). HRMS (EI+) calcd for [$C_{14}H_{11}F_3O$]: 252.0762, found: 252.0763.



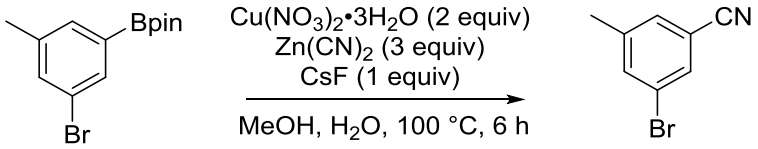
3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methylphenol (**47**): To a solution of **7b** (115 mg, 0.261 mmol) in THF (3 mL) and water (1 mL) was added NaOH (21 mg, 0.53 mmol) and dropwise H_2O_2 (30% aqueous solution, 54 μL). The reaction mixture was stirred at 23 ℃ for 4 h. The reaction was then diluted with ethyl acetate (5 mL) and quenched with $KHSO_4$ (saturated aqueous solution, 2 mL) at 0 ℃. The aqueous phase was extracted with ethyl acetate (4 mL × 4), the combined organic layer was dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by flash column chromatography to give the product as a colorless liquid (79.4 mg, 91% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.95 (s, 1H), 6.85 (s, 1H), 6.69 (s, 1H), 5.14 (bs, 1H), 2.33 (s, 3H), 0.27 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 154.91 (s), 140.31 (s), 139.13 (s), 126.64 (s), 117.35 (s), 116.91 (s), 21.47 (s), 2.00 (s), 0.16 (s). HRMS (EI+) calcd for [$C_{14}H_{28}O_3Si_3$]: 328.1346, found: 328.1353.



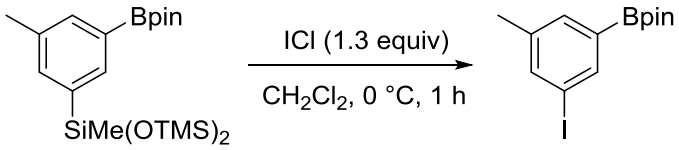
3-Iodo-5-methylphenol (**48**): A procedure similar to the iodination of **13b** was followed with **47** (49.3 mg, 0.150 mmol). The product was obtained as a colorless solid (27.8 mg, 79% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.12 (s, 1H), 7.01 (s, 1H), 6.61 (s, 1H), 4.99 (bs, 1H), 2.25 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 155.96 (s), 141.71 (s), 130.94 (s), 121.76 (s), 115.93 (s), 94.24 (s), 21.04 (s). HRMS (EI+) for [C_7H_7IO]: 233.9542, found: 233.9546.



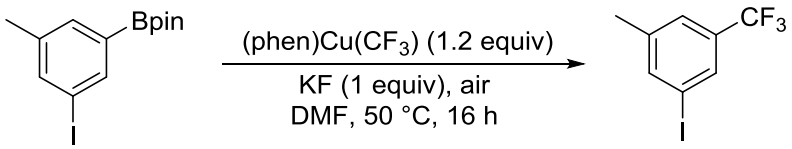
2-(3-Bromo-5-methylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (**49**): A procedure similar to the bromination of **28b** was followed with **7b** (94.8 mg, 0.216 mmol) at 0 ℃ for 30 min. The product was obtained as a colorless solid (53.1 mg, 83% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.74 (s, 1H), 7.54 (s, 1H), 7.42 (s, 1H), 2.33 (s, 3H), 1.34 (s, 12H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 139.66 (s), 134.90 (s), 134.56 (s), 133.98 (s), 122.40 (s), 84.21 (s), 24.96 (s), 21.06 (s). ^{11}B NMR (193 MHz, $CDCl_3$) δ 29.93 (bs). HRMS (EI+) for [$C_{13}H_{18}BBrO_2$]: 296.0583, found: 296.0585.



3-Bromo-5-methylbenzonitrile (**50**) [39]: The literature procedure [32] was followed with **49** (52.6 mg, 0.177 mmol). The product was obtained as a colorless solid (20.5 mg, 59% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.59 (s, 1H), 7.56 (s, 1H), 7.40 (s, 1H), 2.38 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 141.43 (s), 136.92 (s), 131.94 (s), 131.39 (s), 122.75 (s), 117.61 (s), 113.98 (s), 21.06 (s).

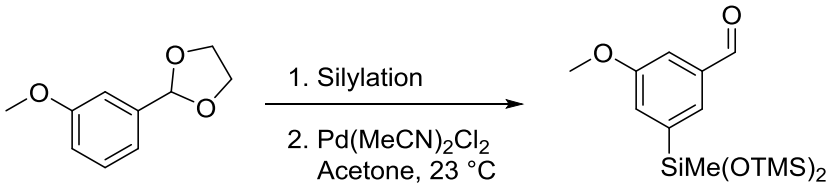


2-(3-Iodo-5-methylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (**51**): A procedure similar to the iodination of **13b** was followed with **7b** (66.6 mg, 0.152 mmol) at 0 ℃ for 1 h. The product was obtained as a colorless solid (45.8 mg, 88% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.94 (s, 1H), 7.64 (s, 1H), 7.57 (s, 1H), 2.30 (s, 3H), 1.34 (s, 12H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 140.85 (s), 140.53 (s), 139.74 (s), 134.59 (s), 94.70 (s), 84.21 (s), 24.97 (s), 20.96 (s). ^{11}B NMR (160 MHz, $CDCl_3$) δ 30.27 (bs). HRMS (EI+) calcd for [$C_{13}H_{18}BIO_2$]: 344.0445, found: 344.0449.



1-Iodo-3-methyl-5-(trifluoromethyl)benzene (52): To a 4-mL vial was added **51** (33.0 mg, 0.0959 mmol), (phen)Cu(CF_3) (36 mg, 0.12 mmol), KF (5.7 mg, 0.098 mmol), and DMF (1.0 mL). Dry air was purged through the mixture for 5 min, and the reaction mixture was heated at 50 ℃ for 16 h. 1-Methoxy-4-(trifluoromethoxy)benzene (26.3 mg, 0.137 mmol) was then added as the internal standard, the reaction mixture was filtered over celite, and the yield of **52** was determined by ^{19}F NMR spectroscopy to be 78%. GC-MS: 286 (M, 100%), 159 (M-I, 45%).

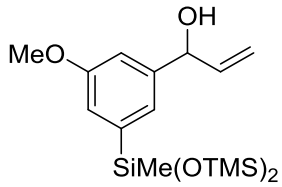
Stability of the Silyl Group



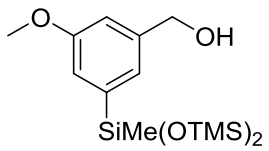
53

3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methoxybenzaldehyde (53): The general procedure for the silylation of arenes was followed with 2-(3-methoxyphenyl)-1,3-dioxolane (375 mg, 2.08 mmol) at 45 ℃ for 36 h. After complete conversion of the starting arene, the volatiles were evaporated. The residue was diluted with acetone (60 mL), and to this mixture was added a solution of $Pd(MeCN)_2Cl_2$ (31 mg, 0.12 mmol) in acetone (20 mL). The reaction mixture was stirred at 23 ℃ for 16 h, and the solvent was evaporated. The residue was adsorbed onto

celite (2 g) and purified by flash column chromatography (0→15% ethyl acetate in hexanes) to afford the product as a colorless liquid (694 mg, 94% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 10.00 (s, 1H), 7.61 (s, 1H), 7.39 (s, 1H), 7.36 (s, 1H), 3.87 (s, 3H), 0.30 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 192.65 (s), 159.70 (s), 141.47 (s), 137.36 (s), 128.86 (s), 126.54 (s), 112.43 (s), 55.50 (s), 1.98 (s), 0.04 (s). HRMS (EI+) calcd for [$C_{15}H_{28}O_4Si_3$]: 356.1295, found: 356.1298.

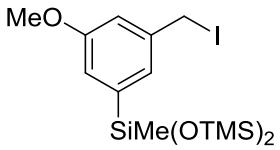


1-(3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methoxyphenyl)prop-2-en-1-ol (54): To a stirring solution of **53** (58.1 mg, 0.163 mmol) in THF (0.5 mL) at 0 ℃ was added drop wise vinylmagnesium bromide (0.19 mL of 1.0 M THF solution), and the reaction mixture was stirred at this temperature for 0.5 h. The reaction was then quenched with NH_4Cl (saturated aqueous solution, 2 mL), and the organic products were extracted with ethyl acetate (3 mL × 4). The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered, and the solvents were evaporated. The residue was purified by flash column chromatography (0→50% ethyl acetate in hexanes) to afford the product as a colorless liquid (47.6 mg, 76% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.12 (s, 1H), 7.02 (s, 1H), 6.96 (s, 1H), 6.04 (ddd, *J* = 16.4, 10.1, 6.1 Hz, 1H), 5.36 (d, *J* = 17.1 Hz, 1H), 5.22 – 5.17 (m, 2H), 3.82 (s, 3H), 2.07 (bs, 1H), 0.27 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.28 (s), 143.59 (s), 140.53 (s), 140.26 (s), 123.69 (s), 118.11 (s), 115.20 (s), 112.85 (s), 75.49 (s), 55.27 (s), 2.01 (s), 0.20 (s). HRMS (EI+) calcd for [$C_{17}H_{32}O_4Si_3$]: 384.1608, found: 384.1610.

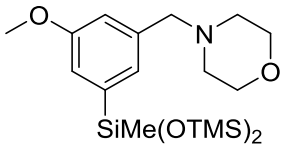


(3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methoxyphenyl)methanol (55): To solution of **53** (106 mg, 0.298 mmol) in a mixture of THF and methanol (1.5 mL each) at 0 ℃ was added $NaBH_4$ (34.0 mg, 0.899 mmol). The reaction was allowed to warm to 23 ℃ and stirred at this temperature for 2 h. The reaction was quenched with acetone (1 mL), the solvents evaporated, and the residue was purified by flash column chromatography (0→100% ethyl acetate in hexanes) to afford the product as a viscous colorless liquid (93.1 mg, 87% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.11 (s, 1H), 7.04 (d, *J* = 2.0 Hz, 1H), 6.95 (s, 1H), 4.67 (s, 2H), 3.82 (s, 3H), 1.96 (bs,

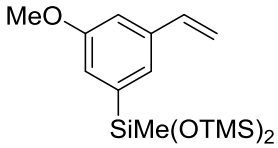
1H), 0.28 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.34 (s), 141.93 (s), 140.56 (s), 124.12 (s), 118.08 (s), 113.55 (s), 65.49 (s), 55.25 (s), 2.00 (s), 0.18 (s). HRMS (EI+) calcd for [$C_{15}H_{30}O_4Si_3$]: 358.1452, found: 358.1450.



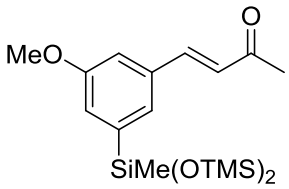
3-(3-(iodomethyl)-5-methoxyphenyl)-1,1,1,3,5,5,5-heptamethyltrisiloxane (56): To a solution of PPh_3 (109 mg, 0.416 mmol) and imidazole (35.4 mg, 0.520 mmol) in anhydrous THF (2 mL) was added a solution of I_2 (98.0 mg, 0.387 mmol) in THF (2 mL). After 5 min, a solution of **55** (89.2 mg, 0.249 mmol) in THF (1 mL) was added. The reaction mixture was stirred at 23 ℃ for 2 h and then diluted with hexanes (20 mL). The mixture was filtered over a short layer of celite, which was subsequently rinsed with ethyl acetate. The solvent was evaporated, and the residue was purified by flash column chromatography (hexanes) to afford the product as a colorless liquid (73.0 mg, 62% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.14 (s, 1H), 6.98 (s, 1H), 6.92 (s, 1H), 4.45 (s, 2H), 3.82 (s, 3H), 0.27 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.12 (s), 141.03 (s), 140.04 (s), 126.03 (s), 118.37 (s), 115.25 (s), 55.29 (s), 5.99 (s), 2.04 (s), 0.11 (s). HRMS (EI+) calcd for [$C_{15}H_{29}IO_3Si_3$]: 468.0469, found: 468.0470.



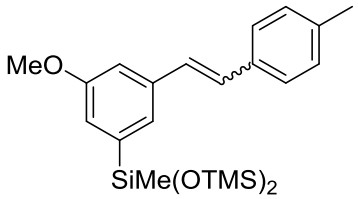
4-(3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methoxybenzyl)morpholine (**57**): To a solution of **53** (63.8 mg, 0.179 mmol) in 1,2-dichloroethane (0.8 mL) was added morpholine (18.7 mg, 0.215 mmol) and $NaHB(OAc)_3$ (57.0 mg, 0.269 mmol), and the reaction mixture was stirred at 23 ℃ for 20 h. The reaction was quenched with aqueous $NaHCO_3$ (2 mL, saturated), and the organic product was extracted with ethyl acetate (3 mL × 4). The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered. The solvent was evaporated, and the residue was purified by flash column chromatography (0→60% ethyl acetate in hexanes on a SiO_2 column pre-treated with 5% Et_3N in hexanes) to afford the product as a colorless liquid (66.5 mg, 87% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.09 (s, 1H), 6.99 (d, J = 2.3 Hz, 1H), 6.92 (s, 1H), 3.82 (s, 3H), 3.76 – 3.65 (m, 4H), 3.49 (s, 2H), 2.44 (s, 4H), 0.27 (s, 3H), 0.11 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.18 (s), 139.97 (s), 138.91 (s), 126.51 (s), 117.26 (s), 115.83 (s), 67.20 (s), 63.57 (s), 55.24 (s), 53.76 (s), 2.01 (s), 0.16 (s). HRMS (EI+) calcd for [$C_{19}H_{37}NO_4Si_3$]: 427.2030, found: 427.2029.



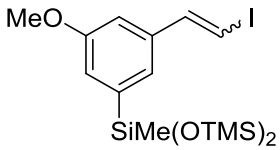
3-(3-Methoxy-5-vinylphenyl)-1,1,1,3,5,5,5-heptamethyltrisiloxane (58): To a solution of Ph_3PMeI (631 mg, 1.56 mmol) in THF (5 mL) at 0 ℃ was added ^{n}BuLi (0.83 mL, 1.6 M hexanes solution, 1.3 mmol). The mixture was stirred at 0 ℃ for 15 min, and to this yellow mixture was added a solution of **53** (410 mg, 1.15 mmol) in THF (2 mL). The reaction mixture was stirred at 23 ℃ for 4 h and quenched with acetone (1 mL). The volatiles were evaporated, and the residue was purified by flash column chromatography (hexanes) to afford the product as a colorless liquid (312 mg, 77% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.20 (s, 1H), 7.02 (d, *J* = 2.4 Hz, 1H), 6.98 (s, 1H), 6.73 (dd, *J* = 17.6, 10.9 Hz, 1H), 5.76 (d, *J* = 17.6 Hz, 1H), 5.26 (d, *J* = 10.9 Hz, 1H), 3.85 (s, 3H), 0.28 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.29 (s), 140.33 (s), 138.41 (s), 137.14 (s), 124.11 (s), 118.24 (s), 114.04 (s), 112.50 (s), 55.26 (s), 2.03 (s), 0.20 (s). HRMS (EI+) calcd for [$C_{16}H_{30}O_3Si_3$]: 354.1503, found: 354.1500.



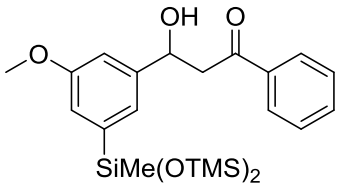
(*E*)-4-(3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methoxyphenyl)but-3-en-2-one (59): To a solution of **58** (66.2 mg, 0.187 mmol) in CH_2Cl_2 (2 mL) was added Hoveyda-Grubbs Catalyst 2nd Generation (10.6 mg, 0.0169 mmol) and methyl vinyl ketone (76.0 mg, 1.08 mmol), and the reaction mixture was stirred at 45 ℃ for 24 h. The solvent was then evaporated, and the residue was adsorbed onto celite (400 mg) and purified by flash column chromatography (0→10% ethyl acetate in hexanes) to afford the product as a colorless liquid (63.4 mg, 86% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.50 (d, *J* = 16.3 Hz, 1H), 7.29 (s, 1H), 7.13 (s, 1H), 7.07 (s, 1H), 6.70 (d, *J* = 16.3 Hz, 1H), 3.84 (s, 3H), 2.38 (s, 3H), 0.28 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 198.50 (s), 159.45 (s), 143.81 (s), 141.18 (s), 135.27 (s), 127.37 (s), 126.26 (s), 121.31 (s), 113.71 (s), 55.32 (s), 27.60 (s), 1.99 (s), 0.05 (s). HRMS (EI+) calcd for [$C_{18}H_{32}O_4Si_3$]: 396.1608, found: 396.1615.



3-(3-Methoxy-5-(4-methylstyryl)phenyl)-1,1,1,3,5,5,5-heptamethyltrisiloxane (60): To a suspension of $Pd(OAc)_2$ (1.0 mg, 4.4 μmol) in a mixture of triethanolamine and THF (0.3 mL each) was added **58** (51.5 mg, 0.145 mmol) and 4-bromotoluene (50.1 mg, 0.293 mmol). The reaction mixture was stirred vigorously at 23 ℃ for 30 min and then at 100 ℃ for 16 h. The reaction mixture was then partitioned between water and hexanes (10 mL each), and the aqueous layer was extracted with hexanes (5 mL × 2). The combined organic layer was washed with water (5 mL) and brine (5 mL), dried over $MgSO_4$, filtered, and the solvent was evaporated. The residue was purified by flash column chromatography (0→5% ethyl acetate in hexanes) to afford the product as a colorless liquid (51.9 mg, 80% yield, *E/Z* = 10:1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.46 (d, *J* = 7.9 Hz, 2H), 7.30 (s, 1H), 7.20 (d, *J* = 7.8 Hz, 2H), 7.10 (d, *J* = 3.6 Hz, 3H), 7.04 (d, *J* = 2.2 Hz, 1H), 3.89 (s, 3H), 2.39 (s, 3H), 0.33 (s, 3H), 0.18 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.38 (s), 140.42 (s), 138.39 (s), 137.66 (s), 134.66 (s), 129.53 (s), 128.88 (s), 127.96 (s), 126.59 (s), 124.46 (s), 117.94 (s), 112.49 (s), 55.29 (s), 21.40 (s), 2.06 (s), 0.22 (s). HRMS (EI+) calcd for [$C_{23}H_{36}O_3Si_3$]: 444.1972, found: 444.1978.



3-(3-(2-Iodovinyl)-5-methoxyphenyl)-1,1,1,3,5,5,5-heptamethyltrisiloxane (61): With the exclusion of light, a solution of CHI_3 (158 mg, 0.401 mmol) in 1,4-dioxane (1 mL) was added drop wise to a stirring suspension of anhydrous $CrCl_2$ (150 mg, 1.23 mmol) in THF (4 mL). To the resulting deep red suspension was added a solution of **53** (69.9 mg, 0.196 mmol) in THF (0.5 mL), and the reaction mixture was stirred at 23 ℃ for 2 h. The mixture was then diluted with hexanes (20 mL) and filtered over a short layer of SiO_2, which was subsequently rinsed with ethyl acetate. The solvent was evaporated, and the residue was purified by flash column chromatography (hexanes) to afford the product as a light yellow liquid (70.8 mg, 75% yield, *E:Z* = 8:1). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.43 (d, *J* = 14.9 Hz, 1H), 7.05 (d, *J* = 9.6 Hz, 2H), 6.83 (d, *J* = 16.0 Hz, 2H), 3.83 (s, 3H), 0.27 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.28 (s), 145.28 (s), 140.76 (s), 138.44 (s), 123.80 (s), 118.82 (s), 112.15 (s), 76.81 (s), 55.30 (s), 2.04 (s), 0.13 (s). HRMS (EI+) calcd for [$C_{16}H_{29}IO_3Si_3$]: 480.0469, found: 480.0469.



3-(3-(1,1,1,3,5,5,5-Heptamethyltrisiloxan-3-yl)-5-methoxyphenyl)-3-hydroxy-1-phenylpropan-1-one (62): Under a nitrogen atmosphere, a solution of (^{i}Pr)$_2$NEt (25.8 mg, 0.200 mmol) in CH_2Cl_2 (0.5 mL) was added drop wise to a stirring mixture of **53** (50.9 mg, 0.143 mmol), acetophenone (22.2 mg, 0.185 mmol), $MgBr_2$ (34.0 mg, 0.185 mmol) in CH_2Cl_2 (1 mL) at 23 ℃. After being stirred at this temperature for 2 h, the reaction mixture was quenched with saturated aqueous NH_4Cl (2 mL). The aqueous layer was extracted with ethyl acetate (5 mL × 2), the combined organic layer washed with brine (5 mL), dried over Na_2SO_4, filtered, and the solvents were evaporated. The residue was purified by flash column chromatography to afford the product as a colorless viscous liquid (65.2 mg, 96% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.96 (d, *J* = 7.5 Hz, 2H), 7.58 (d, *J* = 7.3 Hz, 1H), 7.47 (t, *J* = 7.7 Hz, 2H), 7.17 (s, 1H), 7.06 (d, *J* = 8.9 Hz, 2H), 5.35 (dd, *J* = 7.6, 4.0 Hz, 1H), 3.85 (s, 3H), 3.61 (bs, 1H), 3.43 – 3.33 (m, 2H), 0.28 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 200.28 (s), 159.34 (s), 144.02 (s), 140.53 (s), 136.71 (s), 133.74 (s), 128.82 (s), 128.27 (s), 122.95 (s), 118.08 (s), 112.38 (s), 70.18 (s), 55.29 (s), 47.58 (s), 2.02 (s), 0.19 (s). HRMS (EI+) calcd for [$C_{23}H_{36}O_5Si_3$]: 476.1871, found: 476.1873.

Sonogashira Coupling of Silylarene

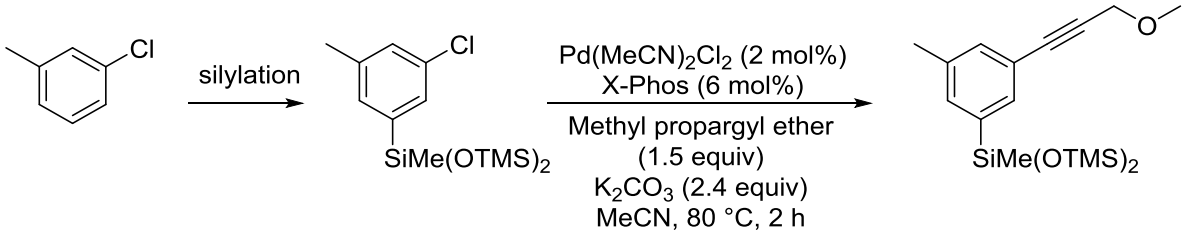


Fig. S3. One-pot silylation and sonogashira coupling of 3-chlorotoluene.

3-(3-(3-Methoxyprop-1-yn-1-yl)-5-methylphenyl)-1,1,1,3,5,5,5-heptamethyltrisiloxane (**63**): The typical silylation procedure was followed with 3-chlorotoluene (26.2 mg, 0.207 mmol). After complete conversion of the starting arene, the volatiles were evaporated, and the residue was suspended in hexanes and filtered through a short pad of silica, which was then rinsed with hexanes. The solvent was evaporated, and to the residue was added $Pd(MeCN)_2Cl_2$ (1.0 mg, 0.0039 mmol), X-Phos (5.8 mg, 0.012 mmol), MeCN (0.5 mL), and K_2CO_3 (66.0 mg, 0.478 mmol), and the mixture was stirred at 23 ℃ for 10 min. Methyl propargyl ether (20.6 mg, 0.294 mmol) was then added, and the reaction mixture was heated at 80 ℃ for 2 h. After cooling to

23 ℃, hexanes (4 mL) were added, and the mixture was vigorous stirred and filtered over a short pad of silica. The solvents were then evaporated, and the residue was purified by flash column chromatography (0→10% ethyl acetate in hexanes) to afford the product as a light yellow liquid (48.2 mg, 61% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.44 (s, 1H), 7.30 (d, J = 5.4 Hz, 2H), 4.34 (s, 2H), 3.46 (s, 3H), 2.33 (s, 3H), 0.26 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 138.80 (s), 137.04 (s), 134.16 (s), 133.85 (s), 133.42 (s), 121.96 (s), 87.03 (s), 84.44 (s), 60.63 (s), 57.74 (s), 21.37 (s), 2.00 (s), 0.10 (s). HRMS (EI+) calcd for [$C_{18}H_{32}O_3Si_3$]: 380.1659, found: 380.1661.

3.5 References

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"Rhodium-Catalyzed, Intermolecular C–H Silylation of Arenes with High Steric Regiocontrol"
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Chapter 4: Mechanistic Studies on the Rh-Catalyzed C-H Silylation

4.1 Introduction

The catalytic functionalization of C-H bonds with main group reagents has become widely used synthetic methodology.[1-7] Our group has published extensively on the borylation of C-H bonds, including the mechanism of the borylation of alkyl and aryl C-H bonds with rhodium and iridium catalysts, respectively.[8-15] We reported in Chapter 3 the rhodium-catalyzed silylation of arenes with $HSiMe(OSiMe_3)_2$ (-$SiMe(OSiMe_3)_2$ = [Si]) that occurs under mild conditions (45 °C) with high regioselectivity derived from the steric properties of substituents on the substrates and on the ligands. This reaction forms synthetically versatile silylarene products in good yields with near-equal stoichiometry of the reaction components.[16]

Methods for the silylation of arenes and alkanes have been reported, but most reactions that have been studied are intramolecular or facilitated by a directing group. For example, our group and the Takai group reported the iridium- and rhodium-catalyzed intramolecular C-H silylation of arenes and alkanes.[17-20] In addition, various research groups have reported the silylation of arenes directed by a coordinating group on the arene. The latter reactions result in functionalization of the C-H bonds *ortho* to the directing group.[21-25]

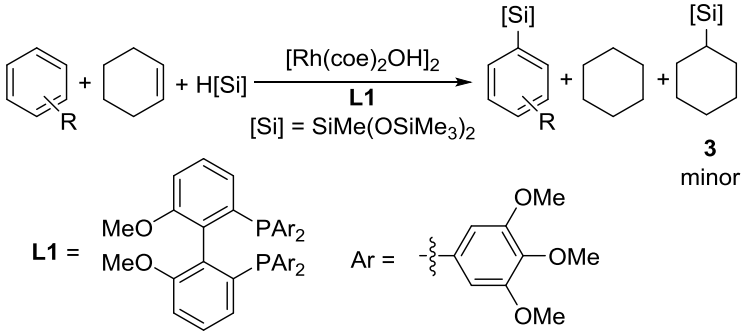
Prior to our recent report, undirected, intermolecular C-H silylation of arenes had only been achieved with a large excess of arene and at high temperatures (>110 ℃). [26-30] The excess of arene limited the synthetic utility of intermolecular silylation. In addition, few detailed mechanistic investigations had been conducted on dehydrogenative silylations;[25] no silyl complex has been isolated that reacts with arenes alone to form arylsilanes. Tilley and co-workers reported a bipyridine-ligated silyliridium(III) phenyl complex that undergoes C-Si reductive elimination to generate silylbenzene, but this complex does not catalyze silylation of arene C-H bonds.[31]

Herein, we report results of a mechanistic investigation of our rhodium-catalyzed silylation of arene C-H bonds. These results provide concrete information on the individual steps of the catalytic cycle and reveal differences between this silylation reaction and the seemingly related borylation of aryl C-H bonds. Our studies indicate that the rate-limiting step (RLS) of the catalytic cycle is not the cleavage of an arene C-H bond, as it is during the borylation of C-H bonds.[32] Instead, hydrogenation of the hydrogen acceptor is rate limiting. We also show that C-H bond cleavage of electron-poor arenes is reversible and that the regioselectivity-determining step of the reactions of these arenes is the C-Si bond-forming reductive elimination, not arene C-H bond cleavage.

4.2 Results and Discussion

The silylation of arenes under investigation occurs with a hydrosilane as the silicon source and cyclohexene as the hydrogen acceptor (Scheme 1). No arylsilane product was observed in the absence of the hydrogen acceptor. Thus, the hydrogen acceptor is intimately associated with the catalytic cycle, and the mechanism of the reaction seems likely to comprise two connected stages: dehydrogenative coupling to form the C-Si bond and hydrogenation of cyclohexene. To elucidate the individual steps of the catalytic process, we sought to identify the catalyst resting state, the kinetic behavior of the reactions, and the relative rates for reactions of different arenes. We used deuterium labeling and kinetic isotope effects to reveal the reversibility of C-H bond cleavage steps. These experiments and the implication of the results of these experiments are described in the following sections.

Scheme 1. Rhodium-catalyzed silylation of arenes.



Identification of the Catalyst Resting State. Monitoring of a silylation reaction between $HSiMe(OTMS)_2$ and 1,3-bis(trifluoromethyl)benzene (**1**) with cyclohexene as the hydrogen acceptor in THF at 45 °C revealed a discrete phosphine-ligated rhodium species. A doublet at 43.0 ppm with a $J_{Rh\text{-}P}$ value of 131 Hz was observed in the ^{31}P NMR spectrum. A hydride signal at -8.0 ppm that possessed a triplet of doublet splitting pattern ($J_{Rh\text{-}H}$ = 23.6 Hz, $J_{P\text{-}H}$ = 44.0 Hz) was observed in the ^{1}H NMR spectrum.

A rhodium complex with spectral data identical to those of the complex observed during catalytic reactions was prepared independently. The complex was prepared by adding H[Si] to [(**L1**)RhCl]$_2$ formed by the combination of $[Rh(C_2H_4)Cl]_2$ and **L1** at 25 °C (Scheme 2).[33] After heating at 45 °C for 3 h, the product was isolated as a light orange solid in 82% yield.

Based on the ^{1}H NMR spectrum, we proposed that this complex is the Rh(III) silyl dihydride **I**. The hydride signal was observed with an intensity corresponding to two hydrogens, and three peaks corresponding to the $SiCH_3$ and the two diastereotopic $OSi(CH_3)_3$ groups of the silyl group were observed with proportional intensities of 3:9:9. A spin correlation between these three ^{1}H NMR signals and three peaks in the ^{29}Si NMR spectrum was established by a $\{^{29}Si\text{-}^{1}H\}$-HMBC experiment (Figure S1). Further evidence supporting this structural assignment in solution was obtained from ESI-HRMS analysis (Figure 1).

Scheme 2. Generation of the catalyst resting state.

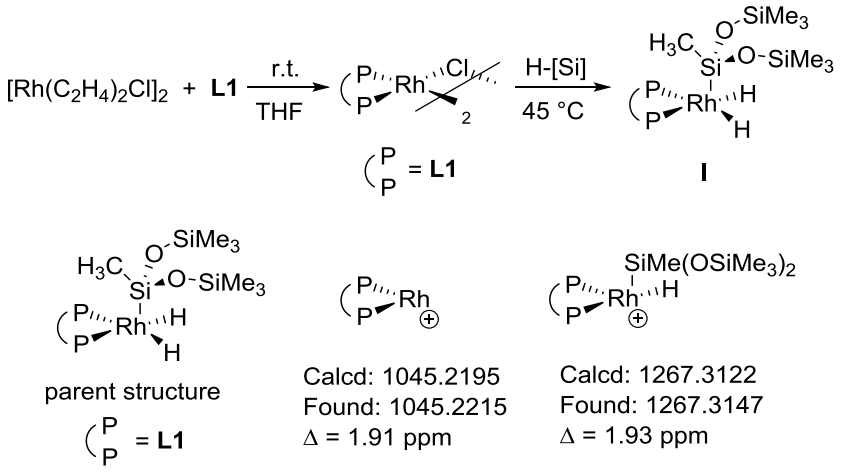


Figure 1. ESI-HRMS analysis of the resting state complex.

Complex **I** was also characterized in the solid state by single crystal X-ray diffraction (Figure 2). Complex **I** contains a distorted square-based pyramidal geometry in which two phosphorus atoms and two hydrides form the square base, and the silyl group occupies the axial position. The distortion from a square-based pyramid is revealed by the hydride-rhodium-silicon angles that are much smaller than the idealized 90°. The two angles are 69° and 58°, and the distances between the silicon and two hydrides differ significantly (2.24 and 1.95 Å). We ascribe this unsymmetrical ligand arrangement to the different steric environment in four quadrants created by the C2-symmetrical ligand and a bonding interaction between the silicon and one of the two hydrides.[34]

The short distance between the silicon and one of the hydrides (1.95 Å) suggests that Si-H reductive elimination should be facile. In agreement with this assertion, subjection of **I** to excess D[Si] at room temperature led to rapid and quantitative incorporation of deuterium into the hydride positions.

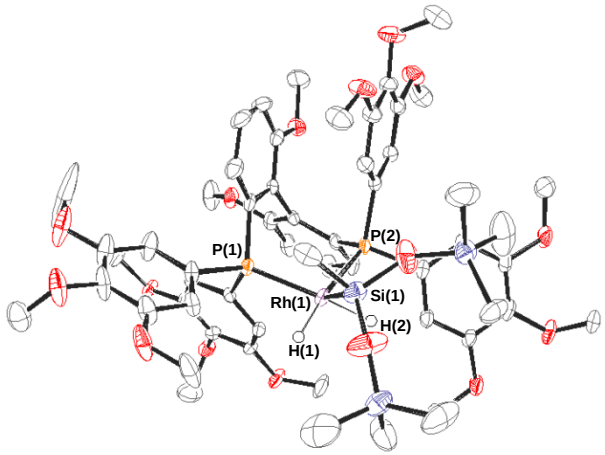


Figure 2. ORTEP diagram of **I** (thermal ellipsoids at 50% probability level). Hydrogen atoms except for the rhodium hydrides are omitted. Selected bond lengths (Å): Rh1-P1 = 2.3119, Rh1-P2 = 2.3391, Rh1-H1 = 1.5269, Rh1-H2 = 1.5138, Rh1-Si1 = 2.2625, Si1-H2 = 1.9523, Si1-H1 = 2.2375. Selected bond angles (°): P1-Rh1-Si1 = 123.4, P2-Rh1-Si1 = 109.1, H1-Rh1-Si1 = 69.3, H2-Rh1-Si1 = 58.3.

Because of the unequal silicon-hydride distances, the two hydrides and two phosphorous atoms are inequivalent in the solid state.[35] However, the two phosphorus atoms and the two rhodium-hydride protons in **I** are equivalent in solution on the NMR timescale. One hydride and one phosphorus signal were observed in the NMR spectra at room temperature. Complex **I** likely undergoes pseudorotation of the ligands in solution, and this pseudorotation allows the two metal-hydride protons and the two phosphorous atoms to undergo site-exchange.

Evaluation of the Kinetic Competency of I. The kinetic relevance of complex **I** was investigated by both stoichiometric and catalytic reactions. Heating **I** with 20 equivalents of 1,3-bis(trifluoromethyl)benzene (**1**) and 20 equivalents of cyclohexene at 45 °C in THF afforded the silylarene product in 83±2% yield in 40 min with a half-life of ~6 min (Scheme 3). This reaction is the first of an isolated silyl complex with an arene to form an arylsilane product without added silane.

The profiles of the reactions of silane with the same arene (**1**) catalyzed by isolated **I** and by the catalyst generated *in situ* from $[Rh(coe)_2OH]_2$ and **L1** are shown in Figure 3. The similarity of these two curves suggests that **I** is likely an intermediate in the catalytic cycle or can enter the catalytic cycle through a low-barrier process. The downward curvature of the reaction profiles suggests a dependence of the reaction rate on the concentration of at least one of the reagents.

Scheme 3. Stoichiometric silylation of **1** with complex **I**.

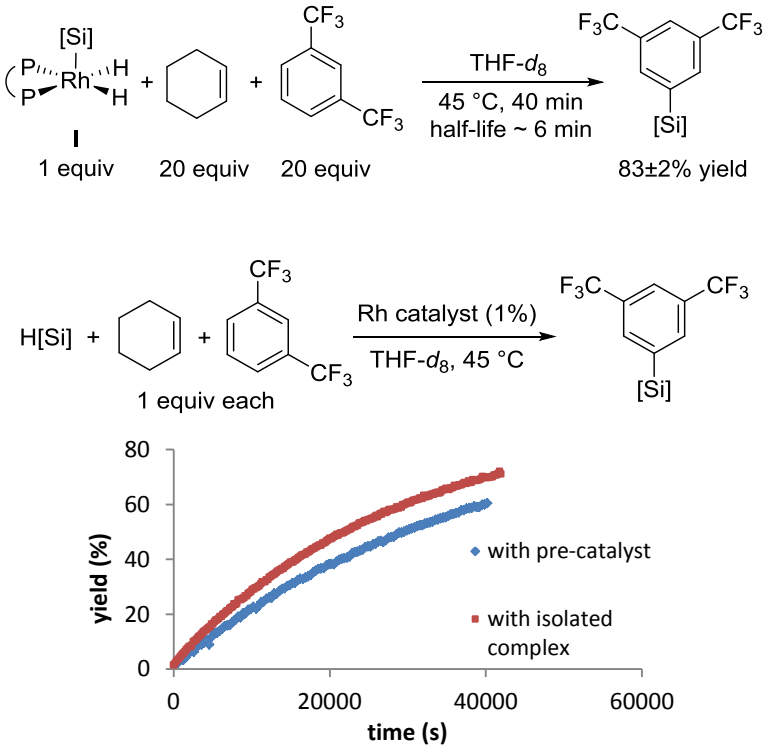
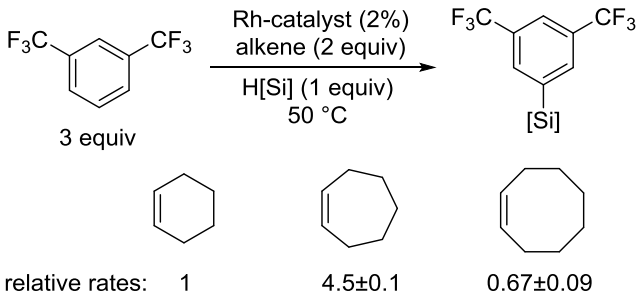


Figure 3. Reaction profiles for the silylation of 1,3-bis(trifluoromethyl)benzene (**1**) catalyzed by **I** and the catalyst generated *in situ*.

Determination of the Experimental Rate Law. The rate law of the catalytic silylation of **1** was determined by the method of initial rates (up to 10% conversion). The mass balance was good (Figure S3); the rate of formation of the product equaled the rate of consumption of the arene. The concentration of each reagent was varied over one order of magnitude. Our results indicate that the reaction is first-order in the concentrations of the catalyst and cyclohexene and zero-order in the concentrations of the silane and the arene (Figure S4).[36] Because the resting state does not contain an arene or an aryl group, the zero-order dependence of the reaction rate on the concentration of arene implies that reaction of the arene, presumably by C-H bond cleavage, occurs after the overall RLS.

On the other hand, the first-order dependence of the rate on the concentration of alkene implies that the reaction of the alkene occurs before or during the RLS. To assess this hypothesis further, the initial rates of reactions run with different alkene-based hydrogen acceptors were measured (Scheme 4). The results showed that the identity of the alkene significantly influences the reaction rates. This result is consistent with a RLS involving the alkenes.

Scheme 4. Relative initial rates of reactions run with different hydrogen acceptors.

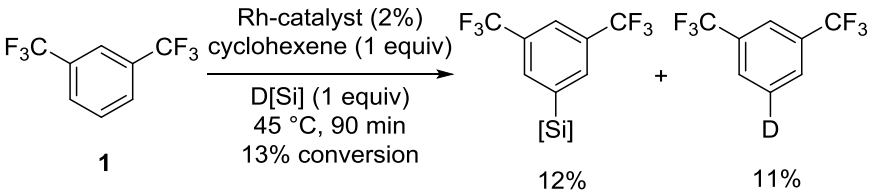


Eyring analysis of the reaction rate (Figure S5) in the temperature range of 308-333 K revealed overall activation parameters of $\Delta H^{\ddagger}$ = 22.4±0.5 kcal·mol^{-1} and $\Delta S^{\ddagger}$ = 1.5±1.6 cal·mol^{-1}·K^{-1}. The small $\Delta S^{\ddagger}$ suggests that there is no significant change in the molecularity from the ground state to the highest-energy transition state.

Measurement of Kinetic Isotope Effects. To assess when the C-H activation of arenes occurs in the catalytic cycle, the rates of the reactions of toluene and toluene-d_8 were measured with the two arenes in separate vessels and in the same vessel. A KIE close to unity (1.3) was observed for reactions with the two arenes in separate vessels, but a primary KIE (5.1) was observed when the two arenes were contained in the same vessel. These results suggest that cleavage of the C-H bond in toluene during the catalytic silylation process is irreversible but is not the rate-limiting step. In addition, a small KIE of 1.0 was observed for the reactions of 1,3-bis(trifluoromethyl)benzene (**1**) and 5-D-1,3-bis(trifluoromethyl)benzene (**1-*d*$_1$**) in separate vessels, but the KIE from reaction of these labeled and unlabeled arenes in the same vessel was 2.9 (see SI). Because the KIE from the competition experiment with the electron-poor arene **1** is smaller than that from the competition reaction of toluene and toluene-d_8, C-H bond cleavage of the electron-poor arene **1** could be partially reversible.[37]

Deuterium-Labeling Experiments. To assess the potential reversibility of the C-H bond cleavage step further, electron-poor arene **1** was allowed to react with D[Si] under the standard conditions for the catalytic silylation process. Analysis of the reaction mixture after 13% conversion revealed the incorporation of deuterium into cyclohexene, cyclohexane, and the starting arene (Scheme 5). These results suggest that insertion of cyclohexene into a rhodium hydride is reversible and that cleavage of the C-H bond in **1** is partially reversible. These results are consistent with a KIE of ~2.9 from the competition experiment.[38]

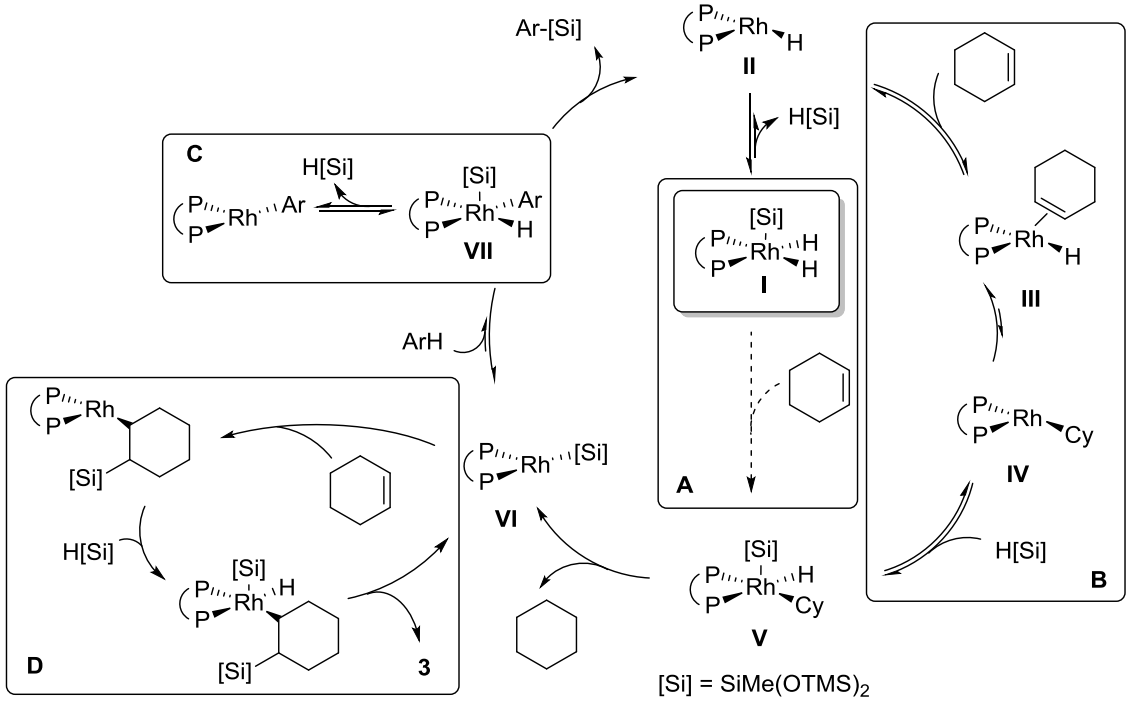
Scheme 5. Reaction of **1** with D[Si].



In contrast to these reactions of the electron-poor arene **1**, reaction of toluene or *m*-xylene (**2**) with D[Si] did not lead to incorporation of deuterium into the starting arene, even at full conversion. This result is consistent with irreversible C-H bond cleavage and a large primary competition KIE (5.1) for the reactions of toluene and toluene-d_8 in the same vessel. The effect of the electronic properties of the arene on the reversibility of the C-H activation step will be discussed in more detail later in this paper.

Proposed Mechanism. Based on the results above, we propose that the Rh-catalyzed silylation of arenes occurs by the pathway shown in Scheme 6. Hydrogen transfer from rhodium silyl

Scheme 6. Proposed mechanism for the silylation of arenes.



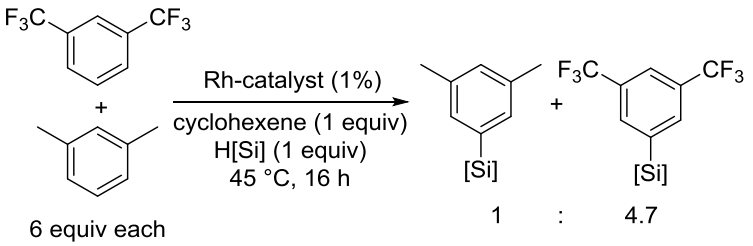
dihydride **I** to cyclohexene generates a rhodium silyl intermediate **VI**, and this intermediate reacts with the arene to generate a rhodium(III) silyl aryl hydride complex **VII**. Complex **VII** undergoes reductive elimination to form the C-Si bond in the silylarene product and the rhodium(I) hydride **II**. Oxidative addition of H[Si] to **II** regenerates the catalyst resting state **I**.

Mechanism of the Cyclohexene Hydrogenation. Two major pathways are plausible for the hydrogenation of cyclohexene. Cyclohexene could bind directly to the resting state **I** and undergo insertion into the Rh-H bond to generate rhodium cyclohexyl silyl hydride **V** (Scheme 6, pathway A). Alternatively, **I** could undergo reversible reductive elimination of the silane to form the rhodium(I) hydride **II**. The release of H[Si] from **I** is supported by the rapid H-D exchange between free silane and **I** at room temperature. The rhodium(I) hydride **II** then binds cyclohexene and undergoes reversible insertion of the alkene into the Rh-H bond (pathway B). Re-addition of H[Si], followed by C-H bond-forming reductive elimination gives cyclohexane and rhodium silyl **VI**. Finally, an associative displacement of the silane by cyclohexene could take place that generates **III** directly from **I**. We were not able to experimentally distinguish among these pathways, because all are consistent with the KIE's and the experimental rate law, but we disfavor pathway A on the basis of DFT calculations we conducted on the binding of cyclohexene to **I'** ($PAr_2 = PPh_2$; [Si] = $SiMe_3$), a model of complex **I.** We were unable to locate a stable structure with cyclohexene bound to the model complex **I'** (pathway A). Any alkene complex structure used to initiate the calculations spontaneously dissociated the free alkene to generate **I'**. For details of these calculations, see the supporting information.

Mechanism of C-H Bond Cleavage and Arylsilane Formation. We propose that the silylarene product is generated by oxidative addition of the arene C-H bond to intermediate **VI** to form silyl aryl hydride complex **VII**, followed by reductive elimination to form the C-Si bond. No formation of product was observed in the absence of cyclohexene, a result that suggests that the rhodium silyl dihydride **I** does not cleave the arene C-H bonds. Instead, removal of both hydrides by the hydrogen acceptor occurs prior to C-H bond cleavage.

The effect of the electronic properties of the arenes on the rate of C-H bond cleavage was investigated. The reaction of 6 equivalents of 1,3-bis(trifluoromethyl)benzene (**1**) and *m*-xylene (**2**) in the same vessel formed the two silylarene products in a ratio of 4.7:1, respectively (Scheme 7). The faster cleavage of the C-H bonds of more electron-deficient arenes by rhodium silyl **VI** is inconsistent with an electrophilic metalation pathway and suggests that a transfer of electron density from the metal to the arene occurs during C-H bond cleavage. Similar relative rates for catalytic C-H functionalization of electronically distinct arenes have been documented.[2, 8] We stress, however, that the initial rates of the catalytic silylation of **1** and **2** in separate vessels are similar (**1** vs **2** = 1.2:1). These similar rates are consistent with the assertion that arene C-H bond cleavage occurs after the overall RLS.

Scheme 7. Competition experiment between **1** and **2**.



We propose that reductive elimination to form the arylsilane and rhodium hydride **II** occurs after C-H bond cleavage. Hydride **II** can bind cyclohexene to initiate the next catalytic cycle (pathway B) or react with H[Si] to afford the resting state **I**.

Reversibility of Arene C-H Oxidative Addition. The results from deuterium-labeling experiments showed that cleavage of the aryl C-H bonds is irreversible for reactions of electron-rich arenes and reversible for reaction of electron-deficient arenes. This difference in the reversibility of C-H bond cleavage for arenes possessing different electronic properties indicates that, for the reactions of electron-rich arenes, the transition state for C-H bond-forming reductive elimination from **VII** to form **VI** (reverse of the C-H oxidative addition step) lies at higher energy than the transition state for reductive elimination to form the C-Si bond in the arylsilane product (Figure 4, solid line). In contrast, for the reactions of electron-poor arenes, the transition state for C-H bond-forming reductive elimination from **VII** to form **VI** lies at an energy similar to that of the transition state for reductive elimination to form the C-Si bond in the arylsilane product (Figure 4, dashed line).[39],[40]

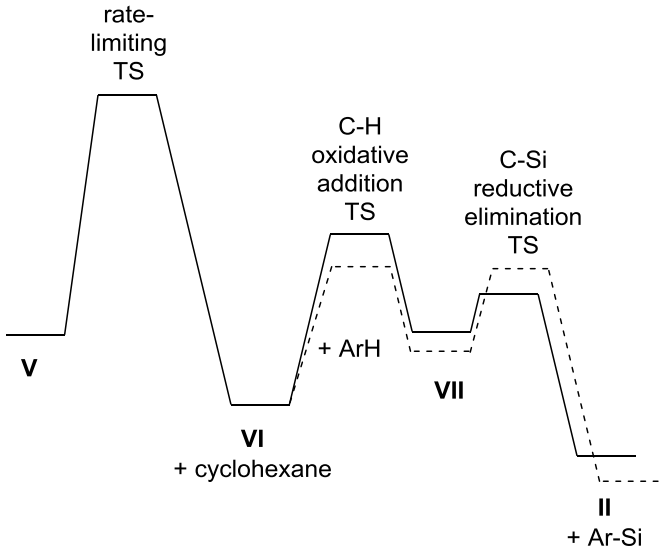


Figure 4. Qualitative free energy diagram for steps involving arenes. Solid line represents reaction with electron-rich arenes; dashed line represents reaction with electron-deficient arenes.

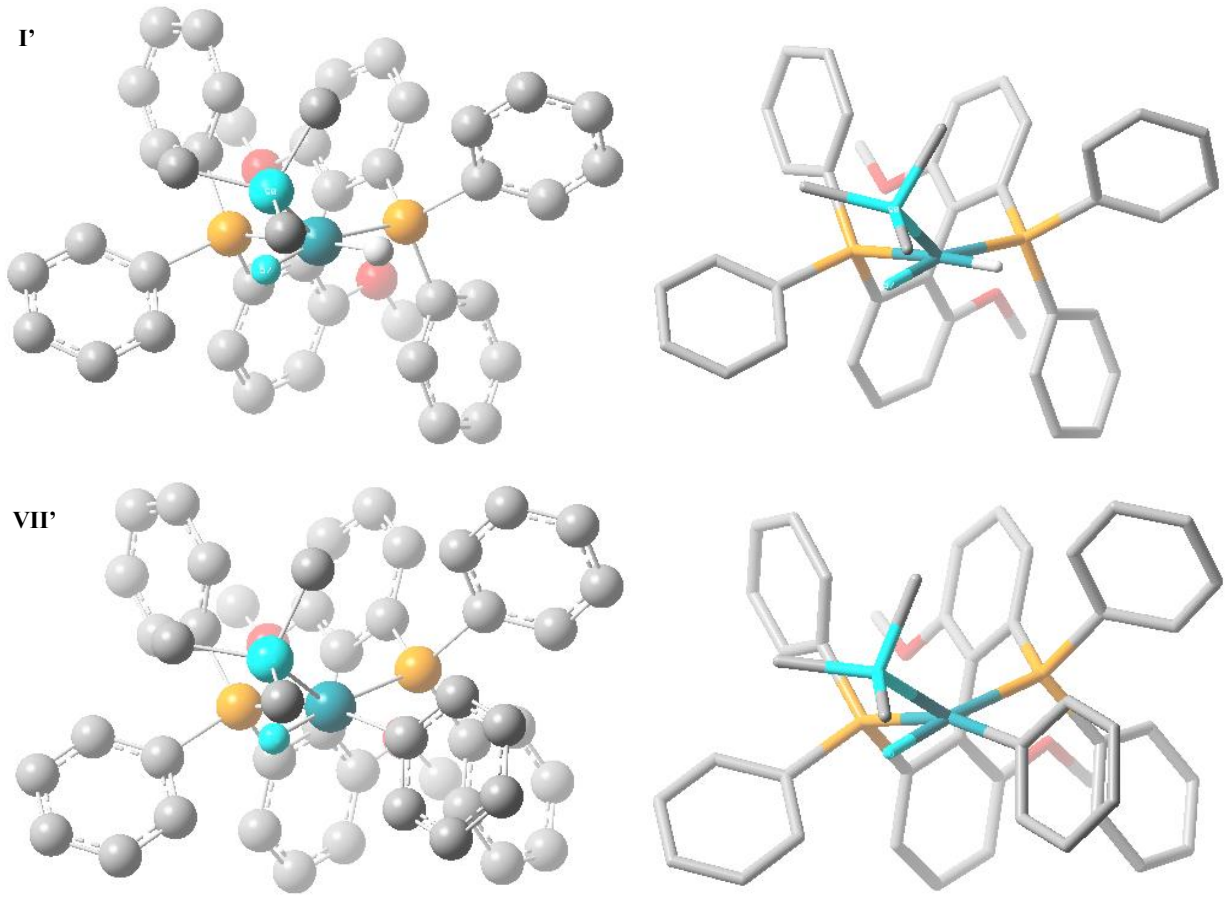


Figure 5. Comparison of the DFT-optimized ground state structures of model complexes **I'** (rhodium silyl dihydride, PAr_2 = PPh_2, [Si] = $SiMe_3$) and **VII' (**rhodium silyl phenyl hydride). The silicon and hydrogen atoms with bonding interaction are highlighted in cyan. Non-essential hydrogen atoms are omitted for clarity. P: orange, O: red, Rh: dark teal.

Mechanism for the Incorporation of Deuterium into the Arene. We deduced the reversibility of arene C-H oxidative addition from the exchange of deuterium between the silane and arenes. To account for this exchange, we invoke a mechanism in which rhodium aryl silyl hydride complex **VII** undergoes reversible exchange with free silane (Scheme 6, pathway C). This exchange allows deuterium to be incorporated into **VII** from the free deuterated silane. We propose that the reductive elimination of silane (H[Si]) occurs by a pathway similar to the exchange of silane with silyl dihydrido **I**. However, the exchange of deuterated silane into **I** cannot lead to deuterium incorporation into the arene because this complex does not cleave arene C-H bonds in the absence of the hydrogen acceptor cyclohexene, which removes both hydrides to form **VI**.[41]

Consistent with the assertion that silane rapidly dissociates from **VII**, DFT calculations suggest that the ground state structure of **VII'** (PAr_2 = PPh_2; [Si] = $SiMe_3$; arene = benzene), a model of

complex **VII**, is similar to that of **I'**. In this structure, the silyl and the hydride groups occupy the same quadrant and the aryl group occupies the opposite quadrant of the structure of **VII'** (Figure 5). The proximity of the silyl and hydride ligands in the model complex **VII'** (Si-H = 1.74 Å, bond order = 0.4467) suggests that H-Si elimination from **VII** and exchange with free silane is likely to occur faster than C-Si reductive elimination from **VII**.

Identification of the Rate-Limiting Step (RLS). Our data imply that the RLS involves a reaction between the rhodium and the alkene. The small difference in the initial rates of reactions of protio- and deuterio-arenes and the zero-order dependence of the reaction rate on the concentration of arene indicate that the arene C-H bond cleavage occurs after the RLS. The first-order dependence of the reaction rate on the concentration of cyclohexene implies that the hydrogen acceptor reacts prior to or during the RLS. Furthermore, the H-D exchange between cyclohexene and D[Si] suggests that reaction of the cyclohexene with the rhodium, presumably by insertion of the alkene into a Rh-H bond, occurs reversibly.

Because two major pathways (A and B, Scheme 6) were proposed for cyclohexene hydrogenation, the RLS for each pathway was analyzed. For pathway A in which cyclohexene inserts directly into the Rh-H bond of **I**, reductive elimination of cyclohexane, which occurs between cyclohexene insertion and arene C-H bond cleavage, is the RLS.

For pathway B, either oxidative addition of H[Si] to rhodium cyclohexyl **IV** or reductive elimination of cyclohexane from **V** could be rate limiting. To probe whether oxidative addition of H[Si] is the RLS, the initial reaction rates of reactions of **3** with H[Si] and D[Si] were measured. A KIE of unity was obtained,[42] which, combined with a small overall $\Delta S^{\ddagger}$, suggests that addition of H-Si to **IV** is unlikely the RLS. Thus, for both pathways A and B, the C–H bond-forming reductive elimination from **V** to release cyclohexane is the RLS.

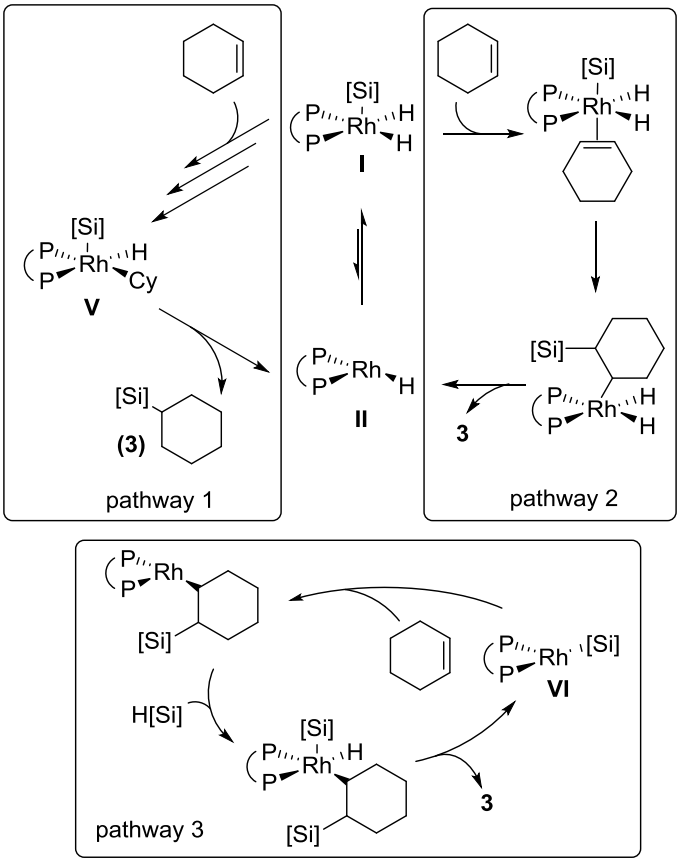
Mechanism for the Formation of Silylcyclohexane and Effect of Ligand Electronic Properties on Arene vs Alkene Silylation. During arene silylation, silylcyclohexane ($C_6H_{11}SiMe(OSiMe_3)_2$ (**3**) from hydrosilylation of cyclohexene formed as a minor product (Scheme 1). Hydrosilylation of alkenes is known to be catalyzed by many rhodium complexes.[43] Several pathways could account for the formation of the hydrosilylation side product **3**. The silylcyclohexane could form (1) by C-Si reductive elimination from **V** (Scheme 8, pathway 1) instead of C-H reductive elimination from **V** in the productive catalytic cycle (Scheme 6); or (2) by insertion of cyclohexene into the Rh-Si bond of **I** (instead of the Rh-H bond of **I** as occurs during the productive pathway),[44] followed by C-H bond-forming reductive elimination (Scheme 8, pathway 2); or (3) insertion of cyclohexene into the Rh-Si bond of **VI** followed by oxidative addition of a second silane and C-H reductive elimination to regenerate **VI** (Scheme 6, pathway D, shown in Scheme 8 as pathway 3).

Pathway 3 differs from pathways 1 and 2 in that silylcyclohexane **3** cannot be generated by pathway 3 without free silane in solution; one hydrogen of **3** originates from a second molecule

of silane. When rhodium silyl dihydride **I** was allowed to react with 30 equivalents of cyclohexene in the absence of free silane, only cyclohexane was generated; no silylcyclohexane (**3**) was observed. This result is consistent with pathway 3 and is inconsistent with pathways 1 and 2.

In addition, pathway 1 is unlikely because intermediate **V** would more likely undergo reductive elimination to form a C-H bond (i.e. as in normal catalytic cycle) rather than reductive elimination to form a C-Si bond. This is because rhodium-catalyzed hydrosilylation usually proceeds through insertion of the alkene into the rhodium-silicon bond, followed by reductive elimination to form the C-H bond (modified Chalk-Harrod mechanism).[45-46] DFT calculations have shown that the C-Si bond-forming reductive elimination from Rh(III) has a very high barrier. [46]

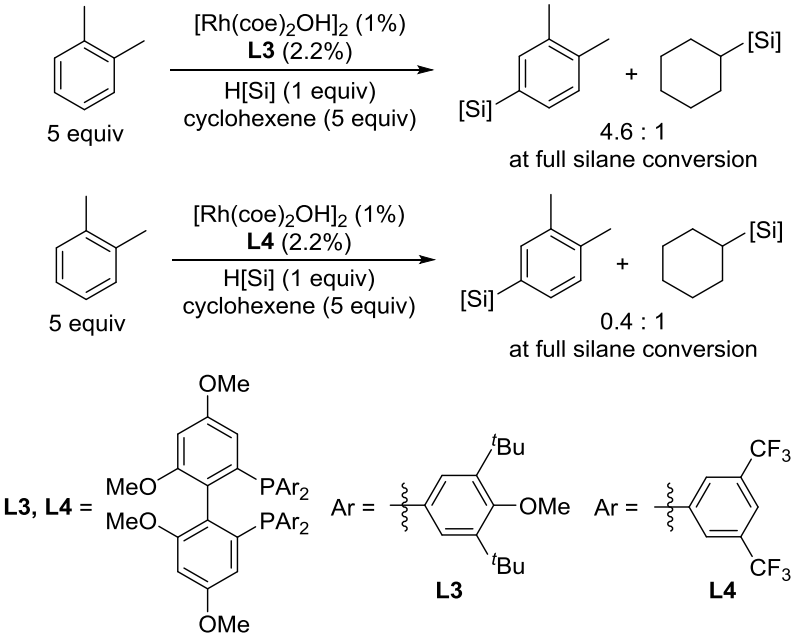
Scheme 8. Possible pathways for the formation of **3**.



Because rhodium silyl **VI** is the common intermediate for C-H activation and alkene hydrosilylation, and because insertion of alkenes into metal-silyl or metal-hydride bonds is usually favored by electron-deficient metal centers, while C-H oxidative addition is usually favored by electron-rich metal centers, perturbation of the electronic properties of the ligands should alter the ratio of hydrosilylation to arene-silylation products. Consistent with this

hypothesis, the reaction of *o*-xylene with H[Si] and cyclohexene catalyzed by $[Rh(coe)_2(OH)]_2$ and **L3** as ligand led to a 4.6:1 ratio of products from arene-silylation and hydrosilylation (Scheme 9), whereas the reaction in the presence of the catalyst generated from the more electron-deficient ligand **L4** produced much more product from hydrosilylation (0.4:1 arene-silylation to hydrosilylation).

Scheme 9. The effect of ligand on the product distribution.



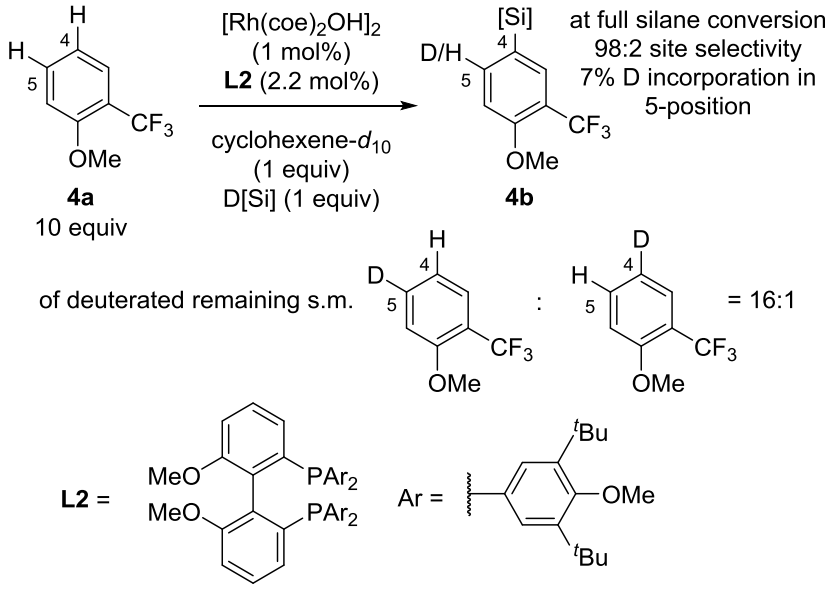
Origin of the Electronic Effect on Regioselectivity. In Chapter 3, we reported that the silylation of arenes occurs with regioselectivity derived from the steric effect of substituents *meta* to reactive C-H bonds. The silylation reactions of *ortho*-disubstituted arenes containing two electronically similar substituents occurred selectively at the C-H bond located further from the larger of the two groups.[16] Yet the silylation of 2-(trifluoromethyl)anisole (**4a**) occurred at the position *meta* to the CF_3 group (4-position),[47] which is the C-H bond closer to the larger of the two substituents.[48][49] In this case, the silylation results from functionalization at the C-H bond that is typically less reactive toward C-H bond cleavage.[50],[51-52]

To assess whether the electronic effect on site selectivity results from an irreversible, kinetic selectivity from C-H bond cleavage or reversible C-H bond cleavage and irreversible C-Si bond formation, we conducted deuterium-labeling experiment with D[Si]. The reaction of D[Si] with 10 equivalents of 2-trifluoromethylanisole (**4a**) and 1 equivalent of cyclohexene-d_{10} formed product **4b** with a selectivity of 98:2 favoring the product in which the silyl group was installed at the 4-position. Most important for understanding the origin of regioselectivity, 7% deuterium-incorporation was found in the 5-position of the arylsilane product, and the ratio of deuterium-

incorporation into the 5-position vs the 4-position in the remaining arene was 16:1 favoring deuteration *para* to the CF_3 group (Scheme 10).

These results imply that C-H activation is reversible at both the 4- and 5-positions. C-H bond cleavage is faster at the more electron-deficient 5-position (rate ~16:1), but reductive elimination is faster (and occurs almost exclusively) from the complex in which Rh is bound to the more-electron rich 4-position on the arene.[53],[54] Thus, the regioselectivity of the silylation of **4a** is determined by a combination of reversible oxidative addition of the C-H bond and irreversible reductive elimination to form the C-Si bond.[55]

Scheme 10. Reaction of 2-(trifluoromethyl)anisole with D[Si].



4.3 Conclusions

The synthesis of Rh-silyl complexes and kinetic measurements have allowed us to propose a catalytic cycle for the silylation of arenes that is grounded in detailed experimental observations. The identification of the silylrhodium dihydride resting state, the rate law, and the influence of the electronic properties of substituents on the reaction rate and site selectivity have allowed us to pinpoint the identity and order of bond cleavages and bond formations that occur during the rate-limiting step and the selectivity-determining step. Starting from the resting state, hydrogenation of cyclohexene is the RLS. This step precedes cleavage of the arene C-H bond by a bisphosphine-ligated Rh(I) silyl intermediate.

1. The catalyst resting state is an unusual, five-coordinate silyl rhodium complex **I**. Complex **I** contains four sterically differentiated quadrants as a result of the C2-symmetric ligand and the pseudo-axial silyl group. The silyl group is located in one of the two less sterically hindered quadrants and is close in distance (1.95 Å) to one of the hydride ligands. The short Si-H distance leads to facile and reversible elimination of the silane.

2. Complex **I** is the first isolated silyl complex that reacts with arenes to form arylsilanes in both single-turnover and catalytic reactions. Complex **I** does not react directly with arenes. Instead, complex **I** reacts with the combination of cyclohexene and arenes to form cyclohexane and arylsilane. The requirement of cyclohexene implies that the cyclohexene reacts with **I** to form a species that reacts with the arene. This reaction is likely transfer of the two hydrogens to form cyclohexane and to form the bisphosphine-ligated silyl Rh(I) complex **VI** , which cleaves the C-H bond of the arene to form a hydrido aryl silyl intermediate.

3. DFT calculations of the structure of **VII'**, a model for the silyl aryl hydride intermediate **VII,** suggests that **VII** adopts a structure that is similar to that of **I** in which the silyl and hydride ligands occupy the same quadrant and the aryl group occupies the opposite quadrant. This type of ligand arrangement is consistent with the observed relative rate of C-Si and H-Si reductive elimination from rhodium silyl aryl hydride **VII**. Our data implies that Complex **VII** undergoes rapid exchange with silane to give rise to H-D exchange between the arene and the silane; reductive elimination from **VII** to form the C-Si bond appears to be slower than the exchange of free silane with **VII**.

4. The catalytic cycle features an unusual rate-limiting step. Contrary to many C-H functionalization reactions in which the C-H activation is the RLS,[2, 32, 56] our data strongly imply that reductive elimination from an alkylrhodium(III) hydride complex, a facile step in many rhodium-catalyzed alkene hydrogenation reactions,[57] is the RLS of the arene silylation reaction.

5. The C-H activation is reversible during reactions of electron-poor arenes and is not the regioselectivity-determining step when the regioselectivity is dominated by electronic effects. We showed that the silylation occurs preferentially at the site that undergoes C-H bond cleavage more slowly, as indicated by the relative incorporation of deuterium from deuterated silane into different sites on 2-(trifluoromethyl)anisole (**4a**). These H/D exchange data and the site selectivity for arene silylation imply that the regioselectivity-determining step is the formation of the C-Si bond. Reversible C-H activation occurs at both positions *para* to electron-donating and electron-withdrawing groups, but the product-forming reductive elimination occurs much faster from the complex containing the metal bound to the more electron-rich carbon.

6. Hydrosilylation of the alkene hydrogen acceptor is catalyzed by the same intermediate (**VI**) that activates the arene C-H bonds. Because alkene insertion and C-H oxidative addition are

usually favored by the opposite electronic properties of the metal center, the competing hydrosilylation is suppressed by using catalysts containing more electron-donating biarylphosphine ligands.

Overall, these studies show that the mechanism of the rhodium-catalyzed silylation is distinct from the mechanism of rhodium- or iridium-catalyzed borylation of arenes. C-H bond cleavage in the borylation processes occur by Rh(III) boryl and Ir(III) boryl intermediates.[32, 58] We presume that the change in rate-limiting step from generation of the reactive intermediate that cleaves the C-H bond (as in silylation) to cleavage of the C-H bond (as in borylation) is a function of the different oxidation states of the boryl and silyl complexes that cleave the C-H bonds. Cleavage of a C-H bond by a Rh(III) or Ir(III) species is likely less facile than cleavage of a C-H bond by a Rh(I) silyl species.

Extensive computational data are needed to gain information on the C-H bond cleavage step and the relationship between the main-group assisted C-H bond cleavage reactions by boryl complexes[59] and the role of silicon in the C-H bond cleavage step of this Rh-catalyzed reaction. Such computational studies and an assessment of the effect of ligands on the individual steps as a means to create more active catalysts will be the studies of future work in our laboratory.

4.4 Experimental

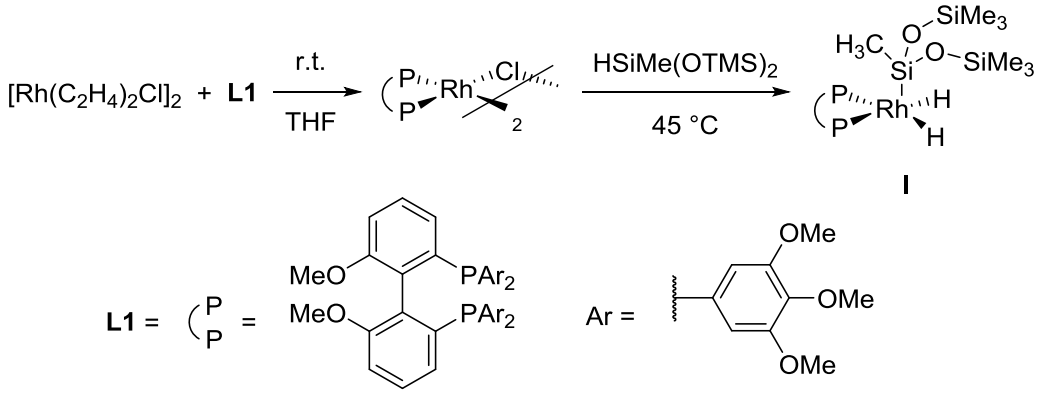
Reagents and Instrumentation

All air-sensitive manipulations were performed in a nitrogen-atmosphere glovebox or using standard Schlenk technique. Pentane and tetrahydrofuran (THF) were distilled from $LiAlH_4$ under nitrogen and stored over 3Å molecular sieves. 1,3-Bis(trifluoromethyl)benzene was distilled from P_2O_5 prior to use. 1,3-Xylene, 1,2-xylene, cyclohexene, and cycloheptene were distilled from $LiAlH_4$ prior to use. Deuterated solvents were purchased from Cambridge Isotope Laboratories and used as received. Cyclohexene-d_{10} was purchased from CDN Isotopes. The bisphosphine ligands were purchased from Strem Chemicals. Commercial **L1** was purified by flash column chromatography over SiO_2 prior to use. Rhodium precursors $[Rh(coe)_2OH]_2$[60] and $[Rh(C_2H_4)Cl]_2$[61] were prepared according to literature procedures. 5-D-1,3-bis(trifluoromethyl)benzene was prepared according to the literature procedure.[62] All other reagents were purchased from commercial sources and degassed prior to use.

NMR spectra were acquired on Bruker AVQ-400, AV-500, and AV-600 spectrometers. ^{1}H NMR chemical shifts were reported in ppm relative to residual solvent peak. ^{31}P NMR chemical shifts were reported relative to an external H_3PO_4 (85% aqueous) sample. ^{29}Si NMR chemical shifts were reported relative to an external Me_4Si sample. High-resolution mass spectra

were obtained at the QB3/Chemistry Mass Spectrometry Facility, and elemental analyses were conducted at the Micro Analytical Facility operated by the College of Chemistry, University of California, Berkeley.

Synthesis and Characterization of Complex I



To a solution of (S)-**L1** (38.8 mg, 0.0412 mmol) in THF (1.2 g) was added $[Rh(C_2H_4)_2Cl]_2$ (8.0 mg, 0.021 mmol), and the mixture was stirred at 25 ℃ for 30 min. To the mixture was then added $HSiMe(OSiMe_3)_2$ (364 mg, 1.64 mmol), and the mixture was stirred at 45 ℃ for 3 h, during which time the mixture turned from dark red to bright orange. The volatile materials were evaporated at 0 ℃, and the residue was triturated with cold pentane (0 ℃, 2.5 mL × 3) to afford complex **I** as a light orange solid (42.7 mg, 82% yield). ^{1}H NMR (600 MHz, C_6D_6) δ 7.86 (d, J = 7.1 Hz, 4H), 7.07 – 6.93 (m, 6H), 6.69 (t, J = 8.0 Hz, 2H), 6.11 (d, J = 8.2 Hz, 2H), 3.89 (s, 6H), 3.76 (s, 6H), 3.63 (s, 12H), 3.46 (s, 12H), 3.19 (s, 6H), 0.83 (s, 3H), 0.47 (s, 9H), -0.08 (s, 9H), -7.51 (td, J_{Rh-H} = 23.5, J_{P-H} 44.4 Hz, 2H). ^{29}Si NMR (119 MHz, C_6D_6) δ 3.08 (s), 2.64 (s), -22.23 (d, J_{Rh-Si} = 41.1 Hz). ^{31}P NMR (243 MHz, C_6D_6) δ 42.58 (d, J_{P-Rh} = 131.3 Hz). ESI-HRMS(+) calcd for $[C_{57}H_{78}O_{16}P_2RhSi_3^+]$ (M-H): 1267.3122, found: 1267.3147; calcd for $[C_{50}H_{56}O_{14}P_2Rh^+]$ (M-$HSiMe(OSiMe_3)_2$-H): 1045.2195, found: 1045.2215. Anal. Calcd (%) for $C_{57}H_{79}O_{16}P_2RhSi_3$: C, 53.94, H, 6.27. Found: C, 53.74, H, 6.02.

Single crystals of **I** suitable for X-ray diffraction were obtained by vapor diffusion of pentane into a saturated ethereal solution of **I** at 25 ℃. A yellow prism 0.070 x 0.050 x 0.020 mm in size was mounted on a Cryoloop with Paratone oil. Data were collected in a nitrogen gas stream at 100(2) K using phi and omega scans. The crystal-to-detector distance was 60 mm, and the exposure time was 10 seconds per frame using a scan width of 0.5 °. Data collection was 100.0% complete to 25.000° in θ. A total of 53092 reflections were collected covering the indices, -15<=*h*<=15, -23<=*k*<=23, -13<=*l*<=16. 12412 reflections were found to be symmetry independent, with an R_{int} of 0.0539. Indexing and unit cell refinement indicated a primitive, monoclinic lattice. The space group was found to be P 21 (No. 4). The data were integrated using the Bruker SAINT software program and scaled using the SADABS software program. Solution by iterative methods (SHELXT) produced a complete heavy-atom phasing model consistent with

the proposed structure. All non-hydrogen atoms were refined anisotropically by full-matrix least-squares (SHELXL-2014). All hydrogen atoms were placed using a riding model. Their positions were constrained relative to their parent atom using the appropriate HFIX command in SHELXL-2014. SQUEEZE was used to treat the diffuse solvent contribution to the electron density and its use has been noted in the CIF file.

Table S1. Crystal data and structure refinement for I.

Empirical formula	C57 H79 O16 P2 Rh Si3	
Formula weight	1269.32	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P 21	
Unit cell dimensions	a = 12.807(3) Å	= 90 °.
	b = 19.191(4) Å	= 91.137(9)°.
	c = 13.761(3) Å	= 90°.
Volume	3381.5(13) $Å^3$	
Z	2	
Density (calculated)	1.247 Mg/m^3	
Absorption coefficient	0.412 mm^{-1}	
F(000)	1332	
Crystal size	0.070 x 0.050 x 0.020 mm^3	
Crystal color/habit	yellow prism	
Theta range for data collection	1.480 to 25.429 °.	
Index ranges	-15<=h<=15, -23<=k<=23, -13<=l<=16	
Reflections collected	53092	
Independent reflections	12412 [R(int) = 0.0539]	
Completeness to theta = 25.000 °	100.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.928 and 0.841	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	12412 / 1 / 813	
Goodness-of-fit on F^2	1.024	
Final R indices [I>2sigma(I)]	R1 = 0.0332, wR2 = 0.0760	
R indices (all data)	R1 = 0.0374, wR2 = 0.0786	
Absolute structure parameter	-0.038(9)	

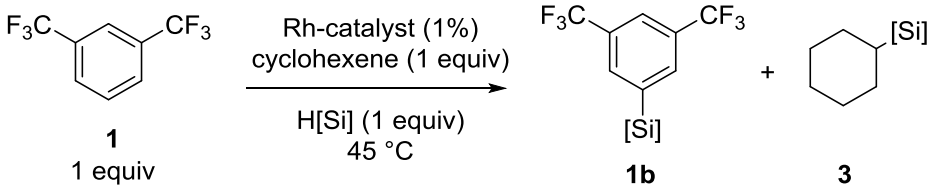
Extinction coefficient	n/a
Largest diff. peak and hole	0.581 and -0.351 e.Å^{-3}

Stoichiometric Silylation of 1 with Complex I (Scheme 3)

To a J-Young NMR tube was added complex **I** (2.3 mg, 1.8 μmol), 1,3,5-trimethoxybenzene (1.0 mg, 6.0 μmol), THF-d_8 (120 μL), cyclohexene (3.7 μL, 0.037 mmol), 1,3-bis(trifluoromethyl)benzene (**1**, 5.7 μL, 0.037 mmol), in this order. The reaction was heated at 45 ℃ for 40 min. The yield of the product was determined by ^{1}H NMR spectroscopy using 1,3,5-trimethoxybenzene as the internal standard. For estimation of the half-life, the reaction was monitored by ^{1}H NMR spectroscopy at 45 ℃ (d1 = 11 s, interval between data points = 30 s).

Reaction Progress Monitored by ^{1}H NMR (Figure S3)

To a J-Young NMR tube was added complex **I** (0.6 mg, 0.5 μmol), 1,3,5-trimethoxybenzene (1.0 mg, 6 μmol), THF-d_8 (100 μL), $HSiMe(OSiMe_3)_2$ (13 μL, 0.046 mmol), cyclohexene (4.8 μL, 0.047 mmol), 1,3-bis(trifluoromethyl)benzene (**1**, 7.3 μL, 0.047 mmol), in this order. The reaction was monitored by ^{1}H NMR spectroscopy (d1 = 11 s, interval between data points = 30 s) at 45 ℃ using 1,3,5-trimethoxybenzene as the internal standard. As shown in Figure S3(b), the total amount of arene-containing species (total Ar-R = **1** + **1b**) and the total amount of cyclohexyl-containing species (total Cy-R = cyclohexene + cyclohexane + **3**) remain constant.



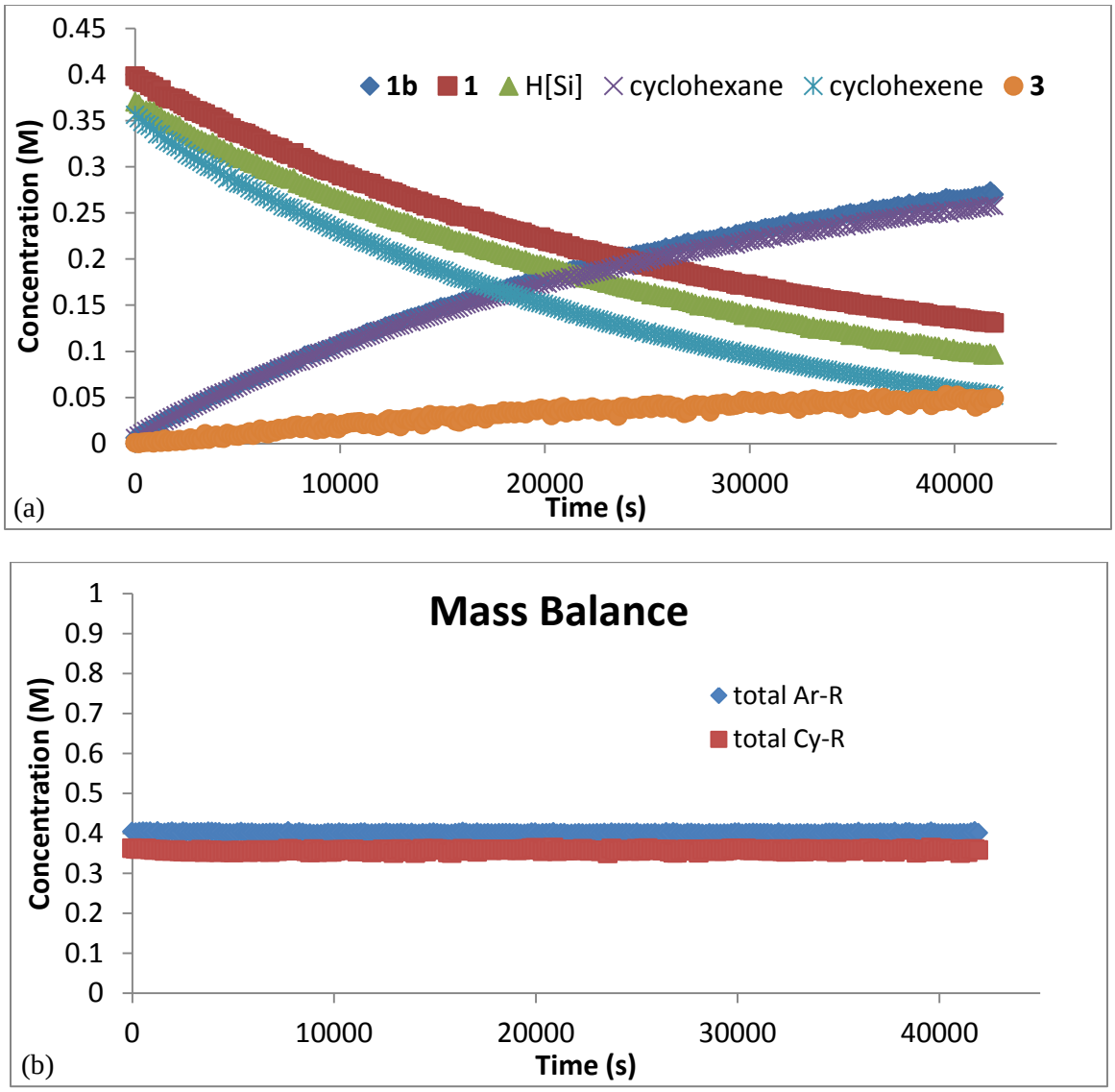


Figure S3. Reaction progress and mass balance of silylation of **1**.

Determination of the Rate Law (Figure S4)

Silylation of **1** was conducted in THF-d_8 with a total volume of 0.12 mL. The concentrations of each reagent under the standard conditions for catalytic silylation are: 0.33 M arene, 0.67 M cyclohexene, 0.67 M silane, 6.7 mM catalyst. To determine the rate dependence on one reagent, the concentration of that reagent was varied, while the concentration of other reagents and the total volume (0.12 mL) were held constant. The concentration of arene was varied between 0.1-2.7 M. The concentration of cyclohexene was varied between 0.2-3.0 M. The concentration of silane was varied between 0.2-2.3 M. The concentration of the catalyst was

varied between 0.5-13 mM. The rate law of the reaction was determined by the method of initial rates (up to 10% conversion) at 45 ℃ monitored by ^{1}H NMR spectroscopy (d1 = 11 s, interval between data points = 60 s) with 1,3,5-trimethoxybenzene as the internal standard. The rates refer to the rates of starting material consumption in units of M s^{-1}. The rate dependence on the concentration of 1,3-xylene was determined in a similar way (0.67 M cyclohexene, 0.67 M silane, 6.7 mM catalyst, 0.17-1.0 M 1,3-xylene, total volume = 0.12 mL).

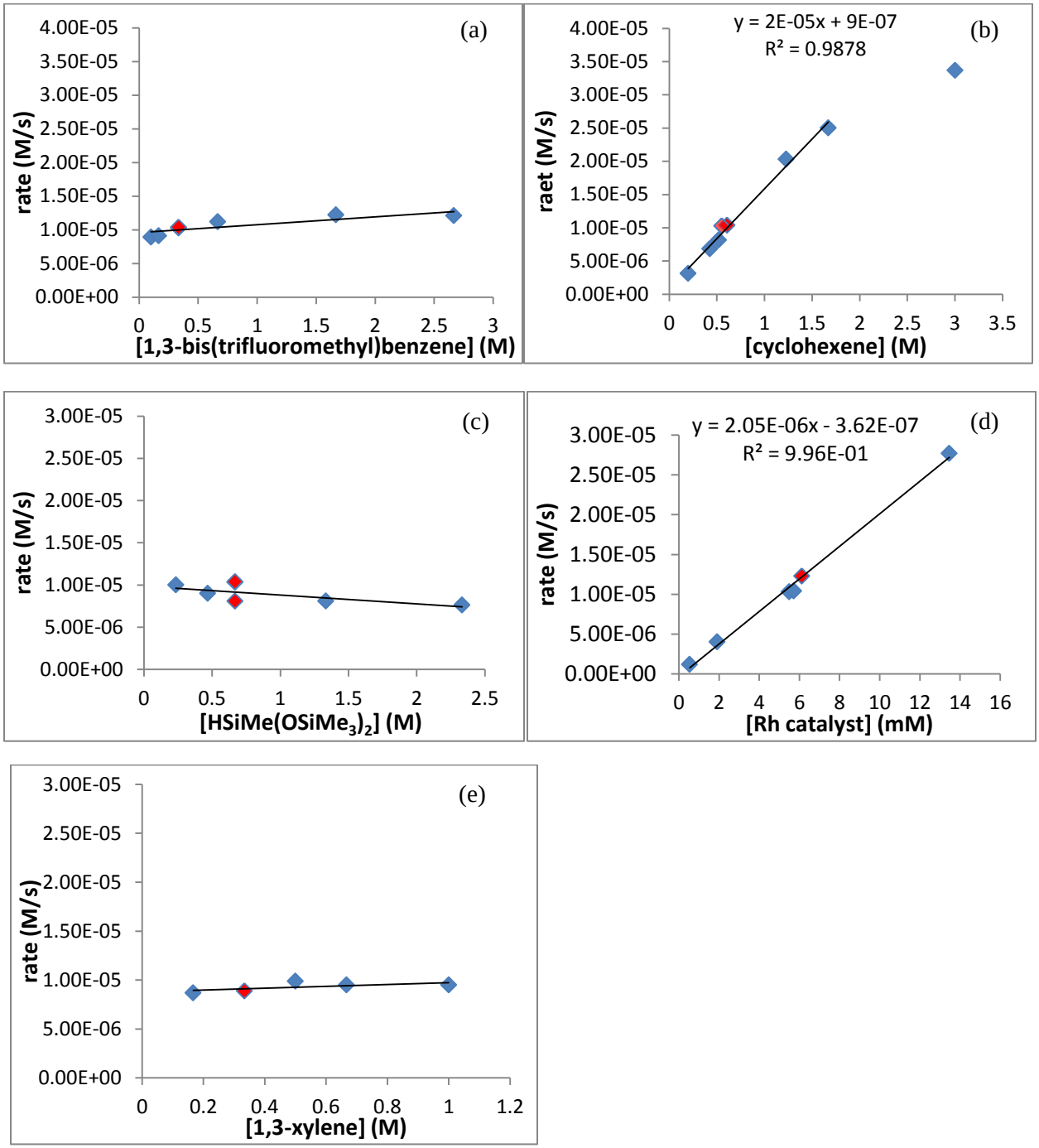


Figure S4. (a-d) Determination of the rate law for the silylation of **1**. Red dots indicate the concentrations of reagents under the standard conditions reported for the catalytic silylation; (e) Determination of the rate dependence on the concentration of 1,3-xylene.

Determination of the Activation Parameters (Figure S5)

To a J-Young NMR tube was added complex **I** (1.0 mg, 0.8 μmol), 1,3,5-trimethoxybenzene (1.0 mg, 6 μmol), THF-d_8 (100 μL), $HSiMe(OSiMe_3)_2$ (11 μL, 0.039 mmol), cyclohexene (4.0 μL, 0.040 mmol), and 1,3-bis(trifluoromethyl)benzene (**1**, 6.2 μL, 0.040 mmol), in this order. The enthalpy and entropy of activation were determined by measuring the initial rates (up to 10% conversion) at 308-333 K monitored by ^{1}H NMR spectroscopy (d1 = 11 s, interval between data points = 30 s) using 1,3,5-trimethoxybenzene as the internal standard. The second order rate constant was calculated from the observed rate by the following equation:

$$k = \frac{k_{obs}}{[cyclohexene] \cdot [catalyst]}$$

The Eyring plot and the data points for the Eyring plot are shown below:

entry	[catalyst] (M)	[cyclohexene] (M)	k_{obs} ($M\ s^{-1}$)	k ($M^{-1}\ s^{-1}$)	T (K)	ln(k/T)	1/T (1/K)
1	3.04E-03	2.86E-01	1.59E-05	1.83E-02	328	-9.80	3.05E-03
2	2.98E-03	2.87E-01	9.14E-06	1.07E-02	323	-10.32	3.10E-03
3	3.02E-03	2.91E-01	5.04E-06	5.75E-03	318	-10.92	3.14E-03
4	2.73E-03	3.07E-01	2.83E-06	3.38E-03	313	-11.44	3.19E-03
5	2.69E-03	3.06E-01	1.65E-06	2.00E-03	308	-11.94	3.25E-03
6	3.03E-03	2.72E-01	2.75E-05	3.34E-02	333	-9.21	3.00E-03
7	3.46E-03	2.96E-01	5.37E-06	5.24E-03	318	-11.01	3.14E-03
8	2.81E-03	2.83E-01	4.61E-06	5.79E-03	318	-10.91	3.14E-03
9	3.01E-03	2.94E-01	5.15E-06	5.81E-03	318	-10.91	3.14E-03
10	2.84E-03	2.84E-01	4.44E-06	5.50E-03	318	-10.96	3.14E-03

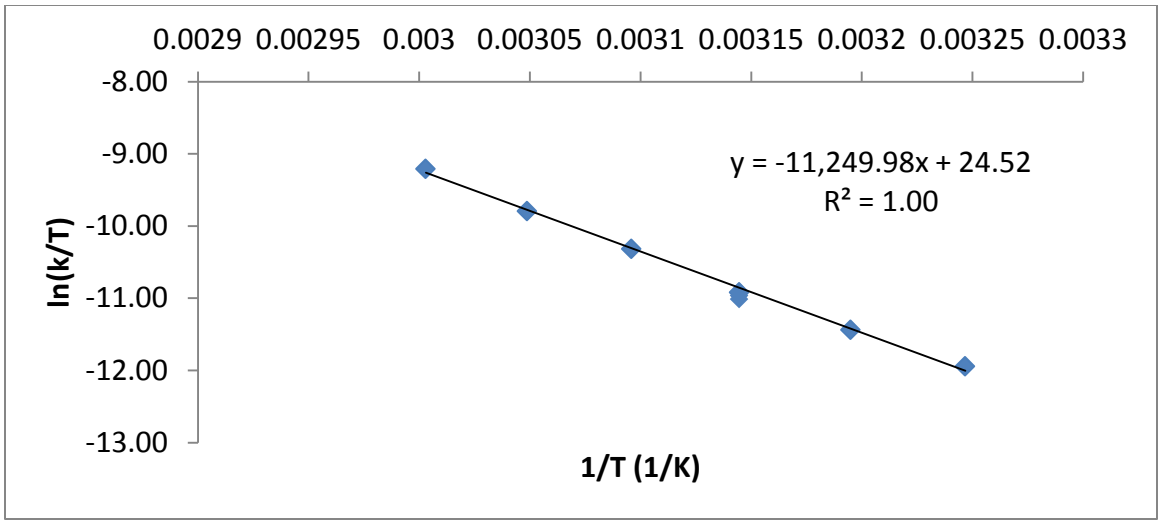


Figure S5. Eyring plot for the silylation of **1** at 308-323 K.

According to the Eyring equation:

$$ln\frac{k}{T} = \frac{-\Delta H^{\ddagger}}{R} \cdot \frac{1}{T} + ln\frac{k_B}{h} + \frac{\Delta S^{\ddagger}}{R}$$

$$\Delta H^{\ddagger} = R \cdot slope = (8.314 \times 11300)\, J \cdot mol^{-1} = 22.4\, kcal \cdot mol^{-1}$$

$$\Delta S^{\ddagger} = R \cdot \left(intercept - ln\frac{k_B}{h}\right) = [8.314 \times (25 - 23.76)]\, J \cdot mol^{-1} \cdot K^{-1}$$

$$= 1.5\, cal \cdot mol^{-1} \cdot K^{-1}$$

The errors in the slope and the intercept were determined via the LINEST function. The errors in $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are 0.5 kcal mol^{-1} and 1.6 cal mol^{-1} K^{-1}, respectively.

Effect of Hydrogen Acceptor on the Initial Rates (Scheme 4)

To a J-Young NMR tube was added complex **I** (1.0 mg, 0.8 μmol), 1,3,5-trimethoxybenzene (1.0 mg, 6 μmol), THF-d_8 (83 μL), HSiMe(OSiMe$_3$)$_2$ (11 μL, 0.039 mmol), cycloheptene (9.3 μL, 0.080 mmol), and 1,3-bis(trifluoromethyl)benzene (**1**, 17 μL, 0.11 mmol), in this order. The initial rates (up to 10% conversion) were measured by monitoring the reaction by ^{1}H NMR spectroscopy at 50 ℃ (d1 = 11 s, interval between data points = 30 s). For reactions with other alkenes (0.08 mmol), the volume of THF-d_8 was adjusted to give a total volume of 0.12 mL.

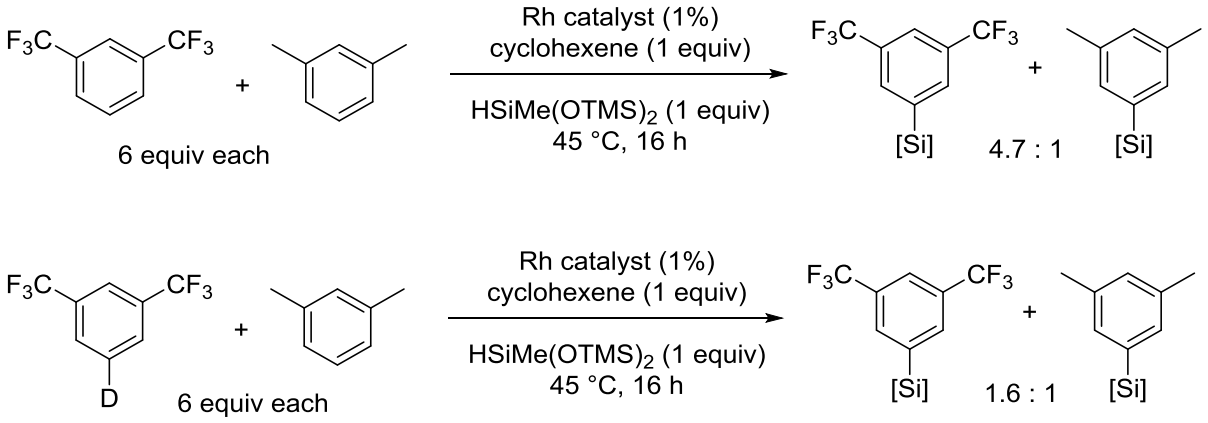
Silylation of 1 with DSiMe(OSiMe$_3$)$_2$ (Scheme 5)

To a 4-mL vial was added $[Rh(coe)_2OH]_2$ (0.7 mg, 1 μmol), **L1** (2.1 mg, 2.2 μmol), THF (150 mg), and $DSiMe(OSiMe_3)_2$ (29 μL, 0.10 mmol), and the mixture was heated at 50 ℃ for 10 min. Cyclohexene (10 μL, 0.10 mmol) and **1** (15.6 μL, 0.100 mmol) were then added, and the mixture was heated at 45 ℃ for 90 min. The mixture was cooled to 23 ℃ and analyzed by ^1H NMR spectroscopy with 1,3,5-trimethoxybenzene as the internal standard.

Competition Experiments

To a 4-mL vial was added the rhodium catalyst **I** (0.6 mg, 0.5 μmol), THF (56 μL), $HSiMe(OSiMe_3)_2$ (14 μL, 0.05 mmol), cyclohexene (5 μL, 0.05 mmol), and two arenes (0.3 mmol each), in this order. The mixture was heated at 45 ℃ for 16 h. The relative rate of reaction between two arenes was determined by measuring the ratio of two products by GC. However, the relative rate of reaction between 1,3-bis(trifluoromethyl)benzene (**1**) and 5-D-1,3(trifluoromethyl)benzene (**1-*d*$_1$**) cannot be determined this way because the silylation products from those two arenes are identical. Thus, the relative rate of reaction between **1** and **1-*d*$_1$** was determined indirectly by allowing each arene to compete against a common third arene, 1,3-xylene (Scheme S1). The ratio of the relative rates between **1** and 1,3-xylene and between **1-*d*$_1$** and 1,3-xylene is the estimated relative rate between **1** and **1-*d*$_1$** (4.7/1.6 = 2.9).

Scheme S1. Competition experiment between **1** and 1,3-xylene and between **1-*d*$_1$** and 1,3-xylene.



Quantitative Estimation of KIE for a Partially Reversible C-H Bond Cleavage Step

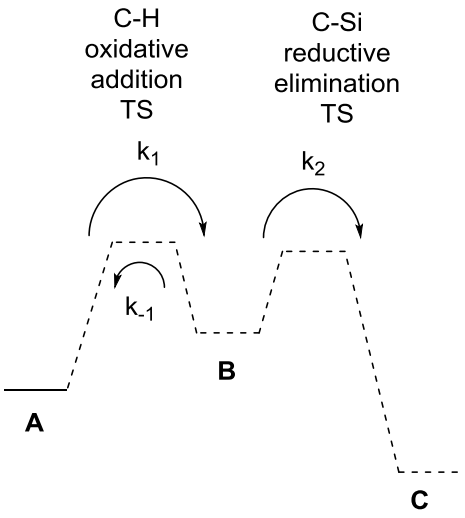


Figure S6. Qualitative free energy diagram for the C-H activation and C-Si reductive elimination steps.

The observed rate of the reaction of A → C is

$$rate = k_2 \cdot [B]$$

Applying steady state assumption for B yields

$$\Delta[B] = 0 = k_1 \cdot [A] - k_{-1} \cdot [B] - k_2 \cdot [B]$$

Solving for [B] yields

$$[B] = \frac{k_1 \cdot [A]}{k_{-1} + k_2}$$

Substituting the expression of [B] into the rate expression yields

$$rate = k_2 \cdot [B] = \frac{k_2 \cdot k_1 \cdot [A]}{k_{-1} + k_2}$$

The reaction of **1-*d*$_1$** with DSiMe(OSiMe$_3$)$_2$ at 13% conversion gave 12% of the silylarene product and 11% of deuterated starting arene (Scheme 5 in the main text). From these data, one can assume that the barrier for the C-H reductive elimination (i.e. the reverse of oxidative addition of C-H bond) and the barrier for the C-Si reductive elimination are similar, i.e.

$$k_{-1(H)} = k_2$$

Assuming that the isotope effect for the C-H oxidative addition (based on the KIE of reaction with toluene and toluene-d_8) is

$$\frac{k_{1(H)}}{k_{1(D)}} = 5$$

Let the equilibrium isotope effect of the C-H oxidative addition be *x*, the kinetic isotope effect for the C-H reductive elimination is then:

$$\frac{k_{-1(H)}}{k_{-1(D)}} = \frac{5}{x}$$

The observed rate of reaction for the protio-substrate is

$$rate(H) = k_2 \cdot [B] = \frac{k_2 \cdot k_{1(H)} \cdot [A]}{k_{-1(H)} + k_2} = \frac{k_2 \cdot k_{1(H)} \cdot [A]}{k_2 + k_2} = \frac{k_2 \cdot k_{1(H)} \cdot [A]}{2 \cdot k_2} = \frac{k_{1(H)} \cdot [A]}{2}$$

The observed rate of reaction for the deutero-substrate is

$$rate(D) = k_2 \cdot [B] = \frac{k_2 \cdot k_{1(D)} \cdot [A]}{k_{-1(D)} + k_2} = \frac{k_2 \cdot \frac{1}{5} \cdot k_{1(H)} \cdot [A]}{\frac{x}{5} \cdot k_{-1(H)} + k_2} = \frac{k_2 \cdot \frac{1}{5} \cdot k_{1(H)} \cdot [A]}{\frac{x}{5} \cdot k_2 + k_2} = \frac{k_{1(H)} \cdot [A]}{5 + x}$$

The relative rate of reaction between the protio- and deutero-substrates (KIE) is

$$KIE = \frac{rate(H)}{rate(D)} = \frac{\frac{k_{1(H)} \cdot [A]}{2}}{\frac{k_{1(H)} \cdot [A]}{5 + x}} = \frac{5 + x}{2}$$

A usual EIE (*x*) for the C-H oxidative addition is 1.25-2.[63] Let *x* = 1.5,

$$KIE = \frac{5 + x}{2} = \frac{5 + 1.5}{2} = 3.25$$

The estimated KIE value (3.3) agrees well with the experimental value (2.9), although the nearly exact agreement is fortuitous because of the many estimated parameters. However, this analysis shows that the KIE for a partially reversible reaction ($k_{-1} = k_2$) can be large.

The Effect of Ligands on the Product Distribution (Scheme 9)

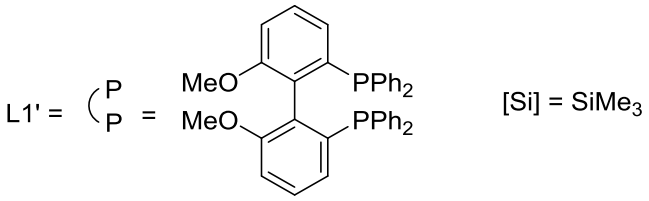
To a 4-mL vial was added $[Rh(coe)_2OH]_2$ (0.33 mg, 0.50 μmol), ligand (**L3** or **L4**, 1.1 μmol), THF (100 μL), $HSiMe(OSiMe_3)_2$ (14 μL, 0.050 mmol), cyclohexene (25 μL, 0.25 mmol), 1,2-xylene (30 μL, 0.25 mmol), and the mixture was heated at 45 ℃ for 16 h. The ratio of silylarene to silylcyclohexane was determined by GC analysis.

Silylation of 2-(Trifluoromethyl)anisole with $DSiMe(OSiMe_3)_2$ (Scheme 10)

To a 4-mL vial was added $[Rh(coe)_2OH]_2$ (0.33 mg, 0.50 μmol), **L2** (1.3 mg, 1.1 μmol), THF (120 mg), $DSiMe(OSiMe_3)_2$ (14 μL, 0.050 mmol), cyclohexene-d_{10} (5 μL, 0.05 mmol), and 2-(trifluoromethyl)anisole (74 μL, 0.5 mmol), and the mixture was heated at 50 ℃ for 14 h. The mixture was cooled to 23 ℃ and analyzed by ^1H and ^2H NMR spectroscopy.

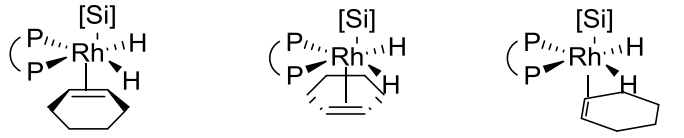
Computational Details

DFT calculations were performed with the Gaussian 09 software package. Geometry optimization of all the minima and transition states was conducted with M06 functionals, the lanl2dz basis set for rhodium, and the 6-31g(d,p) basis set for all other atoms. Bond orders were calculated by applying natural bond orbital (NBO) analysis to the optimized structures. A simplified ligand, **L1'**, (PAr_2 = PPh_2) and a simplified silane ([Si] = $SiMe_3$) were used for calculations. Cartesian coordinates and Gibbs energy are given.



Binding of cyclohexene to I'

Geometry optimizations were initiated with the following structures (Rh-C set to ~2.3 Å), representing three possible ways of binding of cyclohexene to rhodium silyl dihydride **I'**. In the optimized structures, the C-Si distances are > 3.5 Å, and the π-orbitals of the alkene are not oriented toward the rhodium centers, suggesting very little bonding interaction between the alkene and rhodium (Figure S7).



I'-ene A	**I'**-ene B	**I'**-ene C
Rh-C1: 3.684 Å	Rh-C1: 3.550 Å	Rh-C1: 3.726 Å
Rh-C2: 4.278 Å	Rh-C2: 3.839 Å	Rh-C2: 4.390 Å

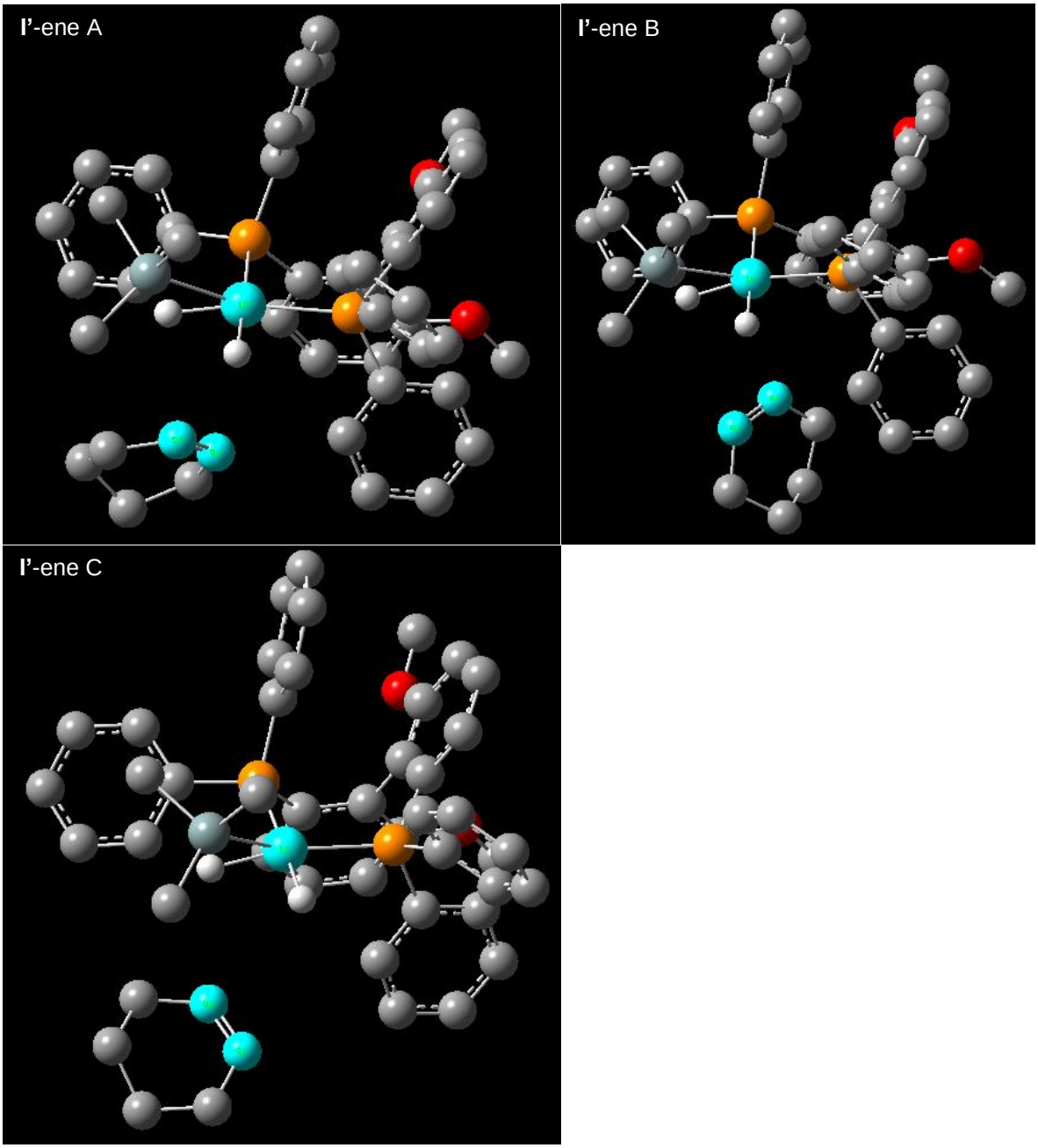
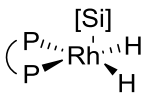


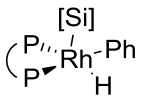
Figure S7. Comparison of three DFT-optimized structures of the attempted binding of cyclohexene to **I'**. The rhodium and alkenyl carbon atoms are highlighted in cyan.



I'

G = -2818.440705 Hatrees

C	-1.63583600	-2.07921500	3.28115200
C	-1.21652600	-2.44114900	2.00300500
C	-1.22717700	-1.51287600	0.94249200
C	-1.68189500	-0.20707900	1.19549300
C	-2.11093100	0.14449600	2.48079600
C	-2.08546200	-0.78537600	3.50825700
C	-0.80664800	-2.00699700	-0.40432600
C	-1.72269000	-2.81829700	-1.10356200
C	-1.40870300	-3.34906800	-2.35215100
C	-0.15665000	-3.10139100	-2.90006300
C	0.76796800	-2.32144800	-2.22427800
C	0.45253400	-1.76286100	-0.97987500
O	-0.76331100	-3.68200000	1.69569100
O	-2.91074000	-3.03282200	-0.48452400
C	-3.85629200	-3.84077400	-1.13608000
C	-0.69062500	-4.63350900	2.72556000
P	-1.50361100	1.10421300	-0.09486600
P	1.58243100	-0.50169700	-0.23458100
Rh	0.71193200	1.65319000	-0.68430800
C	2.92479500	4.63418800	-1.13044800
C	-2.46800700	0.45324800	-1.50787100
C	-3.69973700	-0.18842300	-1.34207300
C	-4.40086100	-0.65325900	-2.44937900
C	-3.86313600	-0.50817400	-3.72657100
C	-2.63045600	0.11325300	-3.89701200
C	-1.93769200	0.59962600	-2.79260100
C	-2.51920200	2.48633700	0.56104900
C	-3.84520700	2.72853500	0.20076400
C	-4.53119300	3.81589600	0.73614300
C	-3.90554900	4.66421500	1.64220200
C	-2.58228600	4.42925900	2.00862600
C	-1.89343600	3.35489100	1.46218400
C	3.21243300	-0.81575100	-1.03946500
C	4.28808100	-1.45202300	-0.41729700
C	5.51900800	-1.55613200	-1.06097800
C	5.68880800	-1.03489500	-2.33743700
C	4.62303400	-0.39883100	-2.96982500
C	3.40146000	-0.27855100	-2.31993600
C	1.83070000	-1.11757300	1.47656700
C	1.78997800	-0.20167100	2.52989300
C	1.99626900	-0.62442700	3.84009100
C	2.25784600	-1.96476800	4.10380200
C	2.30462100	-2.88513000	3.05806900
C	2.08041300	-2.46619500	1.75172500
H	-1.61321700	-2.79565100	4.09654500
H	-2.46932500	1.15087600	2.67942700
H	-2.42234300	-0.50206100	4.50311000
H	-2.12521300	-3.95917400	-2.89309700
H	0.09869900	-3.52800100	-3.86770200
H	1.74408200	-2.14536600	-2.66777100
H	-3.48099200	-4.86295400	-1.28962000
H	-4.14745300	-3.41696100	-2.10895700
H	-4.73400300	-3.87668600	-0.48635300
H	-1.67992300	-4.84684500	3.15554700
H	-0.01264600	-4.30558800	3.52834100
H	-0.29440200	-5.54692800	2.27547900
H	2.11016300	2.11209000	-1.40805300
H	0.11706800	3.11096500	-1.09250600
H	3.44771300	4.31098500	-2.03819300
H	2.01718700	5.16659300	-1.43855300
H	3.57438200	5.33874100	-0.59429600
H	-4.09947500	-0.34299900	-0.33976300
H	-5.36676200	-1.13734100	-2.31454300
H	-4.40913500	-0.88009000	-4.59117600
H	-2.20596400	0.22168000	-4.89244200
H	-0.96703400	1.08667000	-2.90795600
H	-4.34586900	2.07929500	-0.51409800
H	-5.56116200	4.00060200	0.43866300
H	-4.44461900	5.51294800	2.05721000
H	-2.07986500	5.09279700	2.70931500
H	-0.85027400	3.18015100	1.72479400
H	4.17882600	-1.85376400	0.58733100
H	6.34935100	-2.04436400	-0.55538100
H	6.65156700	-1.11528200	-2.83732000
H	4.74895000	0.02132600	-3.96526500
H	2.57957700	0.25718600	-2.79640000
H	1.57308500	0.84446700	2.30742800
H	1.95418900	0.09485700	4.65472500
H	2.42891000	-2.29511100	5.12627000
H	2.51447600	-3.93381100	3.26240000
H	2.08893000	-3.19074500	0.93749700
C	1.73885500	3.93842300	1.54159900
H	2.50258700	4.58308600	2.00192800
H	1.43366400	3.19382000	2.28657100
C	4.09134900	2.32794200	0.48563200
H	4.60176700	1.86720100	-0.37004000
H	3.93206500	1.54410200	1.23746500
H	4.76899800	3.07378400	0.92405800
H	0.87125600	4.55963000	1.29022100
Si	2.47454300	3.16831100	-0.03084900



VII'

G = -3049.238990 Hatrees

C	3.18097800	-2.16161900	2.56958400
C	3.16713200	-1.76527700	1.23490300
C	1.97548800	-2.38078500	3.22300300
H	4.11798400	-2.30794200	3.09765900
C	1.95349900	-1.55796200	0.54996800
O	4.29405300	-1.54106900	0.51442300
C	0.76953700	-2.18459000	2.56823700
H	1.97971900	-2.71012900	4.25976400
C	0.74425500	-1.75943300	1.23435800
C	2.03478400	-1.19796900	-0.89590500
C	5.53186400	-1.73284500	1.14905500
H	-0.15816900	-2.37406200	3.09899400
P	-0.85464300	-1.31758600	0.40937500
C	2.36638900	-2.22766400	-1.79927400
C	1.84976500	0.10425100	-1.38773900
H	5.65573100	-2.76872000	1.49635100
H	5.65655000	-1.05122700	2.00426300
H	6.29907300	-1.51321900	0.40293400
Rh	-1.15094900	0.96996200	-0.14230800
C	-0.90826600	-2.48098600	-1.00537300
C	-2.12534300	-1.96015900	1.56441900
C	2.48845300	-1.97187100	-3.16324100
O	2.54212600	-3.45643800	-1.25367600
C	1.99788900	0.35555600	-2.75707800
P	1.16834500	1.41506900	-0.27168800
C	-0.51089600	-3.81492300	-0.86620900
C	-1.35099900	-2.02182800	-2.24790700
C	-3.01086100	-2.98532100	1.23230600
C	-2.30459300	-1.27869900	2.77460100
C	2.30957900	-0.67565100	-3.62955700
H	2.72926400	-2.76890500	-3.85982000
C	2.84910600	-4.52303500	-2.11429700
H	1.87117800	1.36271400	-3.14406400
C	1.50401300	2.99176100	-1.17331100
C	2.36832500	1.47341200	1.11639300
C	-0.55481400	-4.67492800	-1.95685200
H	-0.15481000	-4.17513600	0.09887800
C	-1.37717500	-2.88058400	-3.34288500
H	-1.67662000	-0.98668800	-2.34750100
C	-4.04870200	-3.32589600	2.09698200
H	-2.90561900	-3.50951500	0.28493100
C	-3.32896000	-1.62794900	3.64391700
H	-1.64530200	-0.44565600	3.01954000
H	2.41984500	-0.46956900	-4.69207900
H	3.81294300	-4.37225700	-2.62175400
H	2.06154800	-4.67098600	-2.86853800
H	2.91105600	-5.41653600	-1.48817700
C	2.47638700	3.91769700	-0.78978900
C	0.65234300	3.32241700	-2.23710800
C	1.87357700	1.59586900	2.41649400
C	3.75129400	1.43339500	0.91064900
C	-0.97815800	-4.20509300	-3.19875100
H	-0.25017000	-5.71363000	-1.84021000
H	-1.71530800	-2.51259100	-4.30869900
C	-4.20866800	-2.65322800	3.30253600
H	-4.73866300	-4.11977000	1.81996800
H	-3.45359400	-1.08485700	4.57832200
C	2.59793800	5.13635400	-1.45370600
H	3.13446400	3.70492100	0.04885400
C	0.78472400	4.52931200	-2.91098200
H	-0.13966700	2.62806700	-2.51974100
C	2.74605600	1.68037300	3.49780200
H	0.79323300	1.60446500	2.57099500
C	4.62244000	1.53000900	1.98955700
H	4.14354500	1.31810000	-0.09956100
H	-1.00436100	-4.87775300	-4.05378700
H	-5.02298000	-2.91939900	3.97258200
C	1.75819100	5.44426100	-2.51633400
H	3.35257400	5.84967100	-1.12952300
H	0.11529000	4.76311000	-3.73571200
C	4.12011800	1.65051300	3.28396400
H	2.35136000	1.76972600	4.50726800
H	5.69800000	1.51166800	1.82100200
H	1.85381400	6.39762000	-3.03116000
H	4.80363100	1.72327600	4.12729800
H	-1.45314300	2.52086100	-0.63589200
C	-3.15633600	0.64982200	-0.61291800
C	-3.50847900	0.96824800	-1.93766900
C	-4.19024900	0.18690200	0.21077400
C	-4.80712000	0.81539900	-2.41631900
H	-2.74819500	1.36276600	-2.61710000
C	-5.49764700	0.04203800	-0.25603700
H	-3.99000000	-0.06390200	1.25235800
C	-5.81431700	0.35199300	-1.57341100
H	-5.03638000	1.07324700	-3.44994700
H	-6.27087300	-0.31933700	0.42164700
H	-6.83307300	0.24054500	-1.93965500
Si	-2.00402000	2.99609900	0.94102300
C	-3.55542200	3.85151800	0.29381500
C	-0.70779700	4.33846500	1.25030200
C	-2.44767200	2.30028400	2.64827300
H	-3.36888300	4.32729000	-0.67680100
H	-4.37679800	3.13740200	0.16383700
H	-3.87820900	4.62880900	0.99935700
H	-0.41466000	4.84319300	0.32115300
H	0.20210300	3.94017600	1.71839400
H	-1.12509600	5.09480600	1.92966700
H	-3.25777600	1.56547100	2.58652400
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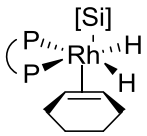
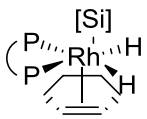
H	-1.58875100	1.83858800	3.14959900



I'-ene A

G = -3052.773201 Hatrees

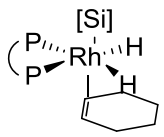
C	4.08466700	-2.23105100	1.12652400
C	2.96321600	-1.72289500	1.77829100
C	2.19152900	-0.69175000	1.20663700
C	2.57001700	-0.18703800	-0.04814100
C	3.69938200	-0.70269400	-0.69636700
C	4.44688500	-1.71131400	-0.10904600
C	1.04943400	-0.16759800	2.01784600
C	1.36728700	0.67026000	3.10569700
C	0.37444000	1.16804000	3.94783900
C	-0.94478800	0.78737700	3.73970100
C	-1.28057600	-0.05276200	2.68998500
C	-0.29643600	-0.52594100	1.81536400
O	2.53214900	-2.18138100	2.97964100
O	2.68465100	0.94921000	3.27119200
C	3.04990000	1.79650600	4.32910700
C	3.26274000	-3.21084100	3.59389200
P	1.48654400	1.02322600	-0.92668900
P	-0.80460000	-1.35514100	0.24466900
Rh	-0.71192100	0.31972400	-1.41558200
C	-3.39501500	0.61391800	-3.99073400
C	1.56121600	2.50551500	0.14644500
C	2.70199900	2.83922000	0.88358700
C	2.71104200	3.98051300	1.67844200
C	1.57685400	4.78565400	1.75892200
C	0.43900800	4.45893500	1.02801400
C	0.43453100	3.32777700	0.21792600
C	2.49925400	1.48123900	-2.38655100
C	3.42994900	2.52110700	-2.40292900
C	4.17152400	2.77817000	-3.55315200
C	3.99601300	1.99658600	-4.69049300
C	3.07020900	0.95659200	-4.68072000
C	2.32407500	0.70690400	-3.53618400
C	-2.49310600	-2.03481500	0.55446400
C	-2.76387000	-3.40146700	0.65223400
C	-4.07520900	-3.86378000	0.73660400
C	-5.13671300	-2.96842700	0.72635800
C	-4.88060000	-1.60260000	0.63036400
C	-3.57402500	-1.14030800	0.53684100
C	0.23568300	-2.86444900	0.16502000
C	0.84693100	-3.18107800	-1.04970900
C	1.61542100	-4.33553400	-1.17197300
C	1.76868400	-5.18678600	-0.08300100
C	1.16207200	-4.87890600	1.13375500
C	0.40891000	-3.71730400	1.26085500
H	4.67099800	-3.02845800	1.57304700
H	3.99771600	-0.31180200	-1.66537100
H	5.32545800	-2.10130100	-0.61839800
H	0.62360900	1.82735500	4.77295500
H	-1.72285600	1.15981100	4.40399400
H	-2.32091600	-0.32986400	2.53929100
H	2.78875700	1.36472200	5.30616300
H	2.57574400	2.78479700	4.23462400
H	4.13462900	1.91550200	4.26968000
H	4.29563700	-2.90346300	3.81327900
H	3.28700200	-4.11776000	2.97090200
H	2.75158000	-3.43540300	4.53276800
H	-2.31893000	0.11638300	-1.65940500
H	-0.72637700	1.53987900	-2.50272600
H	-4.26247700	0.60185700	-3.31802700
H	-3.06141100	1.65417300	-4.08701200
H	-3.72611700	0.26324300	-4.97696000
H	3.57801800	2.19170500	0.85037300
H	3.60598000	4.24032600	2.24156000
H	1.58319400	5.67220200	2.38974000
H	-0.45304500	5.07918100	1.08751200
H	-0.44832600	3.06447400	-0.36593600
H	3.57109700	3.14206800	-1.52032400
H	4.88756900	3.59708600	-3.56012500
H	4.57510000	2.20398500	-5.58768500
H	2.91667700	0.34681500	-5.56882700
H	1.58116500	-0.08952700	-3.52244200
H	-1.95075900	-4.12286200	0.63947800
H	-4.26265500	-4.93345800	0.80053800
H	-6.16060300	-3.33096400	0.78323900
H	-5.70505000	-0.89145500	0.60746100
H	-3.38766300	-0.06942100	0.43437500
H	0.72710300	-2.49608600	-1.89165200
H	2.09368000	-4.57013400	-2.12025400
H	2.36165900	-6.09374000	-0.18021400
H	1.27675700	-5.54708400	1.98563000
H	-0.04866200	-3.46680700	2.21784500
C	-0.73518100	-0.63426500	-4.70659400
H	-1.26483200	-1.00200300	-5.59801400
H	0.04910000	-1.36152400	-4.46319400
C	-2.70094600	-2.20712700	-3.04895500
H	-3.55448300	-2.20364700	-2.35866800
H	-1.94493800	-2.88926900	-2.63747600
H	-3.03934900	-2.62164900	-4.00876500
H	-0.26581100	0.32482900	-4.95078500
Si	-2.00343300	-0.46546600	-3.30528700
C	-2.89345400	2.65709200	1.42740100
H	-1.83193600	2.64269500	1.68316100
C	-3.27050400	2.44910700	0.16186100
H	-2.51331200	2.28075500	-0.61124100
C	-4.70620900	2.35395700	-0.26436500
H	-4.97898400	3.23844800	-0.86299000
H	-4.82381300	1.49652800	-0.94649000
C	-3.86531500	2.88560400	2.54765100
H	-3.90556500	1.98520000	3.18680200
H	-3.50205800	3.69046400	3.20293300
C	-5.64421800	2.21660300	0.93123700
H	-6.68849100	2.34821400	0.62128500
H	-5.55885000	1.19653100	1.34180800
C	-5.26335700	3.20226400	2.02800700
H	-5.99246500	3.18123400	2.84778200
H	-5.27665500	4.22300900	1.61589100



I'-ene B

G = -3052.772852 Hatrees

C	-2.27720700	4.11255700	-0.38355900
C	-1.86698800	3.08810600	-1.23274500
C	-0.81701400	2.21492500	-0.87428400
C	-0.20351200	2.38039100	0.37950800
C	-0.62259800	3.41909700	1.22295900
C	-1.64311200	4.27352500	0.84023700
C	-0.42665700	1.20986800	-1.91212400
C	0.30438900	1.68655600	-3.01846200
C	0.58819400	0.86541300	-4.10700400
C	0.10727800	-0.43705300	-4.11683600
C	-0.60628700	-0.93410300	-3.03726200
C	-0.86860000	-0.12574800	-1.92556700
O	-2.44238000	2.85107600	-2.43827500
O	0.68752000	2.98836500	-2.95723000
C	1.60117500	3.45144600	-3.91876300
C	-3.51933600	3.66340900	-2.82823300
P	0.97081200	1.11887400	1.05225700
P	-1.56124200	-0.87420300	-0.38224100
Rh	0.20002200	-1.10798000	1.17537500
C	0.59849500	-4.11342800	3.33106300
C	2.52883200	1.32761100	0.10877100
C	2.78093600	2.42286000	-0.72091700
C	4.03171700	2.57765300	-1.31399600
C	5.04346700	1.65361700	-1.06962000
C	4.79956700	0.56715500	-0.23375800
C	3.54726300	0.39822700	0.34605100
C	1.44511400	1.85004800	2.66830800
C	2.48747300	2.76733200	2.81544700
C	2.76378500	3.31613200	4.06446900
C	1.99945000	2.96006100	5.17145100
C	0.95649400	2.04838000	5.03026700
C	0.68579400	1.49567600	3.78463200
C	-2.29441700	-2.47144700	-0.93875500
C	-3.66735700	-2.70939700	-1.02334500
C	-4.14901700	-3.97600500	-1.34656300
C	-3.26672900	-5.01848600	-1.60021700
C	-1.89424400	-4.79356100	-1.52097000
C	-1.41336100	-3.53626400	-1.17873200
C	-3.02528400	0.16875700	-0.01535600
C	-3.21677300	0.58961500	1.30203100
C	-4.32068100	1.36636100	1.64109000
C	-5.24585500	1.71968100	0.66441000
C	-5.06172200	1.30638000	-0.65394800
C	-3.94989000	0.54483000	-0.99618200
H	-3.08690400	4.77899300	-0.66458600
H	-0.15213500	3.55913800	2.19160000
H	-1.95468900	5.07632000	1.50485100
H	1.15524400	1.24004000	-4.95343600
H	0.30259400	-1.07458200	-4.97685900
H	-0.95650000	-1.96229300	-3.05808000
H	1.16218800	3.47471000	-4.92660400
H	2.51032000	2.83122100	-3.93642200
H	1.86788700	4.47057800	-3.62675000
H	-3.22197200	4.71750900	-2.92541500
H	-4.35639700	3.59148700	-2.11710600
H	-3.84709500	3.29519000	-3.80317800
H	0.00754000	-2.73275100	1.14891600
H	1.46017900	-1.32512200	2.18987800
H	0.70942400	-4.84362300	2.51977100
H	1.59496300	-3.71915000	3.56440100
H	0.22002500	-4.64176000	4.21609900
H	2.00017800	3.16040200	-0.90086000
H	4.22221200	3.43777600	-1.95396900
H	6.02252300	1.78278100	-1.52603800
H	5.58552700	-0.15932900	-0.03561400
H	3.34615500	-0.45959400	0.98708200
H	3.08824900	3.05185300	1.95240300
H	3.58119700	4.02574300	4.17267400
H	2.21992900	3.38989300	6.14616000
H	0.35849400	1.75755500	5.89182100
H	-0.11634300	0.76975700	3.66194600
H	-4.37468100	-1.90987000	-0.81510100
H	-5.22251600	-4.14535700	-1.39448400
H	-3.64496100	-6.00690500	-1.85145200
H	-1.19391800	-5.60411000	-1.70961500
H	-0.33803700	-3.37796600	-1.08337100
H	-2.47286000	0.31305000	2.05182400
H	-4.45772600	1.69603700	2.66841000
H	-6.11431000	2.31924000	0.92913800
H	-5.78639100	1.58149300	-1.41860100
H	-3.78715000	0.25056000	-2.03325300
C	-0.79500200	-1.66194100	4.39906200
H	-1.18446000	-2.32639800	5.18479400
H	-1.52232400	-0.85316500	4.25734300
C	-2.25851500	-3.45315800	2.46767700
H	-2.23082000	-4.12436700	1.59979100
H	-3.00269100	-2.67353800	2.25745100
H	-2.61094400	-4.02611200	3.33648900
H	0.15150700	-1.23325300	4.74651600
Si	-0.55754300	-2.70587800	2.83147300
C	2.47942400	-2.18305900	-1.32455300
H	1.55246400	-1.68154800	-1.02235600
C	2.96566700	-3.14687200	-0.53640100
H	2.40948500	-3.41643600	0.36449800
C	4.26942300	-3.84026600	-0.80449100
H	4.81630100	-3.98216400	0.13842900
H	4.08483600	-4.85741600	-1.18950800
C	3.14444200	-1.71830300	-2.58335500
H	2.39829600	-1.63819000	-3.38658000
H	3.51499200	-0.68792800	-2.43153800
C	5.11939500	-3.05763500	-1.80054200
H	5.50529700	-2.15112700	-1.30792800
H	5.99235700	-3.64667300	-2.11010900
C	4.28350200	-2.64323000	-3.00486400
H	3.86233600	-3.54878300	-3.46950200
H	4.90638200	-2.16030600	-3.76881700



I'-ene C

G = -3052.769667 Hatrees

C	4.83656500	0.39534400	0.84335200
C	3.99714500	0.62937600	-0.24336400
C	2.75509500	-0.02464100	-0.35960800
C	2.37072600	-0.92110700	0.65180300
C	3.21925200	-1.15007100	1.74132600
C	4.43900800	-0.49744400	1.82980200
C	1.95618400	0.23248300	-1.59750100
C	2.38541300	-0.40452300	-2.78027400
C	1.71788000	-0.20908600	-3.98716200
C	0.63124800	0.65484000	-4.03070200
C	0.20000300	1.30505900	-2.88598900
C	0.84894900	1.09740400	-1.66303200
O	4.30005000	1.49565100	-1.24246000
O	3.46933400	-1.21149900	-2.65780100
C	3.92825900	-1.87570800	-3.80647600
C	5.51209800	2.19997400	-1.16343900
P	0.66834500	-1.63544900	0.64543300
P	0.05594700	1.70858300	-0.10909400
Rh	-1.12708500	-0.12304200	0.78930900
C	-4.49321900	0.13534800	2.36822200
C	0.62215500	-2.59211500	-0.91530700
C	1.71399100	-3.33455700	-1.37598400
C	1.62005800	-4.04688000	-2.56676700
C	0.45125500	-3.99461900	-3.32392200
C	-0.63372600	-3.24559600	-2.87861000
C	-0.55085800	-2.55707100	-1.67329800
C	0.74047900	-2.89940600	1.97219700
C	1.01298400	-4.25094700	1.76013800
C	1.03255700	-5.13951300	2.83280500
C	0.79207700	-4.68599100	4.12456400
C	0.52096000	-3.33764800	4.34519300
C	0.48623000	-2.45497800	3.27388700
C	-0.99681600	3.13487500	-0.62333500
C	-2.23388600	2.84745200	-1.21682500
C	-3.12117500	3.86278800	-1.54988500
C	-2.80121200	5.18832000	-1.26686600
C	-1.58822400	5.48556500	-0.65875500
C	-0.69072700	4.46833600	-0.34293600
C	1.41946900	2.51219500	0.81848300
C	1.52333900	2.25123000	2.18636300
C	2.51941800	2.85688500	2.94681200
C	3.41303400	3.73695300	2.34596700
C	3.31564400	4.00582800	0.98175100
C	2.33038800	3.38947200	0.21879500
H	5.78946500	0.90875900	0.92780100
H	2.92576100	-1.84321800	2.52512800
H	5.09367200	-0.68584900	2.67791800
H	2.04082800	-0.71507800	-4.89146600
H	0.11761700	0.82202300	-4.97501400
H	-0.64841800	1.98162800	-2.94309800
H	4.26318900	-1.16884100	-4.57935100
H	3.15111200	-2.52999100	-4.22913200
H	4.77670600	-2.48839200	-3.49166500
H	6.37986300	1.52460600	-1.17190000
H	5.55549600	2.82745300	-0.26003900
H	5.55392000	2.84199700	-2.04639400
H	-2.53219800	0.71102400	0.65960700
H	-1.97852500	-1.40312400	1.33136100
H	-5.03466300	0.62921600	1.55016300
H	-4.54190600	-0.94666800	2.19404100
H	-5.01562200	0.36343100	3.30657100
H	2.64426300	-3.33751100	-0.80798700
H	2.46766600	-4.63681100	-2.91198300
H	0.38731500	-4.54271400	-4.26177700
H	-1.54836400	-3.19429100	-3.46594600
H	-1.39518300	-1.97448200	-1.30136100
H	1.19590000	-4.62142300	0.75373300
H	1.23494200	-6.19330100	2.65361700
H	0.80678300	-5.38345900	4.95910100
H	0.31980300	-2.97426800	5.35082400
H	0.24788200	-1.40339800	3.43498000
H	-2.51101800	1.80842300	-1.39754000
H	-4.07321800	3.61713000	-2.01606600
H	-3.50137900	5.98409800	-1.51074300
H	-1.33506900	6.51640300	-0.42045700
H	0.24581600	4.72346900	0.14651600
H	0.81864100	1.55242900	2.64170700
H	2.59595200	2.64180300	4.01022300
H	4.18754800	4.21706900	2.94031600
H	4.01164700	4.69848300	0.51117200
H	2.27195100	3.58086000	-0.85266100
C	-1.98104700	0.07249200	4.05726500
H	-2.58284700	0.47712700	4.88458700
H	-0.94219000	0.38840100	4.21265500
C	-2.71940200	2.60668600	2.56367600
H	-3.20605700	3.06388600	1.69111300
H	-1.70379200	3.01950800	2.62629100
H	-3.26497400	2.91912500	3.46464500
H	-2.02511500	-1.02178700	4.09728800
Si	-2.69762600	0.71794000	2.42324800
C	-4.31981800	-2.08397500	-1.49867200
H	-3.53117800	-2.83850700	-1.47302600
C	-3.98900700	-0.79096800	-1.50084000
H	-2.93254400	-0.50581100	-1.49247700
C	-4.99598500	0.31947100	-1.44698300
H	-4.65957300	1.07691800	-0.71846200
H	-5.03083200	0.84021800	-2.42020600
C	-5.73877200	-2.57094700	-1.50553300
H	-5.84503700	-3.41199500	-2.20549600
H	-5.98672200	-2.98317900	-0.51300600
C	-6.38481700	-0.19214300	-1.07681000
H	-6.40316200	-0.42700800	-0.00087700
H	-7.13913100	0.58712700	-1.24414200
C	-6.71600200	-1.45537600	-1.86115500
H	-6.64348600	-1.23894400	-2.93851400
H	-7.74844700	-1.77547300	-1.67215700

4.5 References and Notes

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"Mechanism of the Rhodium-Catalyzed Silylation of Arene C–H Bonds"
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[34] Natural bond orbital (NBO) analysis on the DFT-optimized ground state structure of I', a simplified model (PAr2 = PPh2; [Si] = SiMe3) of rhodium silyl dihydride I, yields a bond order of 0.4211 for the Si-H bond. See the SI for details.
[35] Because the ligand is chiral, the two phosphorous and two hydrides would be inequivalent, even if the silyl group assumed an idealized axial position.
[36] The silylation of 1,3-xylene is also zero-order in the concentration of the arene (see the SI), suggesting that reactions of electron-rich and electron-deficient arenes occur by the same mechanism.
[37] For a quantitative estimation of the KIE for partially reversible reactions, see the SI.
[38] Deuterium exchange among the silane, cyclohexene, and 1,3-bis(trifluoromethyl)benzene (1) could complicate the KIE results because this process lowers the deuterium content in the starting arene. However, because the KIE experiments were conducted with excess arenes, and initial reaction rates (up to 5% conversion) were measured, the experimental results should be close to the true relative rates for reaction of 1,3-bis(trifluoromethyl)benzene and 1,3-bis(trifluoromethyl)benzene-d1.
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[42] The reaction with D[Si] was run with cyclohexene-d10 and 5-D-1,3-bis(trifluoromethyl)benzene to avoid erosion of the deuterium content of the silane caused by H-D exchange with cyclohexene and the arene.
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[47] Only the 4- and 5-positions are available for silylation. The 3- and 6-positions are not available because these C-H bonds have substituents ortho to them.
[48] CF3 A-value = 2.4-2.5, MeO A-value = 0.55-0.75. The large A-value of a trifluoromethyl group does not correctly reflect its size due to the stereoelectronic effect. However, it is generally accepted that a trifluoromethyl group is larger than a methoxy group.
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[55] Based on the rates of C-H activation (16:1 for the 5- vs 4-position) and the product distribution (1:50 for the 5- vs 4-position), the ratio of the rates of reductive elimination step is 1:800 favoring the 4-position. It is possible that this large ratio is not caused by the electronic effect alone, and detailed computational studies to probe the steric effect of the substituents on the rate of reductive elimination will be the focus of future studies.
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Chapter 5: Ir-Catalyzed Silylation of Aryl and Heteroaryl C-H Bonds

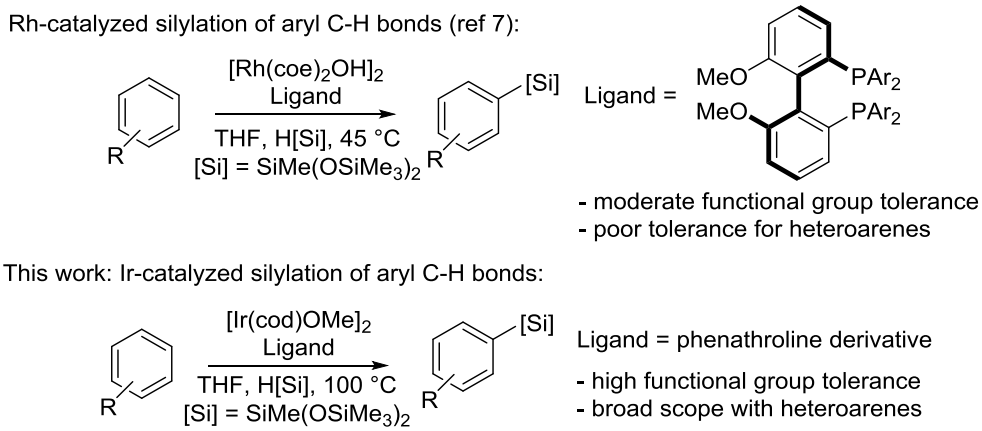
5.1 Introduction

The functionalization of aryl and alkyl C–H bonds with main group reagents, such as boranes and silanes, occurs with unique regioselectivity dictated by the catalysts and provides intermediates that can be derivatized to a wide range of products. Prompted by initial observations of the borylation of arenes and alkanes by isolated metal–boryl complexes,[1-3] the catalytic borylation of C–H bonds with Rh- and Ir-complexes has been reported, including practical borylations of aryl C–H bonds.[3-8] The mechanism of these reactions has been revealed in detail,[9] and applications of C–H borylation in the synthesis of several complex molecules have been reported.[10-12]

Silanes are produced on a larger scale than boranes and can serve as precursors to important commercial materials. Moreover, silanes can contain a broader combination of substituents than boranes and, with the proper choice of substituents, can generate valuable synthetic intermediates. However, the silylation of aryl C–H bonds is less developed than the borylation of aryl C–H bonds. Metal–silyl complexes are less reactive than metal–boryl complexes toward C–H bond functionalization, and most methods for the catalytic, intermolecular silylation of aryl C–H bonds require high temperatures, a large excess of the arene,[13-17] or the presence of directing groups.[18-23] Furthermore, trialkylsilanes have been the most commonly used Si source,[15, 19-23] and aryltrialkylsilanes have limited synthetic utility because they undergo a narrower range of reactions than do organoboranes.

In Chapter 3 we reported a Rh system that catalyzes undirected, intermolecular silylation of aryl C–H bonds (Scheme 21).[24] These reactions occurred with the inexpensive $HSiMe(OSiMe_3)_2$ as the Si source and with arene as the limiting reagent under mild conditions (45 °C). In addition, the arylsilane products are amenable to cross-coupling, oxidation, halogenation, and amination reactions because the silane reagent is activated by the two O-atoms connected to the Si.

Scheme 21. Silylation of Aryl C–H Bonds



However, two main drawbacks were evident from our studies on the Rh-catalyzed silylation of aryl C–H bonds. First, the reaction does not tolerate many of the common functional groups in medicinally important molecules, such as heavy halides, carbonyl groups, and cyano groups; also, the reactions did not occur at the C–H bonds of basic N-containing heteroarenes. Reactions of aryl bromides and iodides led predominantly to protodehalogention of the carbon–halogen bond, and reactions of arenes containing ketone and ester functionalities led to hydrosilylation of the carbonyl groups (tertiary amides were tolerated, however). Coordinating groups, such as nitriles or pyridines, poisoned the catalyst. Second, the chiral biaryl ligands in the Rh catalyst for arene silylation are much more expensive than the bipyridine and phenanthroline ligands in the Ir catalysts for arene borylation, and the cost of the ligands can affect the utility of the reaction on a large scale.

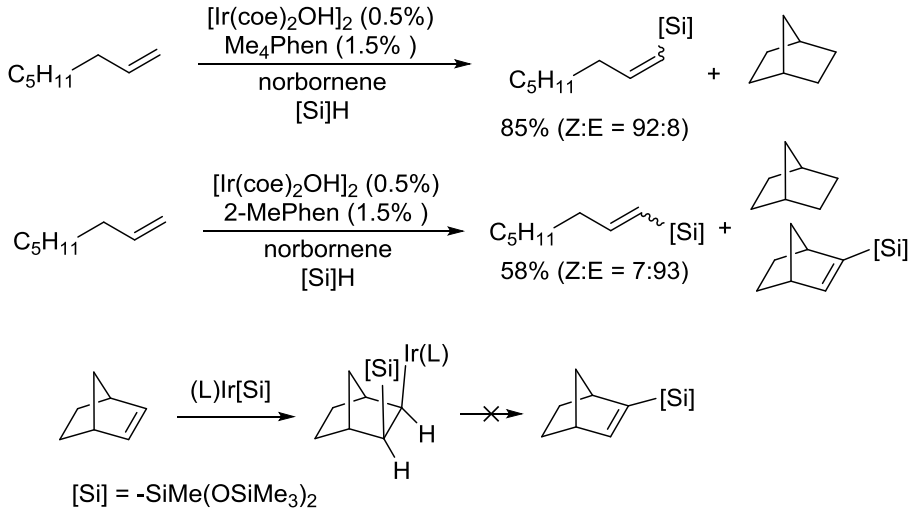
Here the discovery of a combination of an iridium precursor and appropriately substituted phenanthroline ligand that catalyzes the silylation of arenes and heteroarenes with high functional group compatibility and high tolerance for basic heterocycles is reported. This reactivity enables the silylation reaction to form building blocks for medicinal chemistry and to be used for the late-stage functionalization of compounds with biological activity.

5.2 Results and Discussion

To improve the functional group compatibility of the C–H silylation of arenes, we investigated Ir catalysts that might translate the high functional group compatibility of the Ir-catalyzed borylation reactions to the silylation of arenes and heteroarenes. To do so, we conducted silylations catalyzed by the combination of an Ir(I) precursor and various bidentate N-based ligands commonly used for the borylation of aryl C–H bonds.[3, 12] This combination of catalyst components has been reported to induce the silylation of aryl C–H bonds with several tetrafluorodisilanes, but the reactions were conducted with either neat arene or 10 equiv of arene.[13-14]

To test the activity of Ir catalysts for the silylation of arenes, we conducted the reaction of 1 equiv of *m*-xylene with 1.5 equiv of $HSiMe(OSiMe_3)_2$ at 80 °C in THF with a catalyst generated from $[Ir(cod)OMe]_2$ and 3,4,7,8-tetramethyl-1,10-phenanthroline (Me_4Phen). Although this ligand leads to the most active current catalyst for the borylation of aryl and alkyl C–H bonds,[12, 25-26] the corresponding silylxylene was obtained in only 10% yield, as determined by GC. This result implied that a different ligand was necessary for the silylation of arenes with broad scope.

Scheme 22. Dehydrogenative Silylation of Alkenes with Me_4Phen and 2-MePhen as the Ligand[27]



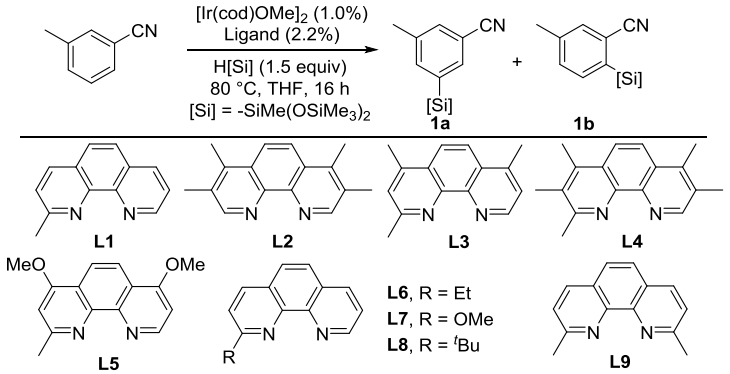
Several considerations pointed to a catalyst for the silylation of arenes in a synthetically valuable fashion. First, during our studies on the dehydrogenative silylation of alkenes,[27] we conducted reactions with a series of 2-substituted phenanthroline ligands and found that reactions catalyzed by complexes of 2-methyl-1,10-phenanthroline (2-MePhen, **L1**) generated a significant amount of product from dehydrogenative silylation of norbornene (Scheme 22). The dehydrogenative silylation of terminal alkenes catalyzed by complexes of Me_4Phen (**L2**) generated only the desired alkene silylation product and the hydrogenation byproduct norbornane. According to D-labeling experiments, the silylation of terminal alkenes occurs by *syn*-insertion and *syn*-β-H elimination.[27] However, this mechanism would not lead to the dehydrogenative silylation of norbornene because the fused-ring structure would inhibit the □-H elimination. Thus, the silylation of norbornene likely occurred by direct C–H activation. This logic led us to consider that 2-substituted phenanthrolines could generate a more active silyl complex for the activation of $C(sp^2)$–H bonds than would Me_4Phen.

Second, the functionalization of arenes with boron reagents occurs faster with electron-poor arenes than with electron-rich arenes.[6] Thus, we studied the silylation of 3-tolunitrile as a model substrate. This substrate is a suitable test of the method for several reasons. First, the nitrile group in this substrate, which can coordinate to the metal center, completely suppressed the Rh

catalyst for the C–H silylation.[24] Second, because the nitrile group contains unsaturation, this substrate would test the chemoselectivity of the catalyst toward C–H silylation vs hydrosilylation. Third, this substrate would test whether the regioselectivity is controlled by steric, electronic, or directing effects because the nitrile is small and strongly electron withdrawing and can serve as an *ortho*-directing group.[28-30] Finally, most functionalized arenes and basic heteroarenes are more electron deficient than benzene; thus, an arene containing an electron-withdrawing group could be a more appropriate model for an arene in a medicinally active compound than would *m*-xylene.

We evaluated the reaction of 3-tolunitrile with catalysts ligated by a series of phenanthroline ligands containing 2-substituents (Table 3). Reaction with 2-MePhen (**L1**) as the ligand at 80 °C in THF for 16 h afforded the desired product (**1a/b**) in 26% yield. Surprisingly, the silylation of 3-tolunitrile with Me_4Phen (**L2**) as the ligand did not give any desired product, even though reaction of *m*-xylene under similar conditions with **L2** formed the corresponding silylxylene in 10% yield. Varying the electronic property on the position *para* to the N-atoms led to a small increase in yields (**L3**–**L5**), with the highest yield obtained when 2,4,7-trimethyl-1,10-phenanthroline (**L3**) was the ligand. Varying the substituent at the 2-position led to decreased yields (**L6**–**L8**) of the arylsilane product. Except for the reaction with **L8** as the ligand, the yields were similar to the conversions.[31] The silylation reaction catalyzed by Ir-**L3** run with a hydrogen acceptor occurred in slightly higher yields than reactions without an acceptor (entry 10). Finally, the reaction conducted at 100 °C occurred to high conversion and afforded **1a/b** in 90% yield (entry 11). Reactions conducted with other hydrosilanes containing at least one alkoxy group connected to Si did not generate significant amounts of desired products (see the Supporting Information (SI)).

Table 3. Evaluation of Reaction Conditions



entry	ligand	conversion (%)[a]	yield (%)[a,b]	**1a**:**1b**[a]
1	**L1**	29	26	19:1
2	**L2**	6	0	-
3	**L3**	38	36	26:1
4	**L4**	39	35	26:1

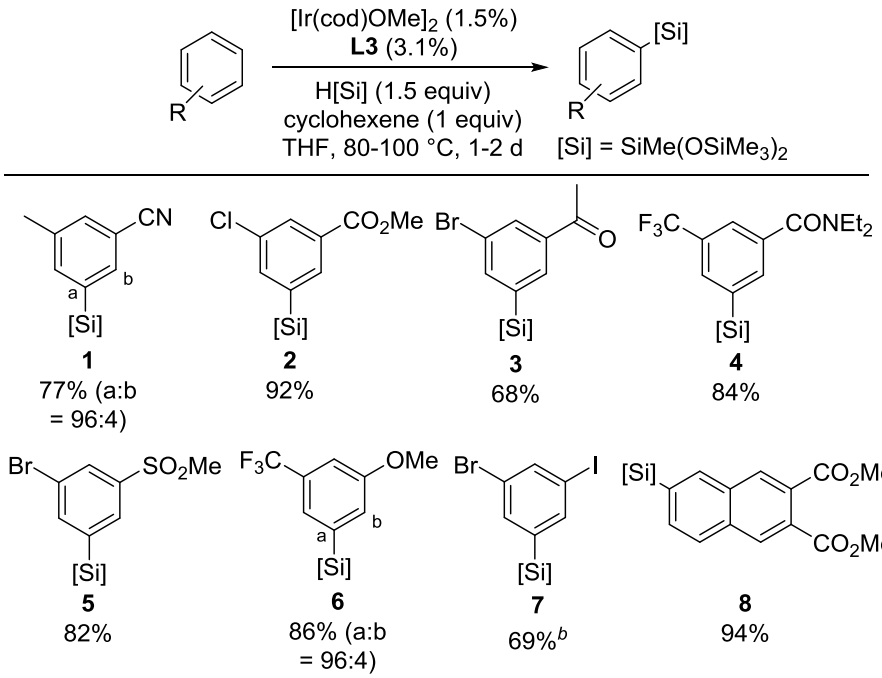
5	**L5**	34	30	24:1
6	**L6**	9	7	20:1
7	**L7**	22	19	6:1
8	**L8**	31	0	-
9	**L9**	45	38	11:1
10[c]	**L3**	53	49	26:1
11[c,d]	**L3**	93	90	25:1

[a] Determined by GC. [b] Combined yield of **1a** and **1b**. [c] Reaction run with 1 equiv of cyclohexene. [d] Reaction run at 100 ℃.

With these conditions for the Ir-catalyzed arene silylation established, we evaluated the functional-group compatibility of this process. The tolerance of the reaction for auxiliary functional groups is striking. The arene silylation is compatible with ester, ketone, bromide, iodide, nitrile, and sulfone functionalities (Scheme 23). Hydrosilylation of ketones and esters was not observed, and the product of protodehalogenation of an aryl iodide was observed in only 3% yield (**7**). In addition, the reaction proceeded with high levels of sterically derived regioselectivity. Various 1,3-disubstituted arenes underwent silylation exclusively at the mutually–*meta* positions, except for 3-CF_3-anisole and 3-tolunitrile, which each afforded 4% of the product in which the silyl group was installed *ortho* to the relatively small OMe (**6**) and CN (**1**) groups. These results are comparable to the results from borylation of 3-CF_3-anisole and 3-tolunitrile, in which 3% and 6% of the products containing the boryl group *ortho* to the OMe and CN group formed, respectively.[32],[33]

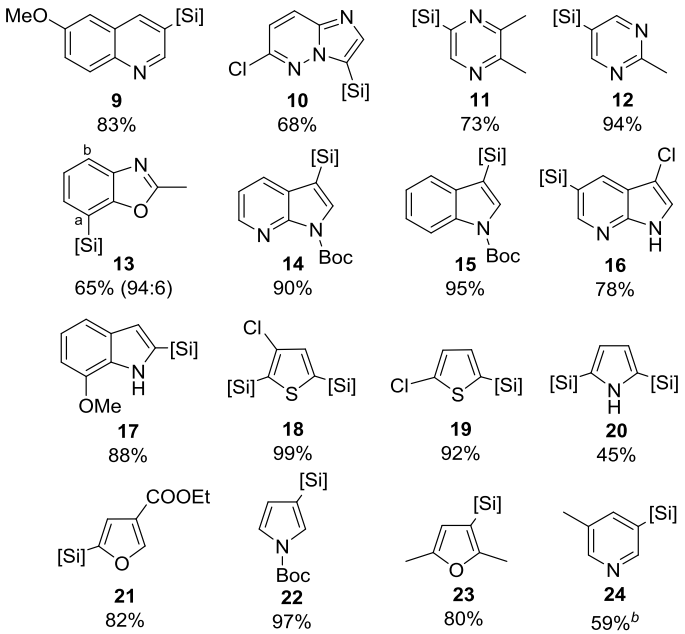
The compatibility with heteroarenes, especially those containing basic N-atoms, was also striking. Silylation of potentially coordinating pyrazines, pyrimidines, and azaindoles afforded the corresponding silylarenes in good yields (Scheme 24). Reaction of five-membered heteroarenes required lower temperatures than reactions of pyrimidines and pyrazines and proceeded with high levels of regioselectivity for functionalization of the C–H bonds α to the heteroatoms. Silylation of heteroarenes in which the α-positions are substituted (**23**) or sterically hindered because of a large substituent on the nitrogen (**22**) occurred at the □-positions. Silylation of the free NH group of 7-methoxyindole (**17**) and of pyrrole (**20**) did not occur under the reaction conditions. However, silylation of unprotected azaindoles first occurred at the N–H bond (**16**).[34],[12, 35] Subsequent silylation at the sterically accessible C–H bond β to the pyridine nitrogen and hydrolysis of the N–Si bond furnished a single product from C–H silylation. Like the borylation of basic N-containing heteroarenes,[8, 12] the silylation occurred at the C–H bond β to the basic nitrogen over the C–H bond α to the basic nitrogen. Silylation of an unhindered pyridine, 3-picoline (**24**), required high temperature (120 °C), but formed the product in an acceptable 59% yield. The slow rate likely results from strong binding of the substrate to the metal center through the basic N-atom.

Scheme 23. C-H Silylation of Arenes[a]



[a] Yields of isolated products. [b] Three percent of inseparable protodeiodination product was also obtained.

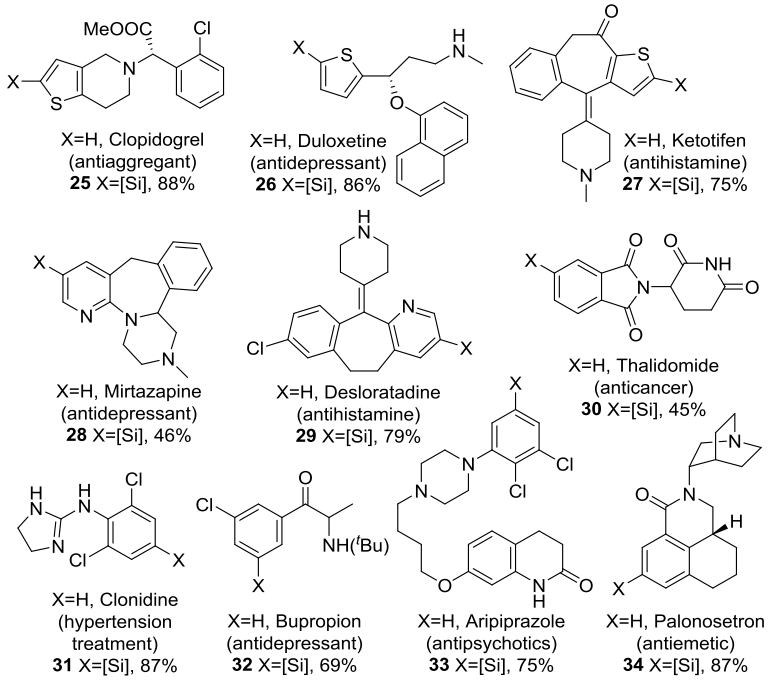
Scheme 24. C-H Silylation of Heteroarenes[a]



[a] Reactions conducted under conditions similar to the conditions in Scheme 23. For detailed procedures, see the SI. Yields of isolated products reported. [b] Reaction conducted at 120 ℃ for 2 d.

The conditions for the silylation of simple arenes were suitable for the functionalization of the active pharmaceutical ingredients (APIs) in some of the most prescribed drugs (Scheme 25),[36],[37] indicating that the scope of the reaction is appropriate for applications in medicinal chemistry. Moreover, these reactions reveal the relative reactivity of different types of aryl and heteroaryl C–H bonds. For example, the silylation of clopidogrel, duloxetine, and ketotifen all occurred selectively at the 2-position of the thiophene moiety over the benzene or naphthalene ring (**25**–**27**). Silylation of the pyridine ring in mirtazapine (**28**) also occurred over silylation of the benzene ring, although 14% of readily separable disilylation products were also obtained. In addition, the secondary alkyl amine moieties in duloxetine (**26**) and desloratadine (**29**) were protected *in situ* by silylation of the N–H bond and did not interfere with subsequent silylation of C–H bonds.[38] In contrast to this reactivity, the C–H borylation does not occur in the presence of secondary alkyl amines. Furthermore, the imidazoline moiety in clonidine (**31**), the secondary amide in aripiprazole (**33**), and the imides in thalidomide (**30**) were all tolerated, and single isomers of the silylation products were obtained from these substrates because of the relative accessibility of the various C–H bonds.

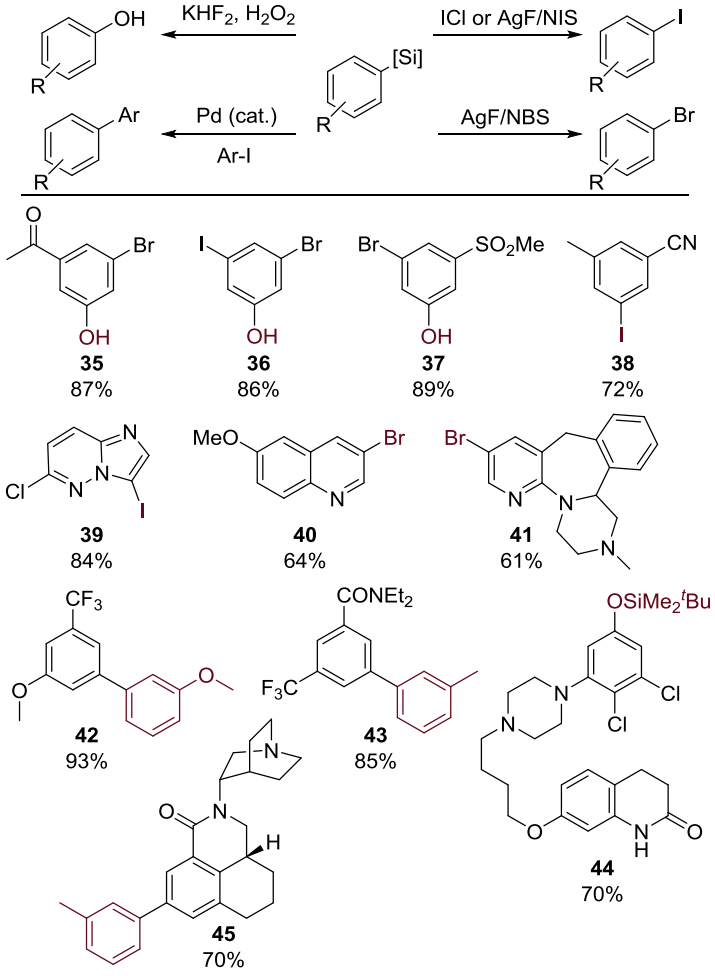
Scheme 25. C-H Silylation of Pharmaceutical Compounds[a]



[a] Reactions conducted under conditions similar to the conditions in Scheme 23. For detailed procedures, see the SI. Yields of isolated products reported.

Because of the presence of the Si–O bonds in the silyl substituent, the silylarene products are suitable for transformations that form C–heteroatom and C–C bonds, such as oxidations,[39] halogenations, and cross-couplings.[40-41] As shown in Scheme 26, reactions of both simple arenes and products from the silylation of APIs occurred to form the corresponding phenols, aryl halides, and biaryls in good isolated yields. The suitability of the methods for functionalization of aryl–Si bonds in several polycylic arylsilanes containing basic heterocycles and potentially reactive functionality (**41**, **44**, **45**) illustrates the suitability of silylation and subsequent derivatization for the late-stage functionalization of complex molecules.

Scheme 26. Functionalization of Silylarene Products[a]



5.3 Conclusions

In summary, we have developed a method for the intermolecular C–H silylation of arenes that occurs with the arene as the limiting reagent and exhibits high levels of sterically derived regioselectivity. Compared to the Rh-catalyzed silylation of aryl C–H bonds, this Ir-catalyzed C–H silylation is compatible with a much broader scope of functional groups and occurs with a broader range of heteroarenes, making it particularly suitable for late-stage functionalization of complex pharmaceutical molecules. However, the reaction requires higher temperatures than the Rh-catalyzed silylation or the C–H borylation, and the regioselectivity of reactions with unsymmetrical 1,2-disubstituted arenes is lower (see the SI). Moreover, the range of reactions of the arylsilanes is narrower than that of aryl boronic esters. Thus, efforts to identify ligands that increase the rate and the regioselectivity of the process, along with methods for further functionalization of the silylarene products, are goals of future studies in our laboratory.

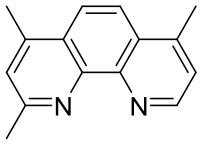
5.4 Experimental

Reagents and Instrumentation

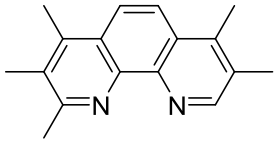
All air-sensitive manipulations were performed in a nitrogen-atmosphere glovebox. THF was purified by an Innovative Technology Pure-Solv solvent purification system. Reagents were purchased from commercial sources unless otherwise indicated and degassed prior to use. $[Ir(cod)OMe]_2$,[5] 2-methyl-1,10-phenathroline (**L1**),[42] 2-methoxy-1,10-phenathroline (**L7**),[43] and 2-*tert*-butyl-1,10-phenathroline (**L8**),[44] were synthesized according to literature procedures. 2-Ethyl-1,10-phenanthroline was synthesized according to the procedure for **L1**[42] using EtLi instead of MeLi, and the NMR data match the literature data.[45] Duloxetine, chlopidogrel, ketotifen, clonidine, bupropion, and palonosetron were purchased as the corresponding ammonium salts and neutralized with K_2CO_3.

GC analyses were conducted on an Agilent 6890 GC equipped with an HP-5 column (25 m x 0.20 mm ID x 0.33 m film) and an FID detector. High-resolution mass spectra were obtained via the Micro-Mass/Analytical Facility operated by the College of Chemistry, University of California, Berkeley. NMR spectra were acquired on Bruker AVQ-400, AVB-400, DRX 500, and AV-600 spectrometers. Chemical shifts were reported in ppm relative to residual solvent peaks ($CDCl_3$ = 7.26 ppm for ^1H and 77.16 ppm for ^{13}C). Coupling constants were reported in Hz. Flash column chromatography was performed on a Teledyne ISCO CombiFlash® Rf system. Preparative TLC was performed on Analtech® Uniplate silica gel plates (20 cm × 20 cm × 1 mm).

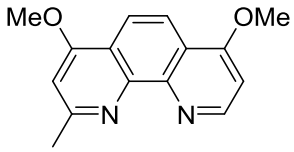
Synthesis of Ligands



2,4,7-Trimethyl-1,10-phenanthroline (**L3**): To a stirring suspension of 4,7-dimethyl-1,10-phenanthroline (1.00 g, 4.80 mmol) in dry THF (10 mL) at 0 ℃ was added drop wise MeLi (3.0 mL of 1.6 M ethereal solution), and the mixture was stirred at room temperature for 16 h. The mixture was then cooled to 0 ℃ and quenched with water (10 mL). The organic solvents were evaporated, and the aqueous layer was extracted with ethyl acetate (15 mL × 3). To the organic layer was added MnO_2 (5.0 g, 58 mmol), and the mixture was stirred vigorously at room temperature for 1.5 h. The mixture was dried with $MgSO_4$, filtered, and solvents were evaporated. The crude product was purified by flash column chromatography (2:8 acetone:hexanes → 100% acetone) to afford the product as a colorless solid (505 mg, 47% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 9.04 (d, *J* = 4.4 Hz, 1H), 7.95 (q, *J* = 9.2 Hz, 2H), 7.41 (d, *J* = 4.4 Hz, 1H), 7.34 (s, 1H), 2.89 (s, 3H), 2.76 (s, 3H), 2.72 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.12 (s), 150.01 (s), 146.07 (s), 145.99 (s), 144.17 (s), 144.16 (s), 128.04 (s), 126.02 (s), 124.70 (s), 123.81 (s), 122.10 (s), 121.08 (s), 25.88 (s), 19.21 (s), 19.08 (s). HRMS (ESI+) calcd for [$C_{15}H_{15}N_2^+$] (M+H$^+$): 223.1230, found: 223.1229.



2,3,4,7,8-Pentamethyl-1,10-phenanthroline (**L4**): This ligand was synthesized from 3,4,7,8-tetramethyl-1,10-phenanthroline (0.93 g, 4.2 mmol) and MeLi according to the procedure for the synthesis of **L3**. The crude product was purified by flash column chromatography (2:8 acetone:hexanes → 100% acetone) to afford the product as a colorless solid (338 mg, 32% yield). ^{1}H NMR (600 MHz, C_6D_6) δ 8.93 (s, 1H), 7.95 (q, *J* = 9.4 Hz, 2H), 2.89 (s, 3H), 2.66 (s, 3H), 2.64 (s, 3H), 2.50 (s, 3H), 2.45 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 158.26 (s), 151.72 (s), 144.81 (s), 143.85 (s), 141.30 (s), 140.86 (s), 130.16 (s), 129.59 (s), 126.91 (s), 125.79 (s), 122.38 (s), 121.02 (s), 25.53 (s), 17.65 (s), 16.07 (s), 14.92 (s), 14.61 (s). HRMS (ESI+) calcd for [$C_{17}H_{19}N_2^+$] (M+H$^+$): 251.1543, found: 251.1541.

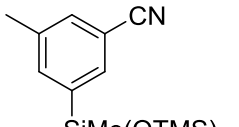


2-Methyl-4,7-dimethoxy-1,10-phenanthroline (**L5**): This ligand was synthesized from 4,7-dimethoxy-1,10-phenanthroline (240 mg, 1.0 mmol) and MeLi according to the procedure for the synthesis of **L3**. The crude product was purified by flash column chromatography (100% acetone) to afford the product as a colorless solid (45.6 mg, 18% yield). ^{1}H NMR (600 MHz, C_6D_6) δ 9.02 (d, *J* = 5.3 Hz, 1H), 8.11 (q, *J* = 9.2 Hz, 2H), 6.96 (d, *J* = 5.3 Hz, 1H), 6.87 (s, 1H), 4.07 (s, 3H), 4.05 (s, 3H), 2.88 (s, 3H). ^{13}C NMR (151 MHz, C_6D_6) δ 162.49 (s), 162.45 (s), 160.62 (s), 151.11 (s), 146.42 (s), 146.24 (s), 121.20 (s), 119.39 (s), 119.13 (s), 118.03 (s),

103.17 (s), 102.64 (s), 55.95 (s), 55.84 (s), 26.45 (s). HRMS (ESI+) calcd for [$C_{15}H_{15}N_2O_2^+$] ($M+H^+$): 255.1128, found: 255.1126.

General Procedure for the Silylation of Arenes

The typical silylation of arenes was conducted on a 0.3 mmol scale. To a solution of $[Ir(cod)OMe]_2$ (3.0 mg, 4.5 μmol) and **L3** (2.1 mg, 9.3 μmol) in THF (300 mg) in a 20-mL vial was added the desired amount of $HSiMe(OSiMe_3)_2$, cyclohexene, and substrate, and the mixture was heated to the desired temperature for 1 d. Purification methods are described below.



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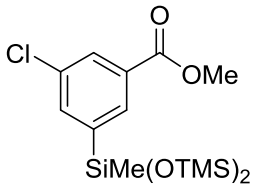
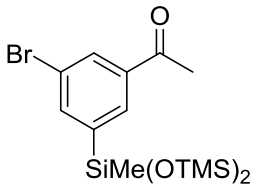
The general procedure was followed with 3-methylbenzonitrile (35.6 μL, 0.300 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 2 d. The crude mixture was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (78 mg, 77% yield, isomeric purity determined by GC: 96%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 (s, 1H), 7.55 (s, 1H), 7.46 (s, 1H), 2.39 (s, 3H), 0.27 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.37 (s), 138.29 (s), 138.16 (s), 134.12 (s), 133.26 (s), 119.49 (s), 111.91 (s), 21.28 (s), 1.92 (s), -0.06 (s). HRMS (EI+) calcd for [$C_{14}H_{24}NO_2Si_3$•] ($M-CH_3$): 322.1115, found: 322.1121.



2

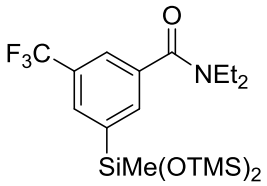
The general procedure was followed with methyl 3-chlorobenzoate (51.4 mg, 0.301 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The crude mixture was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (108 mg, 92% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.10 (s, 1H), 8.04 – 7.97 (t, J = 1.8 Hz, 1H), 7.67 (d, J = 1.5 Hz, 1H), 3.92 (s, 3H), 0.29 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.24 (s), 141.69 (s), 137.52 (s), 134.42 (s), 132.47 (s), 131.29 (s), 130.52 (s), 52.43 (s), 1.93 (s), -0.01 (s). HRMS (EI+) calcd for [$C_{14}H_{24}ClO_4Si_3$•] ($M-CH_3$): 375.0671, found: 375.0671.



3

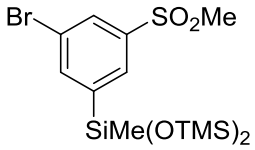
The general procedure was followed with 1-(3-bromophenyl)ethan-1-one (59.0 mg, 0.296 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 2 d. The crude mixture was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (84 mg, 68% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.08 (t, J = 1.8 Hz, 1H), 8.03 (t, J =

1.0 Hz, 1H), 7.82 (dd, *J* = 1.8, 0.6 Hz, 1H), 2.59 (s, 3H), 0.29 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 197.01 (s), 142.31 (s), 140.52 (s), 138.23 (s), 132.16 (s), 131.52 (s), 123.24 (s), 26.74 (s), 1.97 (s), 0.04 (s). HRMS (EI+) calcd for [$C_{14}H_{24}BrO_3Si_3$•] (M-CH_3): 403.0217, found: 403.0216.



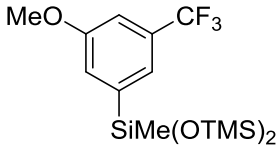
4

The general procedure was followed with *N*,*N*-diethyl-3-(trifluoromethyl)benzamide (73.6 mg, 0.300 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 2 d. The crude mixture was purified by preparative TLC (3:7 ethyl acetate:hexanes) to afford the product as a colorless liquid (117 mg, 84% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79 (s, 1H), 7.68 (s, 1H), 7.62 (s, 1H), 3.54 (bs, 2H), 3.19 (bs, 2H), 1.24 (bs, 3H), 1.10 (bs, 3H), 0.27 (s, 3H), 0.09 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.22 (s), 140.59 (s), 137.19 (s), 134.18 (s), 130.48 (q, *J* = 3.4 Hz), 130.21 (q, *J* = 32.2 Hz), 124.34 (q, *J* = 3.6 Hz), 124.09 (q, *J* = 272.7 Hz), 43.42 (s), 39.51 (s), 14.25 (s), 12.91 (s), 1.85 (s), -0.05 (s). ^{19}F NMR (470 MHz, C_6D_6) δ -63.06 (s). HRMS (EI+) calcd for [$C_{19}H_{34}F_3NO_3Si_3$]: 465.1799, found: 465.1786.



5

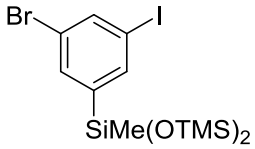
The general procedure was followed with 1-bromo-3-(methylsulfonyl)benzene (73.3 mg, 0.312 mmol), 1.3 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 1 d. The crude mixture was purified by preparative TLC (3:7 ethyl acetate:hexanes) to afford the product as a colorless liquid (116 mg, 82% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.06 (t, *J* = 1.8 Hz, 1H), 7.99 (dd, *J* = 1.5, 0.6 Hz, 1H), 7.88 (d, *J* = 1.8, 0.6 Hz, 1H), 3.04 (s, 3H), 0.29 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.85 (s), 141.77 (s), 141.22 (s), 131.00 (s), 130.23 (s), 123.40 (s), 44.60 (s), 1.92 (s), -0.08 (s). HRMS (EI+) calcd for [$C_{13}H_{24}BrO_4SSi_3$•] (M-CH_3): 438.9886, found: 438.9882.



6

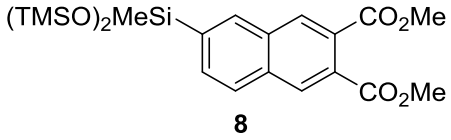
The general procedure was followed with 1-methoxy-3-(trifluoromethyl)benzene (52.2 mg, 0.296 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The crude mixture was purified by flash column chromatography (hexanes) to afford the product as a colorless liquid (101 mg, 86% yield, isomeric purity determined by GC and NMR: 96%). ^{1}H NMR (600 MHz, CDCl3) δ 7.40 (s, 1H), 7.27 (s, 1H), 7.14 (s, 1H), 3.87 (s, 3H), 0.31 (s, 3H), 0.15 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 159.22 (s), 141.68 (s), 131.42 (q, *J* = 31.5 Hz), 124.37 (q, *J* = 272.5 Hz), 122.37 (s), 122.07 (q, *J* = 3.8 Hz), 111.53 (d, *J* = 3.7 Hz),

55.48 (s), 1.95 (s), 0.03 (s). ^{19}F NMR (565 MHz, $CDCl_3$) δ -63.65 (s). HRMS (EI+) calcd for [$C_{15}H_{27}F_3O_3Si_3$]: 396.1220, found: 396.1218.



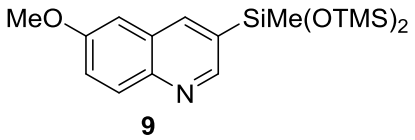
7

The general procedure was followed with 3-bromoiodobenzene (83.9 mg, 0.297 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 2 d. The crude mixture was purified by preparative TLC (hexamethyldisiloxane) to afford the product as a colorless liquid (103 mg, 69% yield, contains 3% inseparable de-iodination product). ^{1}H NMR (400 MHz, C_6D_6) δ 7.87 (t, *J* = 1.7 Hz, 1H), 7.76 (dd, *J* = 1.5, 0.6 Hz, 1H), 7.59 (dd, *J* = 1.8, 0.6 Hz, 1H), 0.27 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (101 MHz, C_6D_6) δ 144.23 (s), 140.61 (s), 140.42 (s), 135.16 (s), 123.27 (s), 95.31 (s), 1.99 (s), -0.04 (s). HRMS (EI+) calcd for [$C_{13}H_{24}BrIO_2Si_3$]: 501.9312, found: 501.9315.



8

The general procedure was followed with dimethyl 2,3-naphthalenedicarboxylate (72.9 mg, 0.298 mmol), 2 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The resulting mixture was purified by preparative TLC (2:8 ethyl acetate:hexanes) to afford the product as a light yellow liquid (130.3 mg, 94%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.29 (s, 1H), 8.24 (s, 1H), 8.13 (s, 1H), 7.90 (d, *J* = 8.1 Hz, 1H), 7.77 (d, *J* = 8.1 Hz, 1H), 3.96 (s, 3H), 3.95 (s, 3H), 0.36 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 168.28 (s), 168.21 (s), 139.67 (s), 134.66 (s), 134.00 (s), 132.74 (s), 132.40 (s), 130.66 (s), 130.01 (s), 129.00 (s), 128.41 (s), 127.65 (s), 52.73 (s), 1.95 (s), 0.02 (s). HRMS (EI+) calcd for [$C_{21}H_{32}O_6Si_3$]: 464.1507, found: 464.1504.

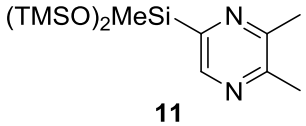


9

The general procedure was followed with 6-methoxyquinoline (48.0 mg, 0.302 mmol), 2 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The resulting mixture was purified by preparative TLC (2:8 ethyl acetate:hexanes) to afford the product as a light yellow liquid (95.2 mg, 83% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.86 (d, *J* = 1.5 Hz, 1H), 8.19 (s, 1H), 7.97 (d, *J* = 9.2 Hz, 1H), 7.36 (dd, *J* = 9.2, 2.8 Hz, 1H), 7.06 (d, *J* = 2.7 Hz, 1H), 3.91 (s, 3H), 0.36 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.73 (s), 151.50 (s), 144.76 (s), 141.07 (s), 131.16 (s), 130.78 (s), 128.64 (s), 122.84 (s), 105.34 (s), 55.58 (s), 1.97 (s), 0.31 (s). HRMS (EI+) calcd for [$C_{17}H_{29}NO_3Si_3$]: 379.1455, found: 379.1456.

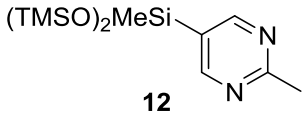
10

The general procedure was followed with 6-chloroimidazo[1,2-*b*]pyridazine (46.1 mg, 0.300 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The resulting mixture was purified by preparative TLC (3:7 ethyl acetate:hexanes) to afford the product as a colorless liquid (84 mg, 68% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.89 (d, *J* = 9.4 Hz, 1H), 7.82 (s, 1H), 7.03 (d, *J* = 9.4 Hz, 1H), 0.39 (s, 3H), 0.10 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 146.22 (s), 142.83 (s), 140.18 (s), 127.94 (s), 126.74 (s), 119.07 (s), 1.81 (s), 0.49 (s). HRMS (EI+) calcd for [$C_{13}H_{24}ClN_3O_2Si_3$]: 373.0865, found: 373.0861.



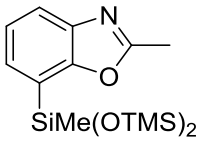
11

The general procedure was followed with 2,3-dimethylpyrazine (33.7 mg, 0.311 mmol), 2 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The resulting mixture was purified by flash column chromatography over silica pretreated with Et_3N (0→10% ethyl acetate in hexanes) to afford the product as a colorless liquid (74.3 mg, 73% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.40 (s, 1H), 2.52 (s, 3H), 2.49 (s, 3H), 0.29 (s, 3H), 0.09 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 155.30 (s), 152.88 (s), 151.89 (s), 145.44 (s), 22.40 (s), 22.34 (s), 1.90 (s), -0.62 (s). HRMS (EI+) calcd for [$C_{13}H_{28}N_2O_2Si_3$]: 328.1459, found: 328.1457.

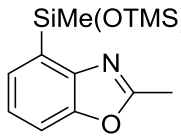


12

The general procedure was followed with 2-methylpyrimidine (28.9 mg, 0.307 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 100 ℃ for 1 d. The resulting mixture was purified by Kugelrohr distillation to afford the product as a colorless liquid (90.8 mg, 94% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.66 (s, 2H), 2.70 (s, 3H), 0.27 (s, 3H), 0.10 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.72 (s), 161.58 (s), 126.68 (s), 26.30 (s), 1.92 (s), 0.38 (s). HRMS (EI+) calcd for [$C_{12}H_{26}N_2O_2Si_3$]: 314.1302, found: 314.1302.

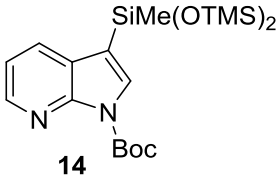


13a



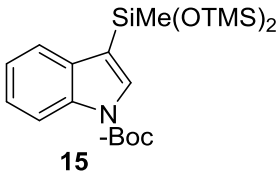
13b

The general procedure was followed with 2-methylbenzoxazole (40.1 mg, 0.301 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 1 d. The resulting mixture was purified by preparative TLC (2:8 ethyl acetate:hexanes) to afford the product as a colorless liquid (69.0 mg, 65% yield, a:b = 94:6). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.67 (d, *J* = 7.8 Hz, 1H), 7.42 (d, *J* = 7.1 Hz, 1H), 7.28 (t, *J* = 7.5 Hz, 1H), 2.64 (s, 3H), 0.39 (s, 3H), 0.11 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 163.71 (s), 155.05 (s), 140.29 (s), 129.90 (s), 123.89 (s), 120.87 (s), 120.47 (s), 14.70 (s), 1.89 (s), 0.94 (s). HRMS (EI+) calcd for [$C_{15}H_{27}NO_3Si_3$]: 353.1299, found: 353.1298.



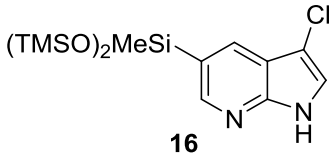
14

The general procedure was followed with *N*-Boc-7-azaindole (62.9 mg, 0.288 mmol), 1.3 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 1 d. The resulting mixture was purified by preparative TLC (2:8 ethyl acetate:hexanes) to afford the product as a light yellow liquid (113.2 mg, 90% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.45 (d, *J* = 4.0 Hz, 1H), 7.91 (d, *J* = 7.5 Hz, 1H), 7.64 (s, 1H), 7.15 (dd, *J* = 7.7, 4.8 Hz, 1H), 1.63 (s, 9H), 0.30 (s, 3H), 0.08 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 149.61 (s), 147.82 (s), 144.85 (s), 133.10 (s), 130.13 (s), 126.28 (s), 118.39 (s), 113.07 (s), 83.93 (s), 28.08 (s), 1.87 (s), 1.24 (s). HRMS (ESI+) calcd for [$C_{19}H_{35}N_2O_4Si_3^+$] ($M+H^+$): 439.1899, found: 439.1896.



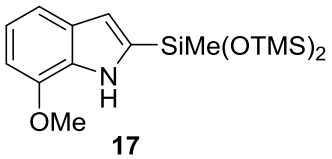
15

The general procedure was followed with 1-boc-indole (64.9 mg, 0.299 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 1 d. The resulting mixture was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (124 mg, 95% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.18 (s, 1H), 7.72 (d, *J* = 7.9 Hz, 2H), 7.35 (t, *J* = 7.6 Hz, 1H), 7.28 (t, *J* = 7.4 Hz, 1H), 1.72 (s, 9H), 0.40 (s, 3H), 0.19 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 149.80 (s), 136.38 (s), 133.95 (s), 132.92 (s), 124.12 (s), 122.63 (s), 122.36 (s), 115.70 (s), 115.20 (s), 83.70 (s), 28.29 (s), 2.04 (s), 1.48 (s). HRMS (EI+) calcd for [$C_{20}H_{35}NO_4Si_3$]: 437.1874, found: 437.1878.



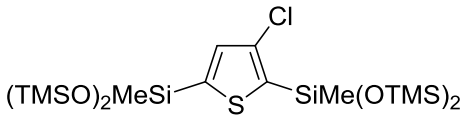
16

The general procedure was followed with 3-chloro-7-azaindole (45.3 mg, 0.297 mmol), 2.5 equiv of silane, and 2 equiv of cyclohexene at 100 ℃ for 1 d. After the reaction, the volatile materials were evaporated, and the residue was dissolved in ethyl acetate (7 mL). To the solution was added methanol (1 mL) and saturated aqueous $NaHCO_3$ solution (2 mL), and the mixture was stirred vigorously at room temperature for 0.5 h. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2×2 mL). The combined organic layer was washed with brine and dried over $MgSO_4$. The solvents were evaporated, and the residue was purified by preparative TLC (3:7 ethyl acetate:hexanes) to afford the product as a light yellow solid (86.3 mg, 78% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.58 (s, 1H), 8.53 (d, *J* = 1.2 Hz, 1H), 8.19 (d, *J* = 1.3 Hz, 1H), 7.38 (s, 1H), 0.41 (s, 3H), 0.19 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.04 (s), 147.56 (s), 132.77 (s), 124.65 (s), 122.14 (s), 118.40 (s), 104.58 (s), 2.08 (s), 0.70 (s). HRMS (EI+) calcd for [$C_{14}H_{25}ClN_2O_2Si_3$]: 372.0912, found: 372.0911.



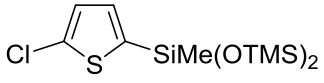
17

The general procedure was followed with 7-methoxyindole (43.7 mg, 0.297 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 65 ℃ for 1 d. The resulting mixture was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (96.5 mg, 88% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.46 (s, 1H), 7.34 (d, *J* = 8.0 Hz, 1H), 7.09 (t, *J* = 7.8 Hz, 1H), 6.82 (d, *J* = 2.2 Hz, 1H), 6.70 (d, *J* = 7.6 Hz, 1H), 4.03 (s, 3H), 0.43 (s, 3H), 0.23 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.35 (s), 135.84 (s), 130.01 (s), 129.01 (s), 120.12 (s), 113.70 (s), 111.84 (s), 102.05 (s), 55.38 (s), 1.99 (s), 0.87 (s). The spectra match the ones reported.[24]



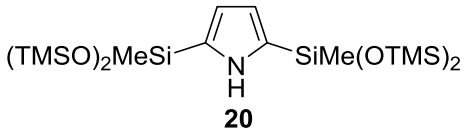
18

The general procedure was followed with 3-chlorothiophene (40.9 mg, 0.345 mmol), 2.5 equiv of silane, and 2 equiv of cyclohexene at 80 ℃ for 1 d. The volatile materials were evaporated, and the resulting mixture was diluted with hexanes and filtered over a pad of silica to afford the product as a colorless liquid (192.6 mg, 99% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.15 (s, 1H), 0.41 (s, 3H), 0.33 (s, 3H), 0.17 (s, 18H), 0.16 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 144.34 (s), 136.76 (s), 136.17 (s), 131.83 (s), 1.95 (s), 1.91 (s), 1.09 (s), 1.00 (s). HRMS (EI+) calcd for $[C_{18}H_{43}ClO_4SSi_6]$: 558.1186, found: 558.1185.



19

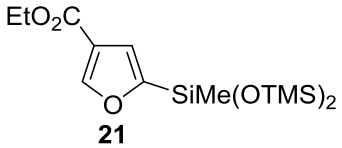
The general procedure was followed with 2-chlorothiophene (37.1 mg, 0.312 mmol), 1.0 equiv of silane, and 1 equiv of cyclohexene at 65 ℃ for 1 d. The volatile materials were evaporated, and the resulting mixture was diluted with hexanes and filtered over a pad of silica to afford the product as a colorless liquid (97.9 mg, 92% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.06 (d, *J* = 2.1 Hz, 1H), 6.95 (d, *J* = 2.1 Hz, 1H), 0.31 (s, 3H), 0.14 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.36 (s), 134.96 (s), 133.98 (s), 127.38 (s), 1.93 (s), 1.01 (s). HRMS (EI+) calcd for $[C_{11}H_{23}ClO_2SSi_3]$: 338.0415, found: 338.0414.



20

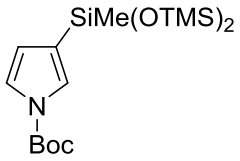
The general procedure was followed with pyrrole (19.1 mg, 0.285 mmol), 2.5 equiv of silane, and 2 equiv of cyclohexene at 80 ℃ for 1 d. The resulting mixture was purified by flash column chromatography (0→15% ethyl acetate in hexanes) to afford the product as a colorless liquid (64.6 mg, 45% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.45 (s, 1H), 6.50 (s, 2H), 0.30 (s, 6H), 0.13 (s, 36H). ^{13}C NMR (151 MHz,

$CDCl_3$) δ 132.72 (s), 118.03 (s), 1.95 (s), 0.96 (s). HRMS (EI+) calcd for [$C_{18}H_{45}NO_4Si_6$]: 507.1964, found: 507.1970.



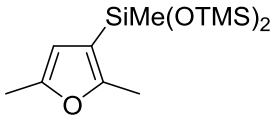
21

The general procedure was followed with ethyl 3-furoate (45.3 mg, 0.323 mmol), 1.2 equiv of silane, and 1 equiv of cyclohexene at 65 ℃ for 1 d. The resulting mixture was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (95.1 mg, 82% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15 (s, 1H), 6.96 (s, 1H), 4.28 (q, *J* = 7.1 Hz, 2H), 1.33 (t, *J* = 7.1 Hz, 3H), 0.26 (s, 3H), 0.09 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 163.54 (s), 160.15 (s), 151.31 (s), 119.78 (s), 119.49 (s), 60.44 (s), 14.45 (s), 1.75 (s), -0.12 (s). HRMS (EI+) calcd for [$C_{14}H_{28}O_5Si_3$]: 360.1245, found: 360.1244.



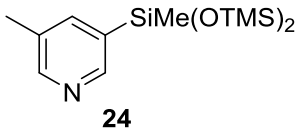
22

The general procedure was followed with *N*-Boc-pyrrole (51.9 mg, 0.310 mmol), 1.3 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 1 d. The resulting mixture was purified by flash column chromatography (0→10% ethyl acetate in hexanes) to afford the product as a colorless liquid (117 mg, 97% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.31 (s, 1H), 7.26 (s, 1H), 6.27 (dd, *J* = 2.9, 1.4 Hz, 1H), 1.61 (s, 9H), 0.23 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 148.98 (s), 126.34 (s), 121.20 (s), 120.83 (s), 115.94 (s), 83.62 (s), 28.09 (s), 1.99 (s), 1.00 (s). HRMS (EI+) calcd for [$C_{16}H_{33}NO_4Si_3$]: 387.1717, found: 387.1714.



23

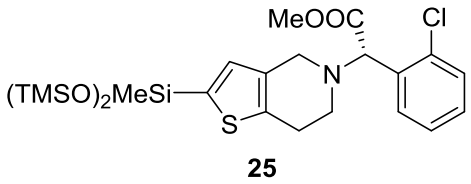
The general procedure was followed with 2,5-dimethylfuran (30.8 mg, 0.320 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 80 ℃ for 1 d. The volatile materials were evaporated, and the resulting mixture was diluted with hexanes and filtered over a pad of silica to afford the product as a colorless liquid (81.6 mg, 80% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.83 (d, *J* = 0.6 Hz, 1H), 2.32 (s, 3H), 2.25 (s, 3H), 0.21 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.04 (s), 149.75 (s), 112.94 (s), 110.01 (s), 14.30 (s), 13.27 (s), 2.00 (s), 1.45 (s). HRMS (EI+) calcd for [$C_{13}H_{28}O_3Si_3$]: 316.1346, found: 316.1343.



24

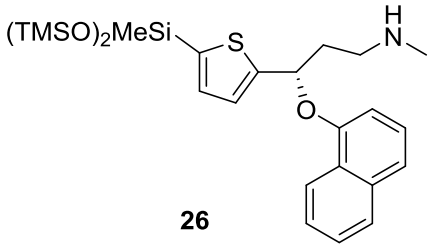
The general procedure was followed with 3-picoline (28.1 mg, 0.302 mmol), 1.5 equiv of silane, and 1 equiv of cyclohexene at 120 ℃ for 2 d. The resulting mixture was purified by flash column chromatography (0→30% ethyl acetate in hexanes) to afford the product as a colorless liquid (56.0 mg, 59% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.51 (s, 1H), 8.42 (s, 1H), 7.58 (s,

1H), 2.31 (s, 3H), 0.27 (s, 3H), 0.10 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 151.20 (s), 151.04 (s), 141.48 (s), 132.54 (s), 132.22 (s), 18.69 (s), 1.95 (s), 0.26 (s). HRMS (EI+) calcd for [$C_{13}H_{27}NO_2Si_3$]: 313.1350, found: 313.1349.



25

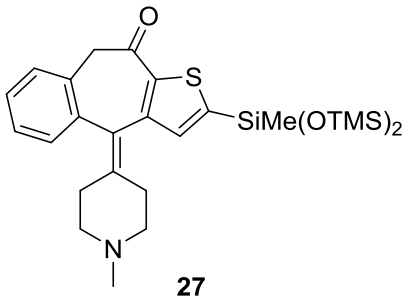
To [Ir(cod)OMe]$_2$ (2.0 mg, 3.0 μmol) and 2,4,7-trimethylphenanthroline (1.4 mg, 6.3 μmol) in a 4-mL vial was added THF (200 mg), HSiMe(OTMS)$_2$ (73.5 μL, 0.260 mmol, 1.3 equiv), cyclohexene (20 μL, 0.20 mmol), and clopidogrel (64.8 mg, 0.201 mmol). The mixture was heated at 80 ℃ for 14 h. The resulting mixture was cooled to room temperature and purified by preparative TLC (2:8 ethyl acetate:hexanes) to afford the product as a colorless viscous liquid (96.0 mg, 88% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (dd, *J* = 7.4, 1.6 Hz, 1H), 7.47 – 7.38 (m, 1H), 7.34 – 7.23 (m, 2H), 6.88 (s, 1H), 4.94 (s, 1H), 3.80 (d, *J* = 14.0 Hz, 1H), 3.74 (s, 3H), 3.66 (d, *J* = 14.1 Hz, 1H), 3.00 – 2.83 (m, 4H), 0.28 (s, 3H), 0.13 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 171.46 (s), 139.05 (s), 135.56 (s), 134.79 (s), 134.66 (s), 134.00 (s), 132.93 (s), 130.10 (s), 129.88 (s), 129.51 (s), 127.27 (s), 68.04 (s), 52.26 (s), 50.80 (s), 48.41 (s), 25.91 (s), 1.95 (s), 1.26 (s). HRMS (EI+) calcd for [$C_{23}H_{36}ClNO_4SSi_3$]: 541.1361, found: 541.1348.



26

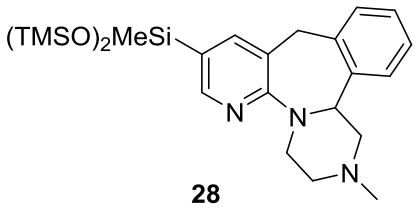
To [Ir(cod)OMe]$_2$ (2.0 mg, 3.0 μmol) and 2,4,7-trimethylphenanthroline (1.4 mg, 6.3 μmol) in a 4-mL vial was added THF (200 mg), HSiMe(OTMS)$_2$ (130 μL, 0.460 mmol, 2.3 equiv), cyclohexene (40 μL, 0.40 mmol), and duloxetine (59.2 mg, 0.199 mmol). The mixture was heated at 80 ℃ for 16 h. The resulting mixture was cooled to room temperature, and the volatile materials were evaporated. To the residue was added ethyl acetate (5 mL) and saturated $NaHCO_3$ (aq, 2 mL), and the mixture was stirred vigorously at room temperature for 30 min. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2 mL × 2). The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (pure ethyl acetate on a TLC plate pre-treated with Et_3N) to afford the product as a yellow viscous liquid (89.1 mg, 86% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.41 (dd, *J* = 6.1, 3.3 Hz, 1H), 7.80 (dd, *J* = 5.9, 3.3 Hz, 1H), 7.55 – 7.46 (m, 2H), 7.41 (d, *J* = 8.2 Hz, 1H), 7.29 (t, *J* = 8.0 Hz, 1H), 7.15 (d, *J* = 3.3 Hz, 1H), 7.11 (d, *J* = 3.3 Hz, 1H), 6.88 (d, *J* = 7.7 Hz, 1H), 5.82 (dd, *J* = 7.5, 5.2 Hz, 1H), 2.85 (td, *J* = 6.8, 3.0 Hz, 2H), 2.53 – 2.46 (m, 1H), 2.45 (s, 3H), 2.27 (dt, *J* = 6.8, 6.3 Hz, 1H), 1.30 (s, 1H), 0.31 (s, 3H), 0.10 (d, *J* = 1.6 Hz, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.58 (s), 150.61 (s), 137.68 (s), 134.66 (s), 134.36 (s), 127.55 (s), 126.36 (s), 126.28 (s), 125.83 (s), 125.62 (s), 125.30 (s), 122.31 (s), 120.64 (s), 107.29 (s), 75.03 (s), 48.46 (s),

39.12 (s), 36.70 (s), 1.85 (s), 1.07 (s). HRMS (ESI+) calcd for [$C_{25}H_{40}NO_3SSi_3^+$]: 518.2031, found: 518.2031.



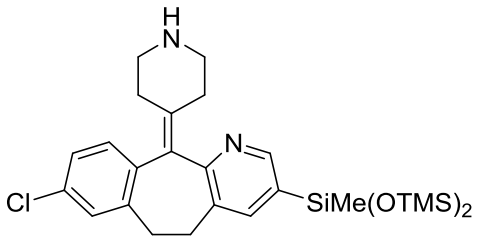
27

To [Ir(cod)OMe]$_2$ (2.0 mg, 3.0 μmol) and 2,4,7-trimethylphenanthroline (1.4 mg, 6.3 μmol) in a 4-mL vial was added THF (200 mg), HSiMe(OTMS)$_2$ (68 μL, 0.24 mmol, 1.2 equiv), cyclohexene (20 μL, 0.20 mmol), and ketotifen (62.2 mg, 0.201 mmol). The mixture was heated at 80 ℃ for 1 d. The resulting mixture was cooled to room temperature and purified by preparative TLC (5:5 ethyl acetate:hexanes on a TLC plate pre-treated with Et_3N) to afford the product as a yellow viscous liquid (79.4 mg, 75% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.32 – 7.28 (m, 1H), 7.21 – 7.16 (m, 3H), 7.15 (s, 1H), 4.20 (d, *J* = 13.5 Hz, 1H), 3.74 (d, *J* = 13.5 Hz, 1H), 2.78 – 2.70 (m, 1H), 2.70 – 2.59 (m, 3H), 2.48 – 2.37 (m, 2H), 2.28 (s, 3H), 2.18 (td, *J* = 10.9, 3.9 Hz, 1H), 2.08 (td, *J* = 10.4, 3.1 Hz, 1H), 0.28 (s, 3H), 0.11 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 189.46 (s), 148.43 (s), 146.01 (s), 141.94 (s), 141.27 (s), 138.30 (s), 136.95 (s), 132.65 (s), 129.57 (s), 129.24 (s), 128.77 (s), 127.23 (s), 126.68 (s), 57.26 (s), 57.21 (s), 49.86 (s), 46.08 (s), 31.61 (s), 31.53 (s), 1.89 (s), 1.00 (s). HRMS (EI+) calcd for [$C_{26}H_{39}NO_3SSi_3$]: 529.1958, found: 529.1957.



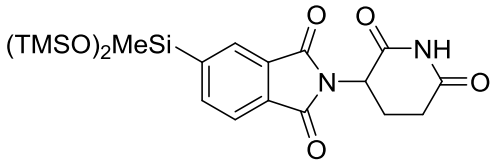
28

To [Ir(cod)OMe]$_2$ (2.0 mg, 3.0 μmol) and 2,4,7-trimethylphenanthroline (1.4 mg, 6.3 μmol) in a 20-mL vial was added THF (200 mg), HSiMe(OTMS)$_2$ (141 μL, 0.500 mmol, 2.5 equiv), cyclohexene (20 μL, 0.20 mmol), and mirtazapine (53.9 mg, 0.203 mmol). The mixture was heated at 80 ℃ for 2 d. The resulting mixture was cooled to room temperature and purified by preparative TLC (7:3 ethyl acetate:hexanes on a TLC plate pre-treated with Et_3N) to afford the product as a yellow viscous liquid (45.7 mg, 46% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.27 (s, 1H), 7.39 (s, 1H), 7.20 – 7.09 (m, 4H), 4.43 (dd, *J* = 23.2, 11.0 Hz, 2H), 3.74 (d, *J* = 12.7 Hz, 1H), 3.49 (dd, *J* = 29.6, 12.1 Hz, 2H), 2.94 (d, *J* = 10.8 Hz, 1H), 2.84 (d, *J* = 10.9 Hz, 1H), 2.55 (t, *J* = 10.3 Hz, 1H), 2.37 (s, 3H), 2.34 (d, *J* = 11.0 Hz, 1H), 0.20 (s, 3H), 0.09 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 160.16 (s), 151.19 (s), 139.71 (s), 138.24 (s), 137.08 (s), 130.02 (s), 129.72 (s), 128.05 (s), 127.60 (s), 127.04 (s), 125.23 (s), 64.56 (s), 64.16 (s), 55.68 (s), 48.87 (s), 45.98 (s), 38.76 (s), 2.01 (s), 0.56 (s). HRMS (EI+) calcd for [$C_{24}H_{39}N_3O_2Si_3$]: 485.2350, found: 485.2355.



29

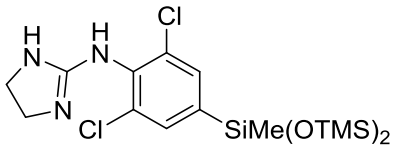
To $[Ir(cod)OMe]_2$ (4.0 mg, 6.0 μmol) and 2,4,7-trimethylphenanthroline (2.8 mg, 13 μmol) in a 20-mL vial was added THF (400 mg), $HSiMe(OTMS)_2$ (141 μL, 0.499 mmol, 2.5 equiv), cyclohexene (40 μL, 0.40 mmol), and desloratadine (62.0 mg, 0.199 mmol). The mixture was heated at 100 ℃ for 2 d. The resulting mixture was cooled to room temperature, and the volatile materials were evaporated. To the residue was added ethyl acetate (5 mL) and saturated $NaHCO_3$ (aq, 2 mL), and the mixture was stirred vigorously at room temperature for 30 min. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2 mL × 2). The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (5:5 acetone:methanol on a TLC plate pre-treated with Et_3N) to afford the product as a brown liquid (83.6 mg, 79% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.48 (d, *J* = 1.3 Hz, 1H), 7.50 (d, *J* = 1.1 Hz, 1H), 7.16 – 7.04 (m, 3H), 3.47 – 3.29 (m, 2H), 3.11 – 2.95 (m, 2H), 2.91 – 2.70 (m, 2H), 2.70 – 2.57 (m, 2H), 2.46 – 2.36 (m, 1H), 2.36 – 2.22 (m, 3H), 1.82 (s, 1H), 0.23 (s, 3H), 0.09 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 158.11 (s), 150.92 (s), 142.54 (s), 139.78 (s), 139.60 (s), 138.06 (s), 132.65 (s), 132.63 (s), 132.41 (s), 131.34 (s), 130.82 (s), 128.93 (s), 126.06 (s), 48.30 (s, two peaks overlapping), 32.88 (s), 32.71 (s), 31.91 (s), 31.63 (s), 1.94 (s), 0.43 (s). HRMS (ESI+) calcd for $[C_{26}H_{40}ClN_2O_2Si_3^+]$: 531.2081, found: 531.2075.



30

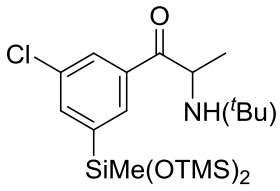
To $[Ir(cod)OMe]_2$ (4.0 mg, 6.0 μmol) and 2,4,7-trimethylphenanthroline (2.8 mg, 13 μmol) in a 20-mL vial was added THF (300 mg), $HSiMe(OTMS)_2$ (222 mg, 1.00 mmol, 5 equiv), cyclohexene (40 μL, 0.40 mmol), and thalidomide (51.9 mg, 0.201 mmol). The mixture was heated at 120 ℃ for 2 d. The resulting mixture was cooled to room temperature, and the volatile materials were evaporated. To the residue was added ethyl acetate (5 mL) and saturated $NaHCO_3$ (aq, 2 mL), and the mixture was stirred vigorously at room temperature for 30 min. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2 mL × 2). The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (3:7 ethyl acetate:hexanes) to afford the product as a colorless solid (43.2 mg, 45% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.47 (s, 1H), 8.04 (s, 1H), 7.94 (d, *J* = 7.1 Hz, 1H), 7.84 (d, *J* = 7.1 Hz, 1H), 5.01 (dd, *J* = 11.7, 4.7 Hz, 1H), 3.01 – 2.69 (m, 3H), 2.21 – 2.04 (m, 1H), 0.31 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 171.31 (s), 168.29 (s), 167.83 (s), 167.61 (s), 147.49 (s), 139.46 (s), 132.43 (s), 130.69 (s), 128.29 (s), 122.86 (s), 49.35 (s), 31.50 (s), 22.75 (s), 1.97 (s), -0.05 (s).

HRMS (ESI+) calcd for $[C_{20}H_{31}N_2O_6Si_3^+]$ ($M+H^+$): 479.1484, found: 479.1492; calcd for $[C_{20}H_{30}N_2NaO_6Si_3^+]$ ($M+Na^+$): 501.1304, found: 501.1304.



31

To $[Ir(cod)OMe]_2$ (4.0 mg, 6.0 μmol) and 2,4,7-trimethylphenanthroline (2.8 mg, 13 μmol) in a 20-mL vial was added THF (400 mg), $HSiMe(OTMS)_2$ (266 mg, 1.20 mmol, 6 equiv), cyclohexene (60 μL, 0.60 mmol), and clonidine (46.1 mg, 0.200 mmol). The mixture was heated at 100 ℃ for 2 d. The resulting mixture was cooled to room temperature, and the volatile materials were evaporated. To the residue was added ethyl acetate (5 mL) and saturated $NaHCO_3$ (aq, 2 mL), and the mixture was stirred vigorously at room temperature for 30 min. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2 mL × 2). The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (5:5 ethyl acetate:hexanes on a TLC plate pre-treated with Et_3N) to afford the product as a light brown liquid (78.8 mg, 87% yield). ^1H NMR (400 MHz, $CDCl_3$) δ 7.38 (s, 2H), 5.18 (bs, 1H), 3.52 (s, 4H), 0.24 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.82 (s), 145.91 (s), 133.58 (s), 132.98 (s), 129.51 (s), 42.58 (s), 1.97 (s), 0.15 (s). HRMS (ESI+) calcd for $[C_{16}H_{30}Cl_2N_3O_2Si_3^+]$: 450.1017, found: 450.1024.

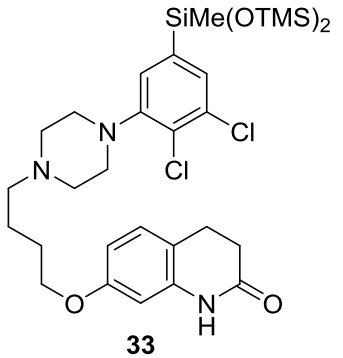


32

To $[Ir(cod)OMe]_2$ (2.0 mg, 3.0 μmol) and 2,4,7-trimethylphenanthroline (1.4 mg, 6.3 μmol) in a 20-mL vial was added THF (300 mg), $HSiMe(OTMS)_2$ (74 μL, 0.26 mmol, 1.3 equiv), cyclohexene (20 μL, 0.20 mmol), and bupropion (49.2 mg, 0.205 mmol). The mixture was heated at 100 ℃ for 1 d. The resulting mixture was cooled to room temperature and purified by preparative TLC (2:8 ethyl acetate:hexanes on a TLC plate pre-treated with Et_3N) to afford the product as a brown liquid (64.7 mg, 69% yield). The product and the starting material slowly oxidize under air and should be stored under an inert atmosphere. ^1H NMR (500 MHz, $CDCl_3$) δ 8.01 (s, 1H), 7.94 (s, 1H), 7.67 (s, 1H), 4.31 (q, J = 7.0 Hz, 1H), 2.40 (bs, 1H), 1.25 (d, J = 7.1 Hz, 3H), 1.04 (s, 9H), 0.30 (s, 3H), 0.12 (s, 18H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 204.27 (s), 142.18 (s), 137.80 (s), 136.07 (s), 135.13 (s), 130.97 (s), 129.30 (s), 52.32 (s), 50.94 (s), 29.84 (s), 22.65 (s), 1.98 (s), 0.04 (s). HRMS (ESI+) calcd for $[C_{20}H_{39}ClNO_3Si_3^+]$: 460.1921, found: 460.1924.

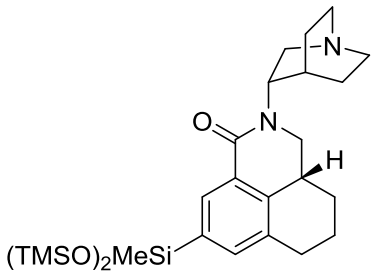
To $[Ir(cod)OMe]_2$ (4.0 mg, 6.0 μmol) and 2,4,7-trimethylphenanthroline (2.8 mg, 13 μmol) in a 20-mL vial was added THF (400 mg), $HSiMe(OTMS)_2$ (222 mg, 1.00 mmol, 5 equiv),

cyclohexene (40 μL, 0.40 mmol), and aripiprazole (90.2 mg, 0.201 mmol). The mixture was heated at 100 ℃ for 1 d. The resulting mixture was cooled to room temperature, and the volatile materials were evaporated. To the residue was added ethyl acetate (5 mL) and saturated $NaHCO_3$ (aq, 2 mL), and the mixture was stirred vigorously at room temperature for 30 min. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2 mL × 2). The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (5:5 ethyl acetate:hexanes on a TLC plate pre-treated with Et_3N) to afford **33** as a colorless solid (101 mg, 75% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 9.40 (s, 1H), 7.27 (d, *J* = 0.9 Hz, 1H), 7.11 (d, *J* = 0.8 Hz, 1H), 7.02 (d, *J* = 8.3 Hz, 1H), 6.51 (dd, *J* = 8.3, 2.4 Hz, 1H), 6.42 (d, *J* = 2.3 Hz, 1H), 3.95 (t, *J* = 6.2 Hz, 2H), 3.08 (bs, 4H), 2.88 (t, *J* = 7.5 Hz, 2H), 2.66 (bs, 4H), 2.64 – 2.58 (m, 2H), 2.52 – 2.44 (m, 2H), 1.85 – 1.77 (m, 1H), 1.75 – 1.66 (m, 1H), 0.24 (s, 3H), 0.11 (s, 18H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 172.61 (s), 158.75 (s), 150.63 (s), 138.70 (s), 138.36 (s), 133.72 (s), 129.18 (s), 128.77 (s), 128.60 (s), 122.91 (s), 115.68 (s), 108.80 (s), 102.40 (s), 67.92 (s), 58.33 (s), 53.44 (s), 51.44 (s), 31.15 (s), 27.36 (s), 24.63 (s), 23.56 (s), 1.96 (s), -0.02 (s). HRMS (ESI+) calcd for [$C_{30}H_{48}Cl_2N_3O_4Si_3^+$] ($M+H^+$): 668.2324, found: 668.2319.



33

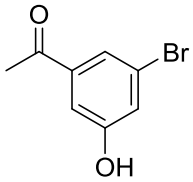
To $[Ir(cod)OMe]_2$ (4.0 mg, 6.0 μmol) and 2,4,7-trimethylphenanthroline (2.8 mg, 13 μmol) in a 20-mL vial was added THF (300 mg), $HSiMe(OTMS)_2$ (141 μL, 0.499 mmol, 2.5 equiv), cyclohexene (20 μL, 0.20 mmol), and palonosetron (59.3 mg, 0.200 mmol). The mixture was heated at 100 ℃ for 2 d. The resulting mixture was cooled to room temperature, and the volatile materials were evaporated. To the residue was added ethyl acetate (5 mL) and saturated $NaHCO_3$ (aq, 2 mL), and the mixture was stirred vigorously at room temperature for 30 min. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (2 mL × 2). The combined organic layer was washed with brine, dried over $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (5:5 acetone:methanol on a TLC plate pre-treated with Et_3N) to afford the product as a yellow wax (89.9 mg, 87% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 (s, 1H), 7.39 (s, 1H), 4.84 – 4.76 (m, 1H), 3.66 (dd, *J* = 11.8, 4.7 Hz, 1H), 3.33 (ddd, *J* = 14.0, 10.2, 1.8 Hz, 1H), 3.23 (t, *J* = 12.5 Hz, 1H), 3.03 – 2.92 (m, 2H), 2.92 – 2.73 (m, 6H), 2.10 – 1.98 (m, 2H), 1.93 (dd, *J* = 5.3, 2.7 Hz, 1H), 1.84 – 1.68 (m, 3H), 1.65 – 1.55 (m, 1H), 1.47 (td, *J* = 10.8, 4.5 Hz, 1H), 1.41 – 1.30 (m, 1H), 0.24 (s, 3H), 0.10 (s, 9H), 0.09 (s, 9H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 165.92 (s), 138.16 (s), 137.14 (s), 136.73 (s),



34

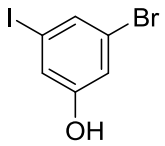
133.62 (s), 131.15 (s), 128.12 (s), 52.48 (s), 50.22 (s), 48.04 (s), 47.66 (s), 46.92 (s), 35.15 (s), 28.73 (s), 28.17 (s), 26.39 (s), 26.26 (s), 22.24 (s), 22.06 (s), 1.96 (s), 0.18 (s). HRMS (ESI+) calcd for [$C_{26}H_{45}N_2O_3Si_3^+$] (M+H^+): 517.2732, found: 517.2725.

Functionalization of Silylarenes



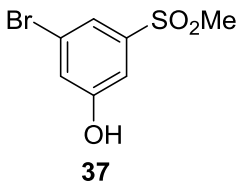
35

To **3** (79.3 mg, 0.189 mmol) in DMF (0.6 mL) was added KHF_2 (44.3 mg, 0.567 mmol, 3.0 equiv) and H_2O_2 (56 μL of 30% w/w in H_2O, 0.49 mmol, 2.6 equiv), and the mixture was stirred at room temperature for 16 h and then partitioned between H_2O and ethyl acetate (4 mL each). The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (4 mL). The combined organic layer was washed with H_2O (3 mL) and brine (2 mL), dried over $MgSO_4$, and concentrated. The residue was purified by flash column chromatography (0 → 50% ethyl acetate in hexanes) to afford the product as a colorless solid (35.3 mg, 87% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.62 (s, 1H), 7.46 – 7.42 (m, 1H), 7.25 (d, *J* = 0.9 Hz, 1H), 6.55 (bs, 1H), 2.59 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 197.94 (s), 157.18 (s), 139.47 (s), 124.30 (s), 123.89 (s), 123.30 (s), 113.94 (s), 26.96 (s). HRMS (ESI-) calcd for [$C_8H_6BrO_2^-$] (M-H^+): 212.9557, found: 212.9557.



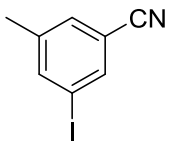
36

The oxidation of **7** (89.9 mg, 0.179 mmol) was conducted following the procedure for the oxidation of **3**. The residue was purified by flash column chromatography (0 → 30% ethyl acetate in hexanes) to afford the product as a colorless solid (46.2 mg, 86% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43 (d, *J* = 1.3 Hz, 1H), 7.17 – 7.12 (m, 1H), 6.99 – 6.95 (m, 1H), 5.09 (bs, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 156.54 (s), 132.48 (s), 123.72 (s), 123.31 (s), 118.71 (s), 94.36 (s). The NMR spectra agree with the literature data.[46]



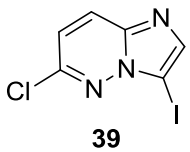
37

The oxidation of **5** (107 mg, 0.235 mmol) was conducted following the procedure for the oxidation of **3**. The residue was purified by flash column chromatography (0 → 60% ethyl acetate in hexanes) to afford the product as a colorless solid (52.6 mg, 89% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.57 (s, 1H), 7.39 (s, 1H), 7.29 (s, 1H), 3.11 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 157.94 (s), 142.11 (s), 124.86 (s), 124.11 (s), 122.03 (s), 113.13 (s), 44.57 (s). HRMS (ESI-) calcd for [$C_7H_6BrO_3S^-$] (M-H^+): 248.9227, found: 248.9227.



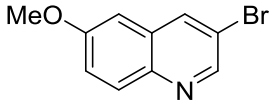
38

To **1** (71.6 mg, 0.212 mmol) in CH_2Cl_2 (1 mL) was added a solution of ICl (37.9 mg, 0.233 mmol) in CH_2Cl_2 (1 mL) dropwise at 0 ℃, and the mixture was stirred at room temperature for 2 h. The volatile materials were evaporated, and the residue was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a yellow solid (37.0 mg, 72% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.77 (s, 2H), 7.42 (s, 1H), 2.35 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 142.74 (s), 141.26 (s), 137.63 (s), 131.91 (s), 117.39 (s), 113.99 (s), 93.92 (s), 20.90 (s). The NMR spectra agree with the literature data.[33]



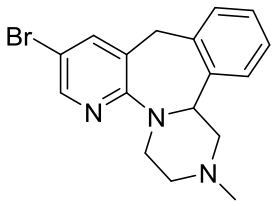
39

To **10** (64.0 mg, 0.171 mmol) in MeCN (2 mL) was added AgF (43 mg, 0.34 mmol) and *N*-iodosuccinimide (38 mg, 0.17 mmol), and the mixture was stirred at room temperature for 2 h. The mixture was then partitioned between ethyl acetate (4 mL) and an aqueous K_2CO_3 solution (4 mL). The organic phase was separated, and the aqueous phase was extracted with ethyl acetate (4 mL). The combined organic layer was washed with water (4 mL), brine (4 mL), and dried over $MgSO_4$, and filtered. The volatile materials were evaporated, and the residue was purified by flash column chromatography to afford the product as a light yellow solid (40.3 mg, 84% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.86 (d, *J* = 9.4 Hz, 1H), 7.83 (s, 1H), 7.09 (d, *J* = 9.4 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.05 (s), 141.13 (s), 140.08 (s), 126.98 (s), 119.51 (s), 69.20 (s). HRMS (ESI+) calcd for [$C_6H_4ClIN_3^+$] ($M+H^+$): 279.9133, found: 279.9133.



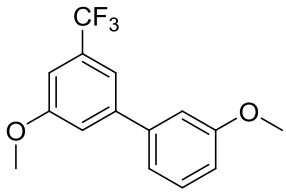
40

To **9** (92.5 mg, 0.244 mmol) in MeCN (2 mL) under nitrogen was added AgF (61.8 mg, 0.488 mmol, 2 equiv) and *N*-bromosuccinimide (47.8 mg, 0.268 mmol, 1.1 equiv), and the mixture was stirred at room temperature for 3 h. The mixture was then filtered, diluted with ethyl acetate (3 mL), and washed with saturated $NaHCO_3$ (4 mL). The aqueous layer was extracted with ethyl acetate (4 mL), the combined organic layer washed with brine, dried with $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (2:8 ethyl acetate:hexanes) to afford the product as a colorless solid (37.4 mg, 64% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.72 (d, *J* = 2.1 Hz, 1H), 8.16 (d, *J* = 1.8 Hz, 1H), 7.94 (d, *J* = 9.2 Hz, 1H), 7.34 (dd, *J* = 9.2, 2.7 Hz, 1H), 6.93 (d, *J* = 2.6 Hz, 1H), 3.90 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.59 (s), 148.81 (s), 142.57 (s), 136.02 (s), 130.96 (s), 130.43 (s), 122.76 (s), 117.83 (s), 104.30 (s), 55.71 (s). HRMS (ESI+) calcd for [$C_{10}H_9BrNO^+$] ($M+H^+$): 237.9862, found: 237.9861.



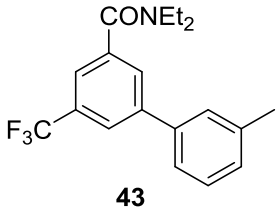
41

To a solution of **28** (45.7 mg, 0.0941) in MeCN (1 mL) under nitrogen was added AgF (23.9 mg, 0.188 mmol) and *N*-bromosuccinimide (17.8 mg, 0.100 mmol), and the mixture was stirred at room temperature for 2 h. The mixture was then diluted with ethyl acetate (4 mL), filtered, and washed with saturated $NaHCO_3$ (4 mL). The aqueous layer was extracted with ethyl acetate (4 mL), the combined organic layer washed with brine, dried with $MgSO_4$, filtered, and the solvents were evaporated. The residue was purified by preparative TLC (7:3 ethyl acetate:hexanes on a TLC plate pre-treated with Et_3N) to afford the product as a colorless solid (19.6 mg, 61% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.17 (d, *J* = 1.9 Hz, 1H), 7.43 (d, *J* = 1.8 Hz, 1H), 7.19 – 7.10 (m, 4H), 4.47 (d, *J* = 13.3 Hz, 1H), 4.33 (d, *J* = 9.6 Hz, 1H), 3.65 (d, *J* = 12.7 Hz, 1H), 3.43 (t, *J* = 11.8 Hz, 1H), 3.38 (d, *J* = 13.3 Hz, 1H), 2.94 (d, *J* = 11.0 Hz, 1H), 2.84 (d, *J* = 11.1 Hz, 1H), 2.49 (t, *J* = 10.5 Hz, 1H), 2.37 (s, 3H), 2.32 (td, *J* = 11.1, 2.7 Hz, 1H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 158.22 (s), 146.92 (s), 137.23 (s), 137.01 (s), 136.91 (s), 133.06 (s), 129.86 (s), 128.21 (s), 127.79 (s), 127.42 (s), 112.22 (s), 64.86 (s), 64.29 (s), 55.54 (s), 49.20 (s), 45.95 (s), 38.24 (s). HRMS (ESI+) calcd for [$C_{17}H_{19}BrN_3^+$] ($M+H^+$): 344.0757, found: 344.0755.



42

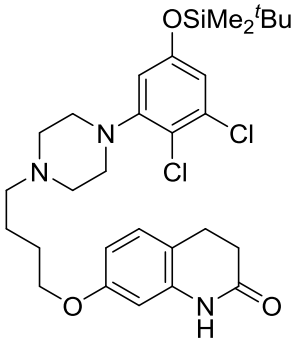
To a solution of $Pd(OAc)_2$ (1.9 mg, 8.5 μmol) and 1,2-bis(dicyclohexylphosphino)ethane (3.8 mg, 9.0 μmol) in toluene (600 mg) was added **6** (87.0 mg, 0.219 mmol), 3-iodoanisole (39.5 mg, 0.169 mmol), and $KOSiMe_3$ (65 mg, 0.51 mmol). The mixture was stirred at room temperature for 20 min and heated at 80 ℃ for 16 h. The mixture was then filtered over a pad of celite, and the volatile materials were evaporated. The residue was purified by preparative TLC (1:9 ethyl acetate:hexanes) to afford the product as a colorless liquid (44.2 mg, 93% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.43 (s, 1H), 7.39 (t, *J* = 7.9 Hz, 1H), 7.28 (s, 1H), 7.18 (d, *J* = 7.7 Hz, 1H), 7.15 – 7.09 (m, 2H), 6.95 (dd, *J* = 8.2, 2.2 Hz, 1H), 3.91 (s, 3H), 3.88 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 160.25 (s), 160.22 (s), 143.61 (s), 141.41 (s), 132.34 (q, *J* = 32.2 Hz), 130.13 (s), 124.15 (q, *J* = 272.6 Hz), 119.80 (s), 116.57 (s), 116.56 (q, *J* = 4.3 Hz), 113.58 (s), 113.19 (s), 109.55 (q, *J* = 3.7 Hz), 55.75 (s), 55.50 (s). HRMS (EI+) calcd for [$C_{15}H_{13}F_3O_2$]: 282.0868, found: 282.0870.



43

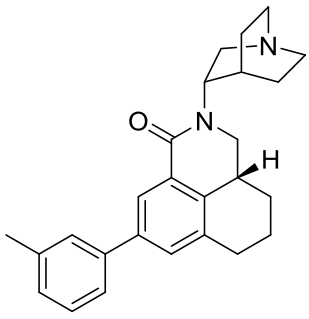
To a solution of $Pd(OAc)_2$ (1.6 mg, 7.1 μmol) and 1,2-bis(dicyclohexylphosphino)ethane (3.2 mg, 7.6 μmol) in toluene (500 mg) was added **4** (87.0 mg, 0.187 mmol), 3-iodotoluene (31.4 mg, 0.144 mmol), and $KOSiMe_3$ (55 mg, 0.43 mmol). The mixture was stirred at room temperature for 20 min and heated at 80 ℃ for 16 h. The mixture was then filtered over a pad of celite, and the volatile materials were

evaporated. The residue was purified by flash column chromatography (0→30% ethyl acetate in hexanes) to afford the product as a viscous colorless liquid (41.1 mg, 85% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.85 (s, 1H), 7.76 (s, 1H), 7.60 (s, 1H), 7.43 – 7.38 (m, 2H), 7.36 (t, *J* = 7.5 Hz, 1H), 7.23 (d, *J* = 7.3 Hz, 1H), 3.59 (d, *J* = 5.8 Hz, 2H), 3.28 (d, *J* = 5.8 Hz, 2H), 2.43 (s, 3H), 1.29 (s, 3H), 1.15 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 169.83 (s), 142.81 (s), 139.06 (s), 138.95 (s), 138.63 (s), 131.53 (q, *J* = 32.5 Hz), 129.29 (s), 129.13 (s), 128.39 (s), 128.05 (s), 124.66 (q, *J* = 3.7 Hz), 124.40 (s), 123.92 (q, *J* = 272.7 Hz), 121.90 (q, *J* = 3.7 Hz), 43.55 (s), 39.65 (s), 21.58 (s), 14.36 (s), 12.99 (s). ^{19}F NMR (376 MHz, $CDCl_3$) δ -61.87 (s). HRMS (EI+) calcd for [$C_{19}H_{20}F_3NO$]: 335.1497, found: 335.1493.



44

To a solution of **33** (66.9 mg, 0.100 mmol) in DMF (0.5 mL) was added KHF_2 (23.4 mg, 0.300 mmol) and H_2O_2 (30 μL, 30% aqueous solution, 0.26 mmol), and the mixture was stirred at room temperature for 16 h. The mixture was diluted with H_2O (10 mL) and extracted with a mixture of MeOH and ethyl acetate (1:20, 20 mL × 3). The organic layer was dried by Na_2SO_4, and the organic solvents were evaporated. The residue was dissolved in anhydrous DMF (2 mL), and to the solution was added imidazole (27.2 mg, 0.300 mmol) and *tert*-butyldimethylchlorosilane (45.2 mg, 0.300 mmol), and the mixture was stirred at room temperature for 16 h. The mixture was partitioned between diethyl ether (4 mL) and H_2O (4 mL), and the organic layer was separated. The aqueous layer was extracted with diethyl ether (3 mL × 3), the combined organic layer washed with H_2O (4 mL), brine (4 mL), dried by $MgSO_4$, and concentrated. The residue was purified by flash column chromatography (0→70% ethyl acetate in hexanes on silica pre-treated with Et_3N) to afford **44** as a colorless solid (40.7 mg, 70% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.75 (s, 1H), 7.03 (d, *J* = 8.2 Hz, 1H), 6.66 (s, 1H), 6.51 (d, *J* = 8.1 Hz, 1H), 6.44 (s, 1H), 6.37 (s, 1H), 3.95 (t, *J* = 6.0 Hz, 2H), 3.03 (s, 4H), 2.89 (t, *J* = 7.3 Hz, 2H), 2.79 – 2.51 (m, 6H), 2.50 – 2.40 (m, 2H), 1.86 – 1.76 (m, 2H), 1.76 – 1.64 (m, 2H), 0.96 (s, 9H), 0.19 (s, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 172.28 (s), 158.77 (s), 154.81 (s), 151.68 (s), 138.29 (s), 133.91 (s), 128.71 (s), 119.95 (s), 116.29 (s), 115.77 (s), 111.25 (s), 108.77 (s), 102.35 (s), 67.97 (s), 58.27 (s), 53.36 (s), 51.41 (s), 31.20 (s), 27.36 (s), 25.73 (s), 24.68 (s), 23.57 (s), 18.33 (s), -4.33 (s). HRMS (ESI+) calcd for [$C_{29}H_{42}Cl_2N_3O_3Si^+$] ($M+H^+$): 578.2367, found: 578.2359.



45

To a solution of $Pd(OAc)_2$ (1.8 mg, 8.0 μmol) and 1,2-bis(dicyclohexylphosphino)ethane (3.6 mg, 8.5 μmol) in toluene (600 mg) was added **34** (85.3 mg, 0.165 mmol), 3-iodotoluene (34.4 mg,

0.158 mmol), and $KOSiMe_3$ (60.7 mg, 0.474 mmol). The mixture was stirred at room temperature for 20 min and then at 80 ℃ for 16 h. The mixture was diluted with ethyl acetate (3 mL) and filtered over a pad of celite. The solvents were evaporated, and the residue was dissolved in Et_2O (2 mL) and treated with HCl (2 N ethereal solution, 2 mL), and the precipitate was separated and purified by HPLC (C18 column, 19 mm × 250 mm, 10 μm pore, 30 mL/min flow rate, 0→50% MeCN in H_2O over 15 min). The product fractions were combined, and the solvents were reduced to 10 mL. The solution was treated with K_2CO_3 (aqueous solution, 10 mL) and extracted with ethyl acetate (10 mL × 3). The combined organic layer was washed with brine, dried over $MgSO_4$, and filtered, and the solvents were evaporated to afford **45** as a colorless solid (42.6 mg, 70% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (s, 1H), 7.45 (d, *J* = 10.4 Hz, 2H), 7.41 (d, *J* = 7.8 Hz, 1H), 7.31 (t, *J* = 7.6 Hz, 1H), 7.15 (d, *J* = 7.4 Hz, 1H), 4.90 – 4.77 (m, 1H), 3.70 (dd, *J* = 11.8, 4.7 Hz, 1H), 3.45 – 3.37 (m, 1H), 3.29 (t, *J* = 12.5 Hz, 1H), 3.15 – 3.00 (m, 2H), 2.99 – 2.78 (m, 6H), 2.40 (s, 3H), 2.10 (t, *J* = 12.7 Hz, 2H), 2.01 (d, *J* = 2.4 Hz, 1H), 1.91 – 1.72 (m, 3H), 1.68 (ddd, *J* = 17.2, 11.7, 5.8 Hz, 1H), 1.55 (t, *J* = 12.0 Hz, 1H), 1.40 (dd, *J* = 23.9, 11.4 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 165.92 (s), 140.41 (s), 139.89 (s), 138.49 (s), 135.99 (s), 135.33 (s), 130.77 (s), 129.51 (s), 128.78 (s), 128.26 (s), 127.94 (s), 124.98 (s), 124.15 (s), 52.11 (s), 50.43 (s), 48.41 (s), 47.55 (s), 46.87 (s), 35.05 (s), 28.41 (s), 28.35 (s), 26.50 (s), 26.36 (s), 22.14 (s), 22.07 (s), 21.62 (s). HRMS (ESI+) calcd for [$C_{26}H_{31}N_2O^+$] ($M+H^+$): 387.2431, found: 387.2430.

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Chapter 6: Summary and Outlook

The silylation of C-H bonds is a relatively young field. The first observed silylation of a C-H bond was in 1982 when Curtis and Epstein reported the unselective silylation of neat benzene accompanied by silane redistribution,[1] and significant developments of this reaction have been made recently to create silylations of aryl and alkyl C-H bonds that occur in synthetically valuable ways. The reactions described in the early reports of C-H bond silylation typically required harsh conditions and neat substrates. More recent reports showed that the silylation of C-H bonds can occur under milder conditions in a more general fashion and be synthetically valuable. The Rh-catalyzed intermolecular silylation of arenes reported in Chapter 3 occurs at mild temperature (45 ℃) and does not require an excess of arenes.[2] These features, combined with the versatility of the arylsilane products, render this method suitable for synthetic applications. In addition, various directed or intramolecular *ortho*-silylations of aryl C-H bonds have been developed that proceed with arene as the limiting reagent.

The silylation of alkyl C-H bonds is less developed than the silylation of aryl C-H bonds. The intramolecular silylations of silyl ethers and silyl amines to form five-membered oxasiloles or azasiloles are the current significant examples of the silylation of alkyl C-H bonds, and these methods have been applied to the synthesis and derivatization of complex molecules. Directed intermolecular silylations of alkyl C-H bonds reported so far install a triethylsilyl group on an alkyl chain, which is synthetically less useful than silyl groups in which the silicon is connected to one or more electronegative heteroatoms. Undirected intermolecular silylation of benzylic C-H bonds only has been observed as a minor side product during arene silylations. Finally, catalytic silylation of methane by a Sc-complex has been reported, although the reaction is slow, requiring 7 d at 80 ℃ to afford the product in 50% yield (5 turnovers).

Thus, a major goal for the future development of the silylation of C-H bonds is the development of practical methods for the intermolecular silylation of alkyl C-H bonds. In addition, methods for the silylation of C-H bonds with trialkoxysilanes would be desirable because of the high reactivity of organotrialkoxysilanes as well as the potential for alkyltrialkoxysilanes to undergo cross-coupling selectively at the alkyl C-Si bond.

Compared to the borylation C-H bonds, the silylation of C-H bonds occurs with slower rates and requires higher temperatures and higher catalyst loadings. Thus, improving the catalyst activity for the silylation of C-H bonds will be a high priority and will be tied closely to mechanistic investigations.

Finally, development of further functionalizations of organosilicon reagents, such as trifluoromethylation or cyanation, would increase the synthetic utility of the silylation of C-H bonds. As organosilanes become more accessible through C-H bond functionalization, further derivatizations of organosilanes at the Si-C bond will likely be revealed.

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Chapter 7: Synthesis of Degradable Polymers from Biorenewable Feedstocks

7.1 Introduction

The global production of plastics reached 300 million metric tons in 2013.[1] The vast majority of these materials are sourced from non-renewable fossil fuels.[2] For many reasons, it is beneficial to develop alternative polymer materials sourced from renewable feedstocks. Currently, several renewable polymers have been developed and commercialized, including poly(lactic acid) (PLA), (polyhydroxyalkanoates) PHA, polyamide 11, and bio-polyethylene. However, the total volume of biorenewable polymers represents a very small fraction of the global plastic production, and less than half of those materials are biodegradable.[2]

Issues concerning the disposal of plastics must also be addressed. The thermal, oxidative, and hydrolytic stability of most synthetic polymers leads to their accumulation in the biosphere. It is estimated that a quarter of plastic worldwide is disposed in landfills, and tens of millions of metric tons of plastics accumulate in the oceans, causing damage to aquatic ecosystems.[1] Thus, it is important to design, synthesize and evaluate polymers that can be degraded under mild, ambient conditions to low-molecular weight monomers or oligomers that can either be further metabolized by microorganisms or otherwise assimilated.[3] Usually, biodegradable polymers contain heteroatom linkages in the backbone (such as polyesters) that allow for degradation through hydrolysis or enzymatic chain scission.

To develop new renewable and (bio)degradable polymers, we sought to incorporate Si-O linkages into the polymer backbone. Silyl ethers are common protecting groups used in organic synthesis and can be cleaved by hydrolysis under acidic or basic conditions to give the corresponding alcohols and siloxanes.[4-6] The rate of hydrolysis depends on the steric properties of the substituents on the silicon and the carbon atoms alpha to oxygen.[7] In addition, the relatively large Si-O and Si-C bond lengths can increase the flexibility of the polymer backbone, leading to low glass transition temperatures, a property that is important for creating elastomers or toughers for other plastic materials.[8-9]

Polymers containing C-Si-O-C or C-O-Si-O-C linkages in the repeating unit have been synthesized by several methods: 1) uncatalyzed melt-condensation of aryl- or biaryldiols with dianilino- or diphenoxysilanes;[10-12] 2) reactions of dichlorosilanes with bis(epoxide)s or bis(oxetane)s catalyzed by quaternary ammonium salts,[13-15] resulting in polymers with reactive pendant chloromethyl groups; 3) hydrosilylation of aliphatic and aromatic ketones or benzoquinones with hydrosilanes catalyzed by Ru- and Pd-complexes;[16-18] and 4) dehydrogenative coupling of alcohols with hydrosilanes catalyzed by Pd- and Rh-complexes.[19-20] Polysilylethers (PSEs) bearing aryl and biaryl backbones are typically solids with softening temperatures above 65 and 100 ℃, respectively,[10-11] whereas those bearing aliphatic backbones typically have glass transition temperatures (T_g's) below –80 ℃.[16] These studies have shown, as expected from the chemistry of silyl protective groups, that PSEs synthesized from secondary

alcohols or from silanes bearing bulky groups (e.g., Ph)[15, 20] are much more resistant to hydrolysis or methanolysis than are PSEs made from primary alcohols or from silanes bearing unhindered groups (e.g., Me).[16, 20] Most recently, polymers containing C-O-Si-O-C linkages were synthesized through silicon acetal metathesis polymerization catalyzed by a strong acid.[21] The methanol byproduct was actively removed during the reaction to drive the equilibrium to the polymer product.[21]

We considered undecenoic acid derivatives to be a desirable starting material to prepare polysilylethers (PSE) for several reasons. Undecenoic acid is derived from pyrolysis of rincinoleic acid, a principal component of castor oil.[22] Undecenoic contains a terminal alkene and a terminal carboxylic acid that allows for sequential functionalization to construct and A-B type bifunctional monomers.[23] Once reduced to undecenol, the molecule contains 11 CH_2 units, which should further increase the flexibility of the polymer chain.

We report the synthesis of a novel, bifunctional monomer containing Si-H and OH functionalities from an undecenoic acid derivative and polymerization of this monomer to afford PSEs with controlled molar mass. The PSEs undergo controlled degradation in neutral to moderately acidic (pH 2) aqueous media and are suitable for constructing polyurethanes (PU) using PSEs as macromolecular diol soft segments

7.2 Results and Discussion

We envisioned a method to combine commodity silanes with undecenol by hydrosilylation of the alkene, and subsequent polycondensation forming Si-O bonds. Although Si-O bonds can be formed through the direct reaction of Si-Cl and R-OH moieties, this reaction requires stoichiometric amount of base and separation of the stoichiometric corresponding salt byproduct. In addition, a monomer containing a Si-Cl moiety will be sensitive to moisture. Thus, we sought to use the catalytic dehydrogenative condensation of Si-H and OH groups[24-26] as an alternative strategy to form the Si-O bonds. The advantage of this strategy is that Si-H bonds are hydrolytically stable and do not readily react with OH groups in the absence of a catalyst. In addition, the only byproduct of this coupling process is H_2, which is easily removed.

To synthesize a bifunctional molecule from undecenoic acid containing one Si-H and one OH moiety, we conducted the hydrosilylation of methyl 10-undecenoate with Me_2SiClH catalyzed by 10ppm of Karstedt's catalyst[27] (Fig. 1). The Si-Cl moiety was used as a masked Si-H group because Me_2SiH_2 is a catalyst poison.[28][29-30] One-pot, consecutive reduction of both the Si-Cl and the ester groups with $LiAlH_4$ (which ensures that the Si-Cl and OH moieties are not present in the same pot given the Si-Cl reduction is much faster than the ester reduction) furnished the novel bifunctional monomer **1** on a decagram-scale. The monomer was further distilled to obtain

material in purity (99.5% by GC analysis) suitable for synthesis of high molar mass polymers by step-growth polymerization.

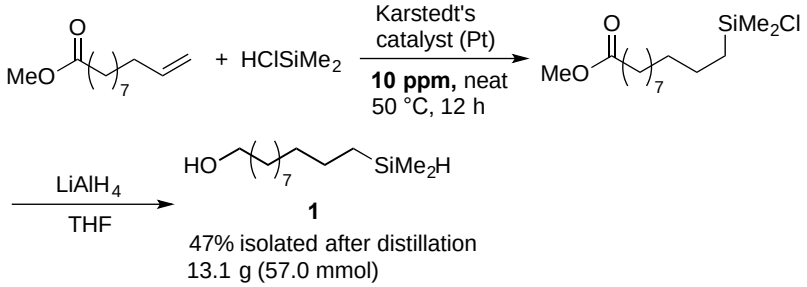


Figure 1. Synthesis of bifunctional monomer **1**.

Several methods for the dehydrogenative silylation of alcohols are known, including reactions catalyzed by transition metal complexes[20, 31] and by boranes.[24] We first attempted the dehydrogenative polymerization of **1** with $[Ir(coe)_2Cl]_2$ as the catalyst, based on prior work on the Ir-catalyzed dehydrogenative silylation of alcohols by one of the authors' group.[31] However, polymerization of **1** catalyzed by $[Ir(coe)_2Cl]_2$ at temperatures ranging from 20 ℃ to 80 ℃ led to insoluble products. This material was tentatively assigned to be a cross-linked polymer, because the reaction of a hydrosilane with an Ir precursor lacking strongly coordinating ligands has been shown to form a silane-bridged dimeric Ir species containing multiple silyl groups bound to Ir.[32-33] Similarly, polymerization conducted with $[Ru(p\text{-cymene})Cl_2]_2$ as the catalyst led to an insoluble material. Thus, we conducted the polymerization with the more defined, single-site Ir catalysts reported by Crabtree.[34] However, the molar mass of the resulting polymeric products was relatively low.

Although many other transition metals could be evaluated for this process, these Ir and Ru catalysts are among the most active for dehydrogenative silylation. Thus, we investigated reactions catalyzed by alkali metal alkoxides. The ring opening polymerization of octamethyltetrasiloxane (D4) catalyzed by alkali metal hydroxides[35] and the dehydrogenative silylation of alcohols catalyzed by strong inorganic bases are known.[36-39] Thus, we investigated the polymerization of neat **1** with CsOH (0.2 – 1 mol%) as the catalyst. The polymerization proceeded rapidly at 140 ℃ under these conditions to afford a transparent viscous oil. KH was also studied as the catalyst; in this case the reaction proceeded at 100 ℃ with 1 mol % of KH. The NMR spectrum of the product consisted of well-resolved signals for the silicon methyl groups, the methylene group *alpha* to silicon, and the methylene groups *alpha* and *beta* to oxygen. Signals corresponding to the monomer were not observed. These data provided preliminary evidence for formation of the targeted polymer and high conversion of the monomer.

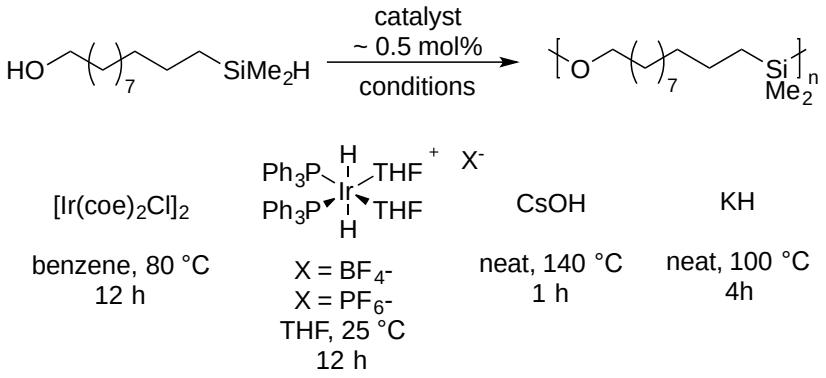


Figure 2. Dehydrogenative polymerization of **1** by various catalysts.

The functionality at the terminus of the polymer chains was deduced by analysis of the end groups (Figure 3). The ^{1}H-NMR spectrum of the polymer contained a triplet at 3.57 ppm, corresponding to the C*H*$_2$OSi group, a multiplet at 0.60 ppm, corresponding to the SiOC*H*$_2$ group, and a singlet at 0.09 ppm, corresponding to the Si(C*H*$_3$)$_2$. No signals from the Si-H functionality were observed indicating complete reaction of these bonds. The ^{1}H-NMR spectrum revealed a group of small triplets (3.66-3.60ppm) that resonate 0.08 ppm downfield of the major C*H*$_2$OSi signal (3.56 ppm) of the polymer chain, a small multiplet (0.51 ppm) that resonates 0.09 ppm upfield of the major C*H*$_2$SiO signal (0.60ppm), and a small singlet (0.04 ppm) that resonates 0.05 ppm upfield of the major Si(C*H*$_3$)$_2$ signal (0.09 ppm). Together, these signals indicate the presence of Si-O-Si linkages within the polymer chain. Assuming the Si-O-Si linkage results from reaction of two Si-H ends of a monomer with H_2O (most likely formed from reaction of CsOH with the OH groups of the monomer), an excess of OH groups would be present in the reaction. Thus, both ends of the polymer should be terminated by OH groups.

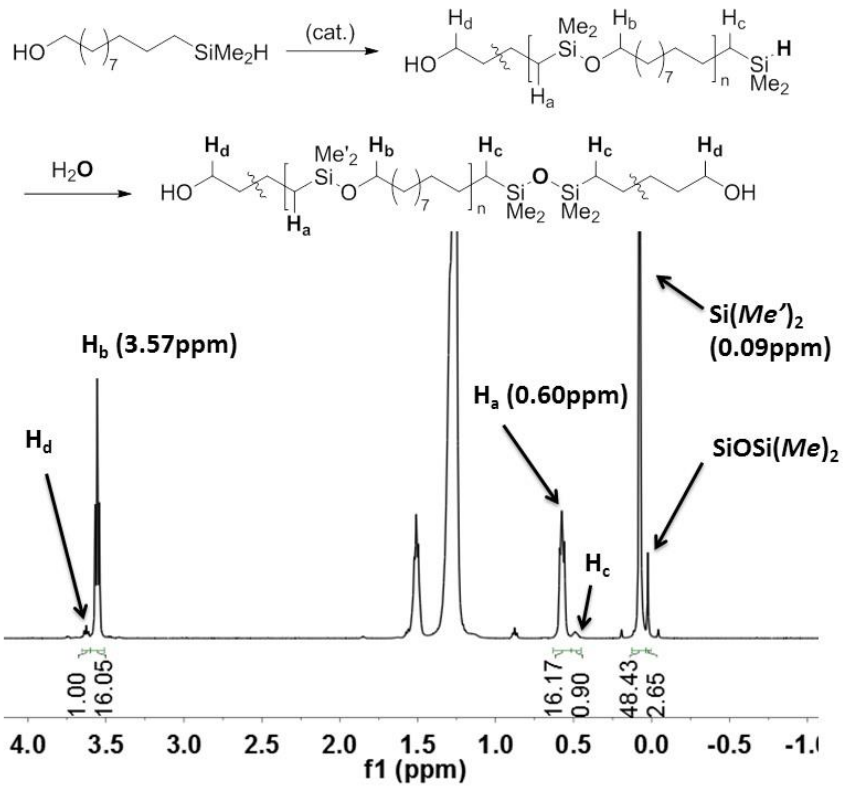


Figure 3. Detailed structure of the PSE with signals corresponding to the end groups labeled in blue.

This hypothesis is supported by comparing the chemical shifts of the aforementioned protons to those of a model compound **2** (Figure 4). The Si(C*H*$_3$)$_2$ and C*H*$_2$SiO signals of the proposed Si-O-Si linkages in the polymer overlap with those of **2**, and the signal from the C*H*$_2$OH unit in the proposed OH end groups in the polymer overlap with those of the C*H*$_2$OH end of **2**. Consistent with this assignment, the ratio of the integrations between the major and the minor signals due to the C*H*$_2$O, C*H*$_2$SiO, and Si(C*H*$_3$)$_2$ groups are consistent with this assignment.

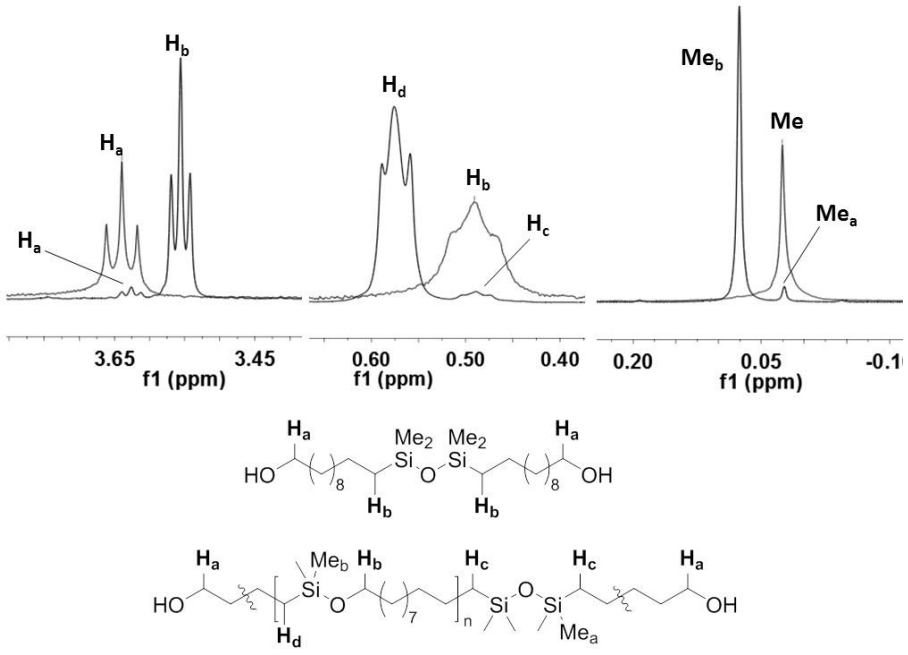
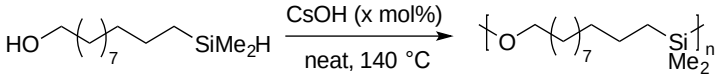


Figure 4. Comparison of the ^{1}H-NMR spectrum of PSE to that of the model compound 2.

The molar mass of the polymer can be estimated from the ratio of the C*H*$_2$OH and C*H*$_2$OSi by NMR spectroscopy (M_n = 21k, see SI) assuming exactly two end groups per chain. These data agree with the molar measured by light scattering size exclusion chromatography analysis (M_n = 23 kg/mol, Table 1).

Because H_2O can effectively act as a dihydroxy AA-type monomer that introduces a stoichiometric imbalance during polymerization,[40] we hypothesized that the degree of polymerization could be controlled by varying the amount of catalyst (and thus H_2O) in the system.[41] To test this hypothesis, we conducted the polymerization with 0.5-2.5% CsOH and examined the molar masses by both NMR analysis and by SEC equipped with a differential refractive index (RI) and light scattering (LS) detectors. Indeed, the molar masses of the polymer formed from reactions conducted with larger quantities of H_2O (from CsOH) was lower than that from reactions with smaller quantities of H_2O (Table 1).

Table 1. The effect of catalyst loading on the molar mass of the polymers.[a]

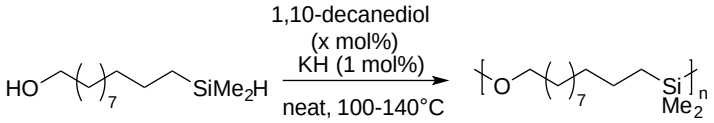


entry	x	M_n[b]	M_n[c]	M_w[c]	$Đ$[c]	M_n[d]	M_w[d]	$Đ$[d]
1	0.2	30	49	85	1.74	37	65	1.72
2	0.5	21	38	63	1.65	23	40	1.69
3	1	16	24	43	1.80	17	29	1.73
4	2.5	7	9	16	1.88	8	11	1.40

[a] dn/dc = 0.049. dn/dc of the polymer was determined using a sample with a M_n of 10 kg/mol (by SEC). Molar masses are in kg/mol. [b] Determined by NMR spectroscopy. [c] Determined by SEC with RI. [d] Determined by SEC with LS.

To avoid side reactions associated with excess, unquenched hydroxide catalysts, we conducted the polymerization with a constant (1 mol%) amount of KH and controlled the molar mass by adding various amounts of AA-type monomer 1,10-decanediol as opposed to various amounts of CsOH.[42] The molar mass of the polymer formed from a series of polymerizations with 1-8 mol% 1,10-decanediol decreased with increased loading of 1,10-decanediol (Table 2).

Table 2. The effect of 1,10-decanediol on the molar masses of PSE.[a]



entry	x	M_n[b]	M_n[c]	M_w[c]	$Đ$[c]	M_n[d]	M_w[d]	$Đ$[d]
1	1	14	23	43	1.89	16	33	2.03
2	2	8.1	11	15	1.361	nd	nd	nd
3	4	4.9	5.6	9.0	1.606	nd	nd	nd
4	8	2.6	3.6	6.3	1.76	3.1	4.6	1.46

[a] Molar masses are in kg/mol. [b] Determined by NMR spectroscopy. [c] Determined by SEC with polystyrene standards. [d] Determined by SEC with light scattering.

The PSEs produced by the based-catalyzed polymerization were, in general, colorless, viscous oils or gels, depending on the molar mass. Analysis of the PSE with an M_n of ~23 kg/mol by thermogravimetric analysis showed that this material lost 1% of its weight at 244 ℃ and 5% of its weight at 278 ℃. Thus, the PSEs are significantly more thermally stable than polysilicon acetals containing aliphatic backbones[21] but less stable than PSEs containing aromatic

backbones.[10, 17, 20] The T_g of the polymer is -67 ℃, and no significant melting or crystallization transitions were observed by differential scanning calorimetry.

Having designed the polysilylethers to undergo hydrolysis at the Si-O bonds, we tested the stability of the PSE materials toward mixtures of aqueous and organic solvents and water alone under hydrolytic degradation conditions. Dissolution of a PSE sample (M_n ~23 kg/mol) in a common organic solvent, such as THF, followed by addition of an equal volume of neutral water led to complete degradation to the model siloxane **2** under these biphasic conditions after 24 h at 50 ℃ or after 2 d at 23 ℃. In addition, complete degradation of the same polymer at 50 ℃ occurred within 7 days in water only at pH 2 and within 50 days at pH 4 to give **2** a white foam in the aqueous layer, despite the low solubility of the starting polymer in water.[43] At room temperature, complete degradation at pH 2 occurred over 22 d. Degradation even occurred at neutral pH at 50 ℃; 10% of the Si-O bonds hydrolyzed after 50 d (Figure 5).

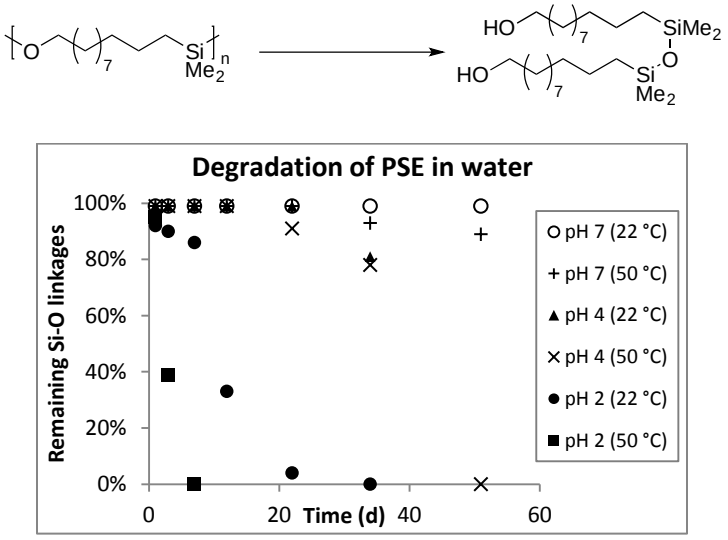


Figure 5. Depolymerization of PSE in water. Conversion of the silylether linkages determined by NMR spectroscopy.

To exploit the low T_g of the polysilylethers and the hydroxy termini, we synthesized polyurethanes from a hydroxy-telechelic PSE (~3 kg/mol) and a diisocyanate. The polymerization was conducted with methylene diphenyl diisocyanate (MDI) in THF at 65 ℃ for 4 h with 2 mol% of $Sn(Oct)_2$ (relative to PSE, 1 mol% per OH end) as the catalyst. The formation of polyurethanes was evidenced by the NMR spectral and SEC data of the material obtained after precipitation in MeCN to give a colorless and rubbery solid. The ^{1}H-NMR spectrum of the polyurethane lacks the signal from the CH_2OH of the polymer initiator at 3.62-

3.68 ppm. Instead, a triplet at 4.13 ppm was observed, corresponding to the CH_2C(O) units at the carbamate linkages (see the SI). Comparison of the SEC traces of the polysilylether and the material formed after reaction with MDI indicates that the molar mass increased significantly (Figure 6). The M_n and M_w values, relative to polystyrene standards, were 29 kg/mol and 85 kg/mol, respectively. The relatively large dispersity ($Đ$ = 2.94) results from a minor shoulder with a longer retention time than that of the main peak (Figure 6, blue trace). This lower molecular-weight material most likely corresponds to a small amount of PSEs lacking hydroxyl end groups. The M_n and M_w determined by light scattering are 45k and 70k. The polymer exhibited good thermal stability (1% weight loss at 209 ℃ and 5% weight loss at 309 ℃) and a glass transition at -68 ℃.

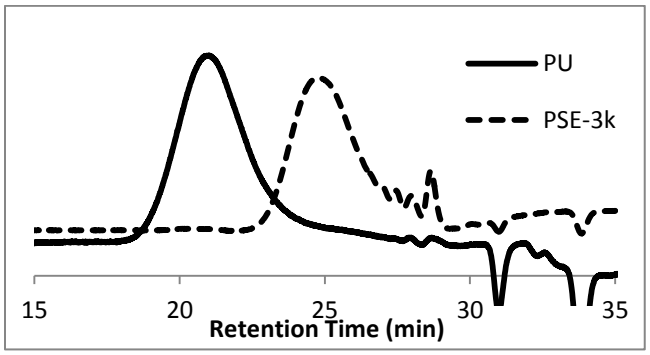


Figure 6. Overlay of the SEC traces of PU (blue) and PSE (red).

7.3 Conclusions

In conclusion, we have synthesized a novel polysilylether that is sourced from a renewable feedstock and can be hydrolyzed under mild conditions. The molar mass of the polymer can be controlled by varying the amount of A-A type monomer in the reaction system. In addition, we have synthesized a polyurethane from methylene diphenyl diisocyanate (MDI) and a dihydroxy-telechelic polysilylether. Further studies on the relationship between the length of the PSE and the physical and mechanical properties of the resulting polyurethane, and further studies on synthesizing additional copolymers with PSE structures are underway.

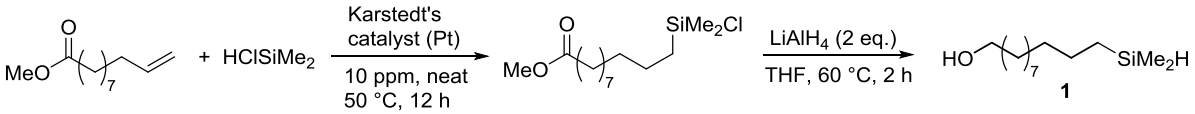
7.4 Experimental

Reagents and Instrumentation

Methyl 10-undecenoate, 10-undecenol, Me_3SiCl, Et_3N, $HMe_2SiOSiMe_2H$, $HClSiMe_2$, Karstedt's catalyst, $LiAlH_4$, and $Sn(Oct)_2$ were purchased from commercial sources and used without purification. CsOH·H_2O was purchased from Sigma-Aldrich and dried under high vacuum at 120 ℃ for overnight. (D,L)-Lactide was purchased from commercial sources and purified by recrystallization from toluene according to the literature procedure.[44] THF, toluene, and hexanes were dried by an Innovative Technology Pure-Solv solvent purification system and stored over molecular sieves.

NMR spectra were acquired on Bruker AVQ-400, AVB-400, DRX 500, and AV-600 spectrometers. Chemical shifts were reported in ppm relative to residual solvent peaks ($CDCl_3$ = 7.26 ppm for ^1H and 77.16 ppm for ^{13}C). Coupling constants were reported in Hz. SEC was performed on a Malvern Viscotek TDAMax chromatography system equipped with TGuard T2000, T3000, T4000, and T5000 columns using THF as the eluent (30 ℃, 1 mL/min). DSC was performed on a TA Instruments Q200 calorimeter (purge gas: He, flow rate: 25 mL/min, ramp rate: 20 ℃/min, temperature range: -90 - 200 ℃). TGA was performed on a TA instrument Q500 thermogravimetric analyzer under nitrogen from 25 to 500 ℃ at a ramp rate of 10 ℃/min.

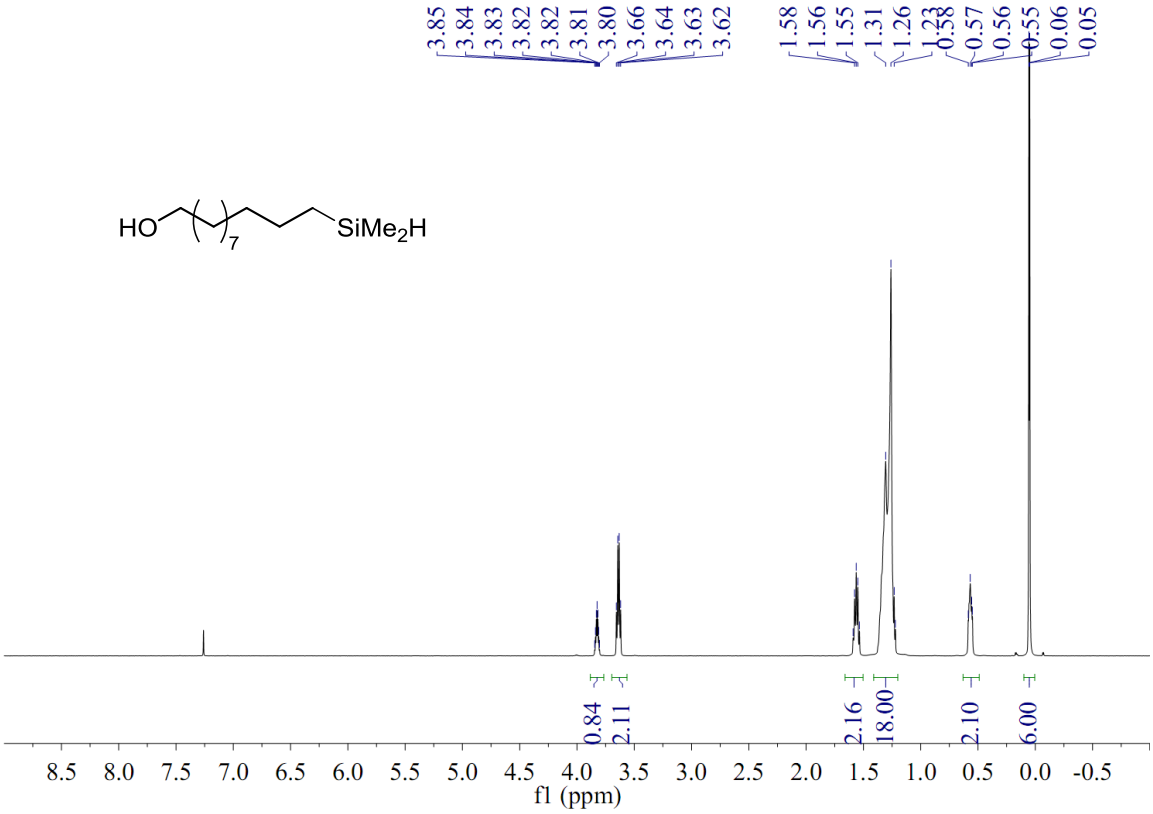
Synthesis of Monomer 1

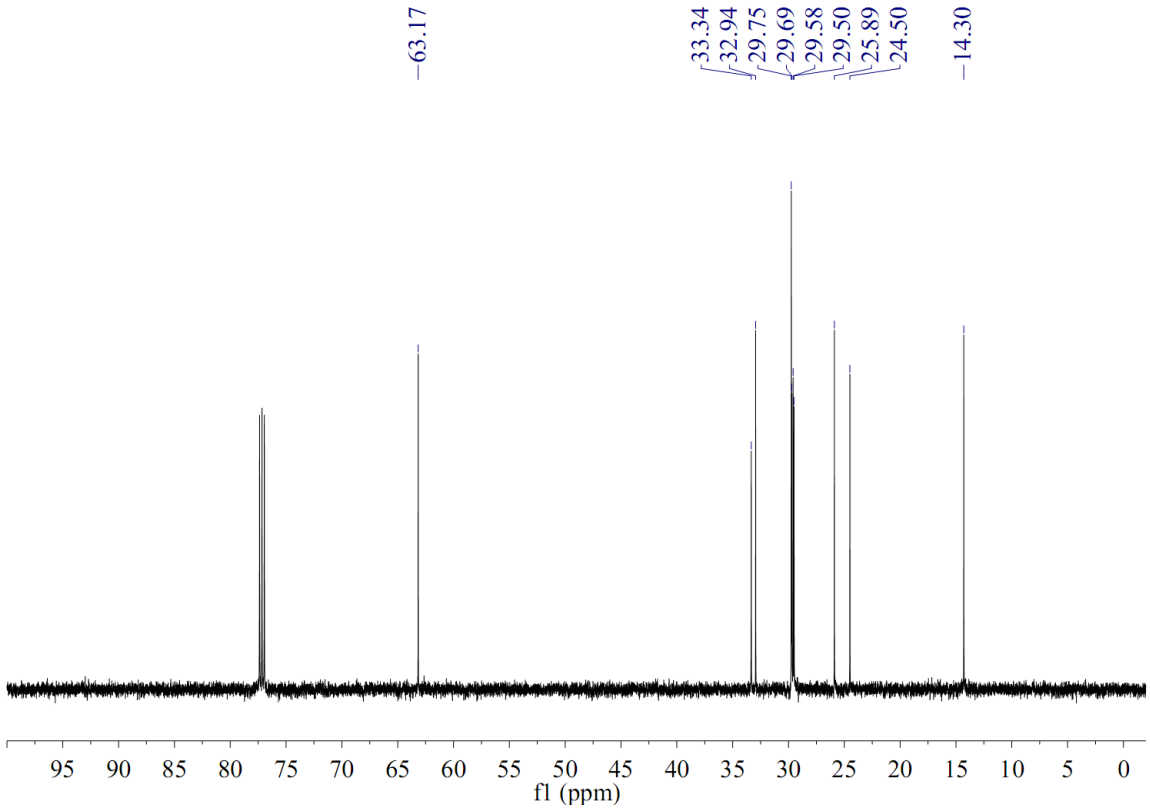


To a mixture of $HClSiMe_2$ (13.7 g, 145 mmol) and methyl 10-undecenoate (23.8 g, 120 mmol) in a 100-mL glass round-bottom flask equipped with an egg-shaped Teflon-coated magnetic stir bar was added Karstedt's catalyst (~2% xylene solution, 12 μL, 0.001 mol%), and the flask was capped with a rubber septum and heated under N_2 at 50 ℃ for 12 h. After cooled to room temperature, the content of the flask was added dropwise to a stirring suspension of $LiAlH_4$ (4.94 g, 130 mmol) in dry THF (500 mL) in an oven-dried 1-L round-bottom flask equipped with an egg-shaped magnetic stir bar under N_2 at 0 ℃. The flask was shaken by hand occasionally to break up the chunk formed. After the addition of the chlorosilane intermediate, the flask was heated in an oil bath at 55 ℃ for 2 h before cooled to 0 ℃. The reaction mixture was quenched by slow addition of ethyl acetate (100 mL). To the mixture was added an aqueous solution of Rochelle salt (60 g in 200 mL H_2O), and the mixture was stirred vigorously. Then the layers were separated, and the aqueous layer was extracted with hexanes (100 mL × 2). (If the resulting emulsion did not separate into two layers, we found that filtering the mixture over celite afforded a mixture that readily separated.) The combined organic layer was washed with H_2O (100 mL × 2) and brine (100 mL), dried over Na_2SO_4, filtered, and the solvents were evaporated. The residue was purified by silica gel column chromatography (1:9 → 2:8 ethyl acetate:hexanes) and then distilled (100-110 ℃, 20 mTorr) to afford monomer 1 as a colorless liquid (13.1 g, 47%

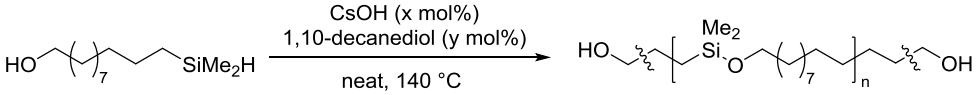
yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.82 (dp, *J* = 7.0, 3.5 Hz, 1H), 3.64 (dd, *J* = 12.2, 6.4 Hz, 2H), 1.66 – 1.50 (m, 2H), 1.41 – 1.20 (m, 16H), 0.63 – 0.49 (m, 2H), 0.05 (d, *J* = 3.6 Hz, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 63.17 (s), 33.34 (s), 32.94 (s), 29.75 (s), 29.69 (s), 29.58 (s), 29.50 (s), 25.89 (s), 24.50 (s), 14.30 (s), -4.30 (s). HRMS (EI+) calcd for $C_{13}H_{30}OSi$: 230.2066, found: 230.2009.

NMR Spectra of Monomer 1



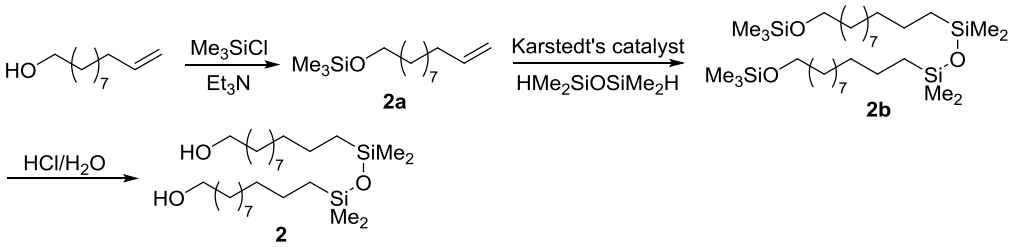


Typical Procedure for the Polymerization of 1



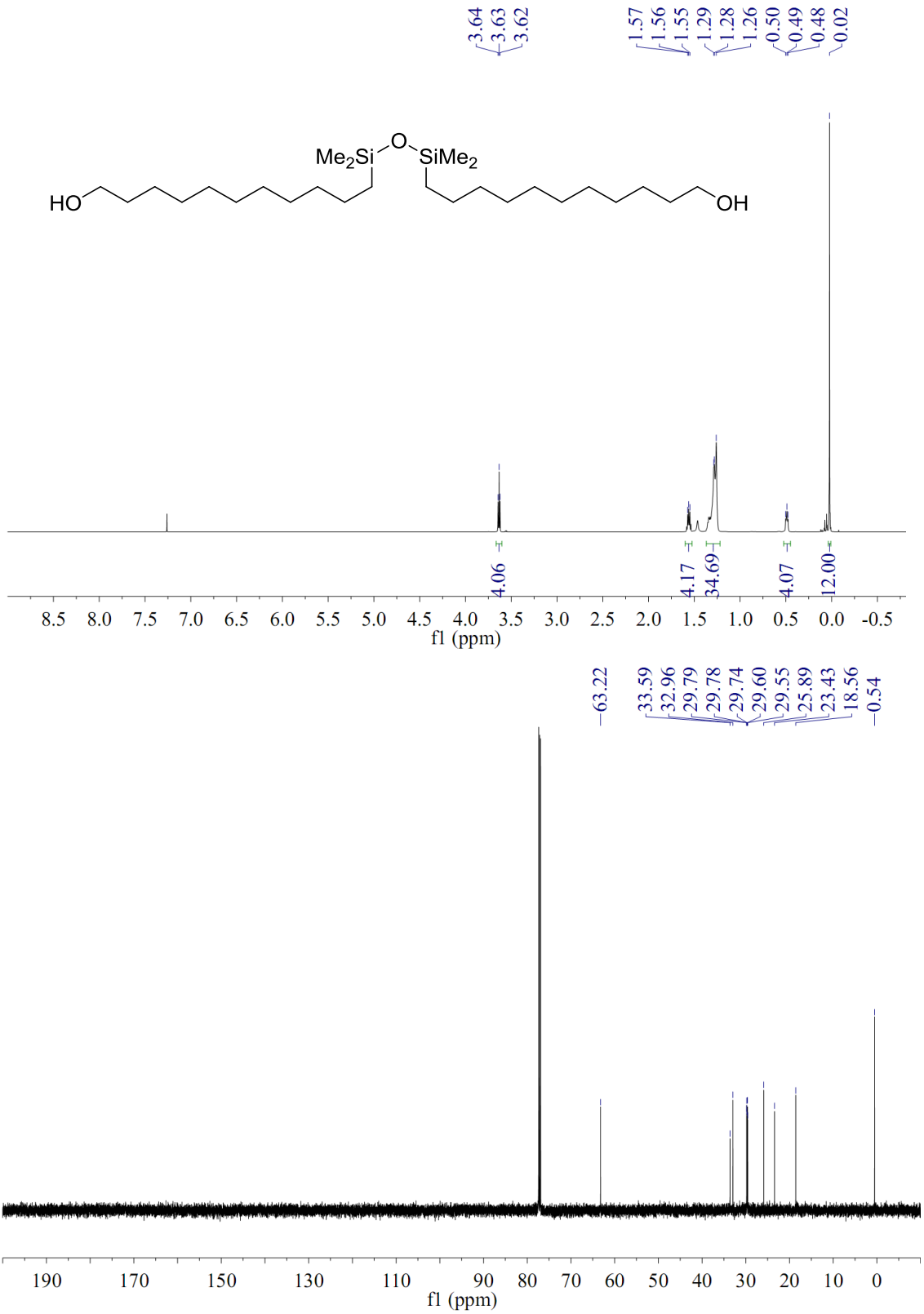
To an oven-dried 4-mL glass vial equipped with a 12.7 mm×3 mm octagonal Teflon-coated magnetic stir bar was charged CsOH (3.3 mg, 0.022 mmol, 0.5 mol%), 1,10-decanediol (15.2 mg, 0.087 mmol, 2 mol%), and monomer 1 (1.00 g, 4.35 mmol). The vial was heated at 140 ℃ for 1 h under an N_2 atmosphere (connected to an N_2 Schlenk line). For reactions conducted on a smaller scale (e.g. 0.5 mmol of 1), the vial was sealed with a Teflon-lined cap and heated. After the polymerization (usually the stir bar was trapped in the polymer), the reaction mixture was cooled to room temperature, and the content was analyzed by NMR spectroscopy and SEC analysis.

Synthesis of Model Compound 2



To a solution of 10-undecenol (200 μL, 1.00 mmol) and Et_3N (167 μL, 1.20 mmol) in dry hexanes (10 mL) in a 20-mL glass vial was added slowly Me_3SiCl (152 μL, 1.20 mmol) under an inert atmosphere, and the reaction mixture became turbid. The mixture was stirred vigorously at room temperature for 20 min and then filtered by suction, and the solids were rinsed with hexanes (5 mL). The volatile materials were evaporated to give **2a** (200 mg, 0.825 mmol). To a mixture of **2a** (200 mg, 0.825 mmol) and $HMe_2SiOSiMe_2H$ (72.9 μL, 0.825 mmol) was added Karstedt's catalyst (1 μL of 2 wt % xylene solution), and the mixture was stirred at 50 ℃ for 12 h to afford **2b**. To **2b** (30 mg, 0.050 mmol) was added an aqueous HCl solution (1.0 N, 0.25 mL), and the mixture was stirred at room temperature for 1 h, at which point the mixture became a colorless mash. The mixture was partitioned between ethyl acetate (2 mL) and water (2 mL), and the organic layer was separated, the aqueous layer extracted with ethyl acetate (2 mL), and the organic layers were combined, washed with brine (2 mL), dried over Na_2SO_4, and the solvents were evaporated to give **2** as a colorless liquid (23 mg, 99% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 3.63 (t, J = 6.7 Hz, 4H), 1.60 – 1.53 (m, 4H), 1.37 – 1.22 (m, 32H), 0.49 (t, J = 7.7 Hz, 4H), 0.02 (s, 12H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 63.22 (s), 33.59 (s), 32.96 (s), 29.79 (s), 29.78 (s), 29.74 (s), 29.60 (s), 29.55 (s), 25.89 (s), 23.43 (s), 18.56 (s), 0.54 (s). HRMS (ESI+) calcd for $C_{26}H_{59}O_3Si_2^+$ [M+H$^+$]: 475.3997, found: 475.3994.

NMR spectra of 2



Determination of the Molecular Weight by NMR Spectroscopy

The molecular weight of the polymer was determined from the ratio of repeating units to end groups. The triplet at 3.56ppm corresponds to the C*H*$_2$OSi of the repeating unit, and the group of triplets at 3.65-3.61ppm corresponds to the C*H*$_2$OH of the chain end. Because there are two chain ends per chain, the average number of repeating units in a chain is:

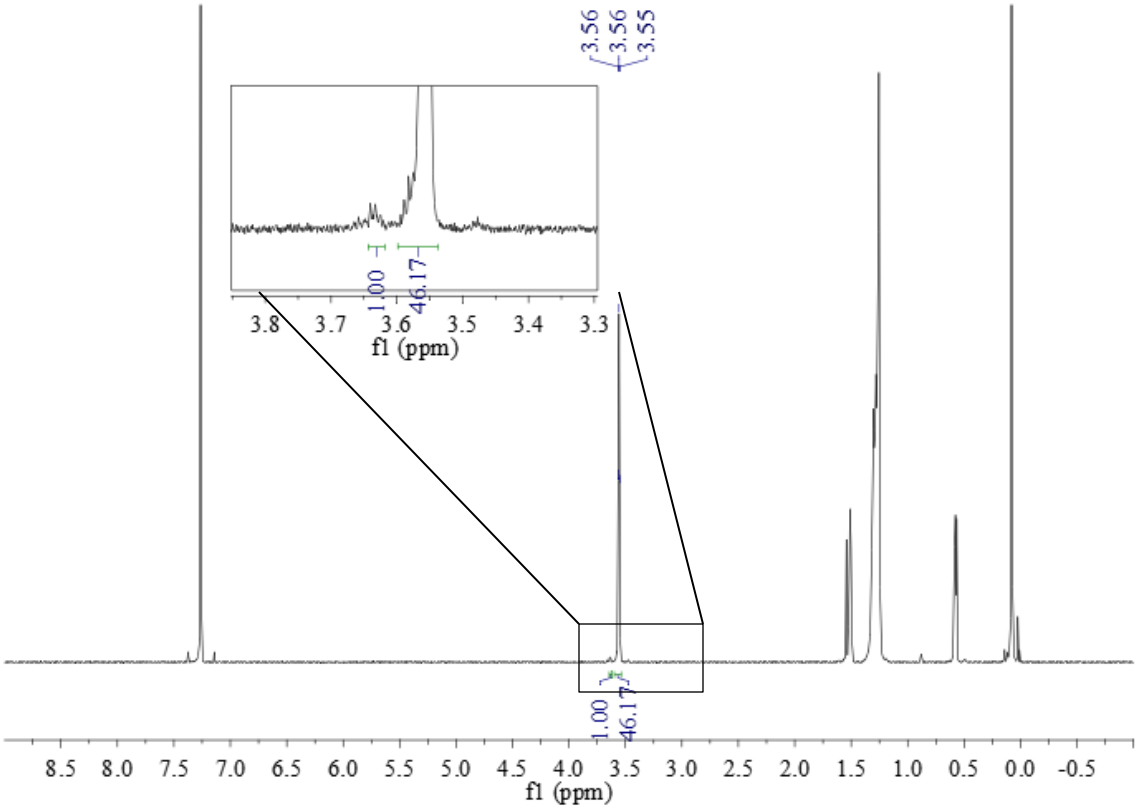
$$X_n = \frac{N_{CH_2OSi}}{0.5 \times N_{CH_2OH}} = 2 \times \frac{N_{CH_2OSi}}{N_{CH_2OH}}$$

and the average molecular weight is:

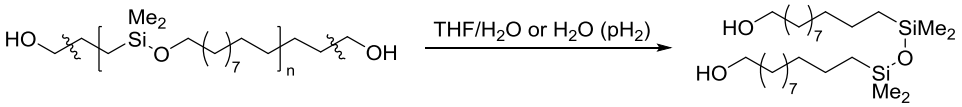
$$Mn = X_n \times MW_{repeating\ unit} = 2 \times \frac{N_{CH_2OSi}}{N_{CH_2OH}} \times MW_{repeating\ unit}$$

For a representative NMR spectrum shown below, the ratio of C*H*$_2$OSi to C*H*$_2$OH is 46:1. Thus, the average molecular weight is:

$$Mn = 2 \times \frac{N_{CH_2OSi}}{N_{CH_2OH}} \times MW_{repeating\ unit} = 2 \times 46 \times 228 = 21{,}000$$

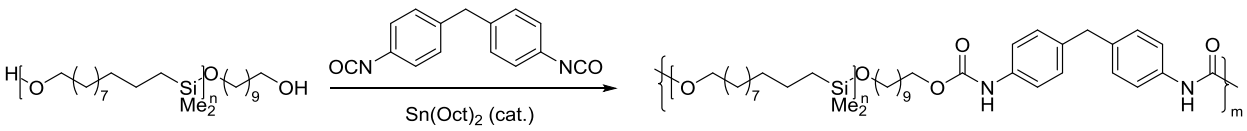


Degradation of the Polymer



The PSE (~20 mg, M_n = 23 kg/mol) was placed in a 4-mL glass vial equipped with a stir bar, and the appropriate solvent/mixture (0.5 mL aqueous buffer solutions or 0.5 mL plus 0.5 mL THF) was added. The mixture was stirred at the desired temperature, and aliquots were taken at the desired time points, the volatile materials evaporated, and the residue analyzed by NMR spectroscopy. A typical ^{1}H NMR spectrum of an aliquot is shown below. The ratio of the triplet at 3.64 ppm (C*H*$_2$OH of 2) to the triplet at 3.56 ppm (C*H*$_2$OSi of PSE) was used to calculate the percentage of CH_2O-Si linkages remaining.

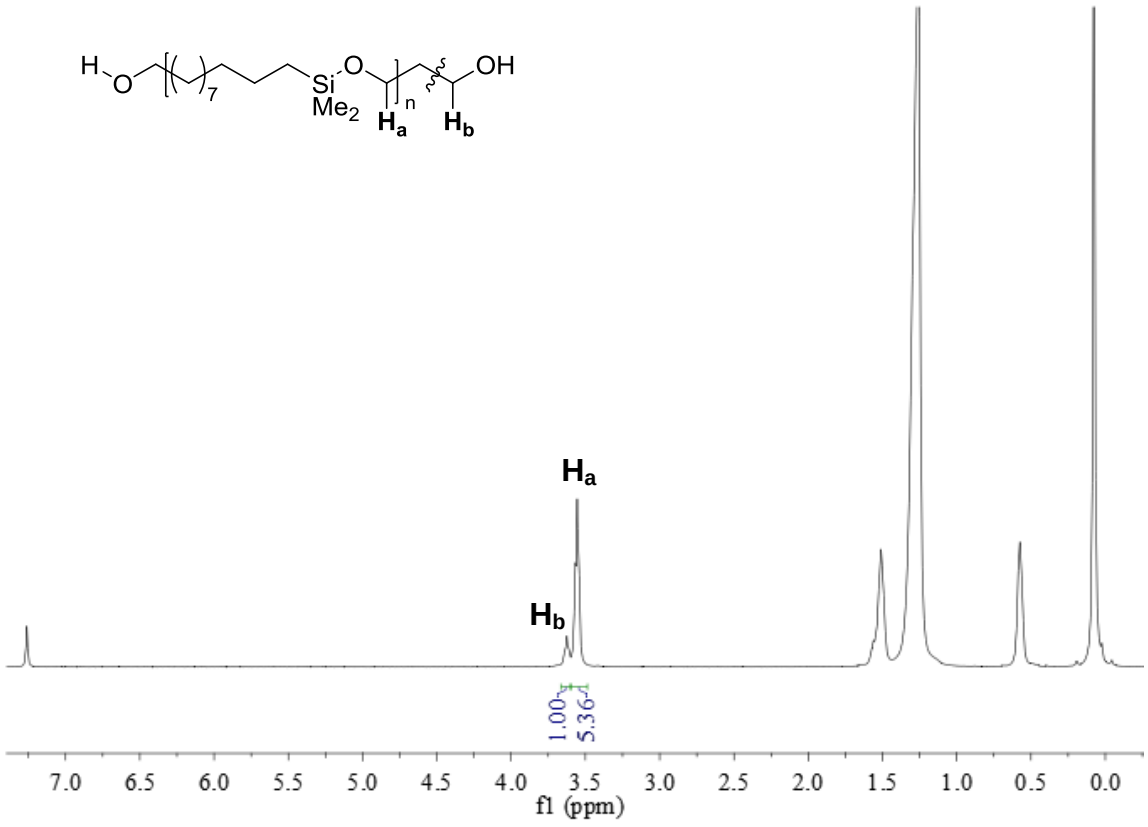
Typical Procedure for the Synthesis of PU



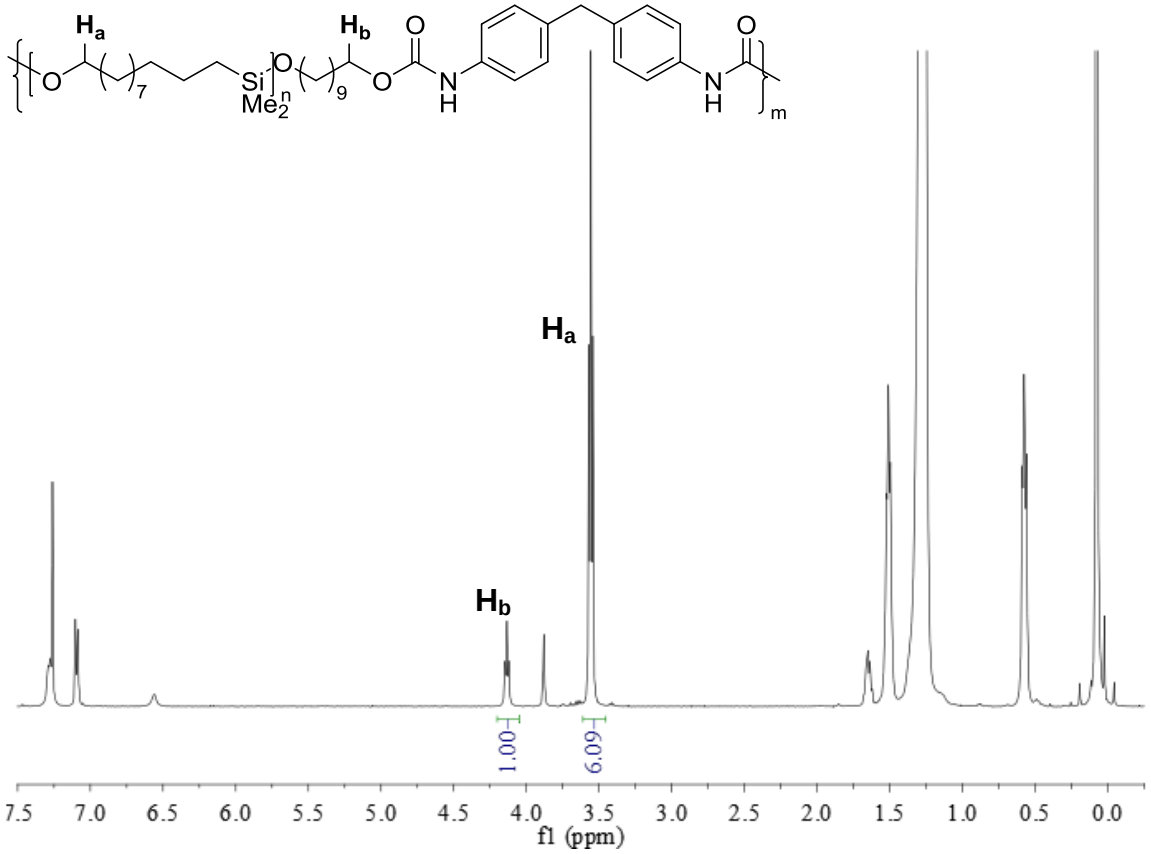
To a solution of PSE (102 mg, M_n = 2.6 kg/mol by NMR spectroscopy) in dry THF (0.5 mL) in a 4-mL glass vial was added a solution of methylene diphenyl diisocyanate (9.8 mg, 0.039 mmol) in dry THF (1 mL). The content was mixed well, $Sn(Oct)_2$ (30 μL of a 0.65 v/v% THF solution, Sn content: 60 μmol) was added, and the vial was sealed with a Teflon-lined cap and heated at 65 ℃ for 4 h. The mixture was cooled to room temperature, and the PU was precipitated in dry MeCN (50 mL) under vigorous stirring. The polymer was washed with MeCN (10 mL), and dried under vacuum at 23 ℃ for 12 h to afford the product as an off-white rubbery solid (82 mg, 73% yield).

NMR Analysis of the Copolymer

^{1}H NMR spectrum of the starting macromolecular diol (CH_2OH:CH_2OSi = 1:5.36):

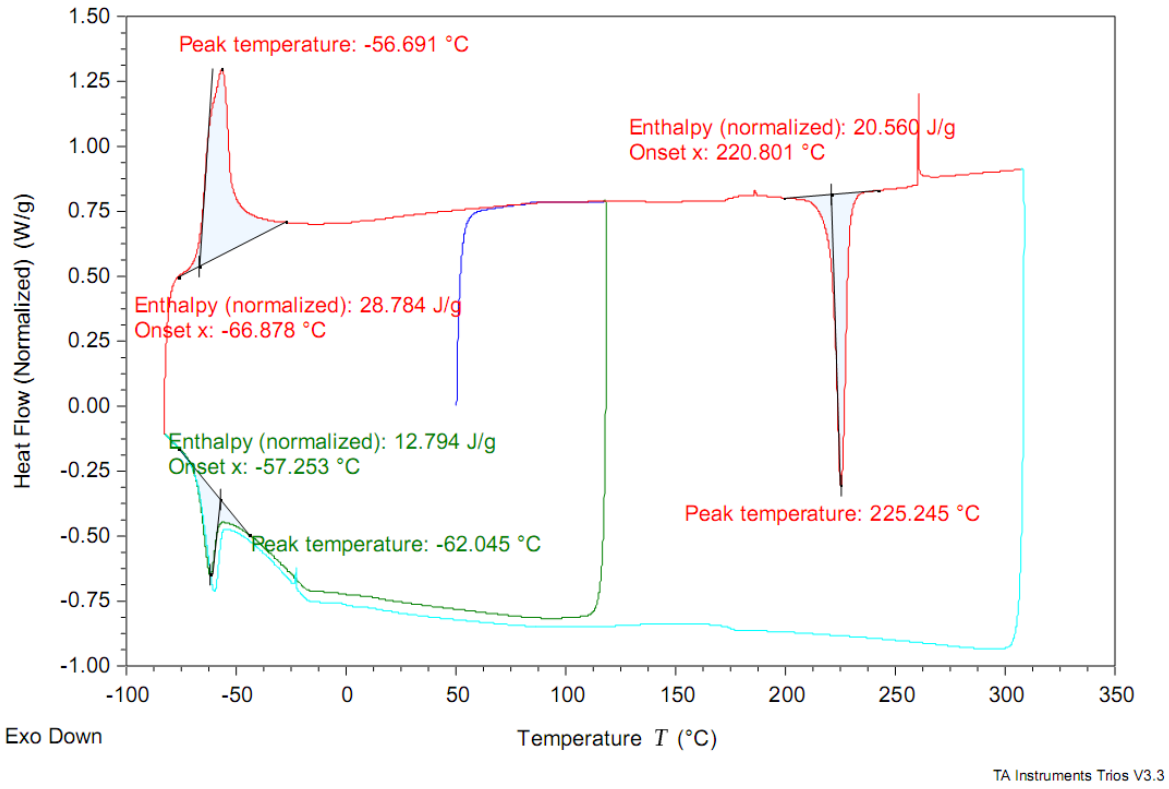


^{1}H NMR spectrum of the PU. Note the complete absence of the signals at 3.62-3.68 ppm, and presence of the signal at 4.13 ppm, corresponding to the C*H*$_2$C(O) units at the urethane linkages. In addition, the ratio between the C*H*$_2$OC(O) and C*H*$_2$OSi is 1:6.09, matching the ratio between C*H*$_2$OH and C*H*$_2$OSi (1:5.36) in the macromolecular initiator.

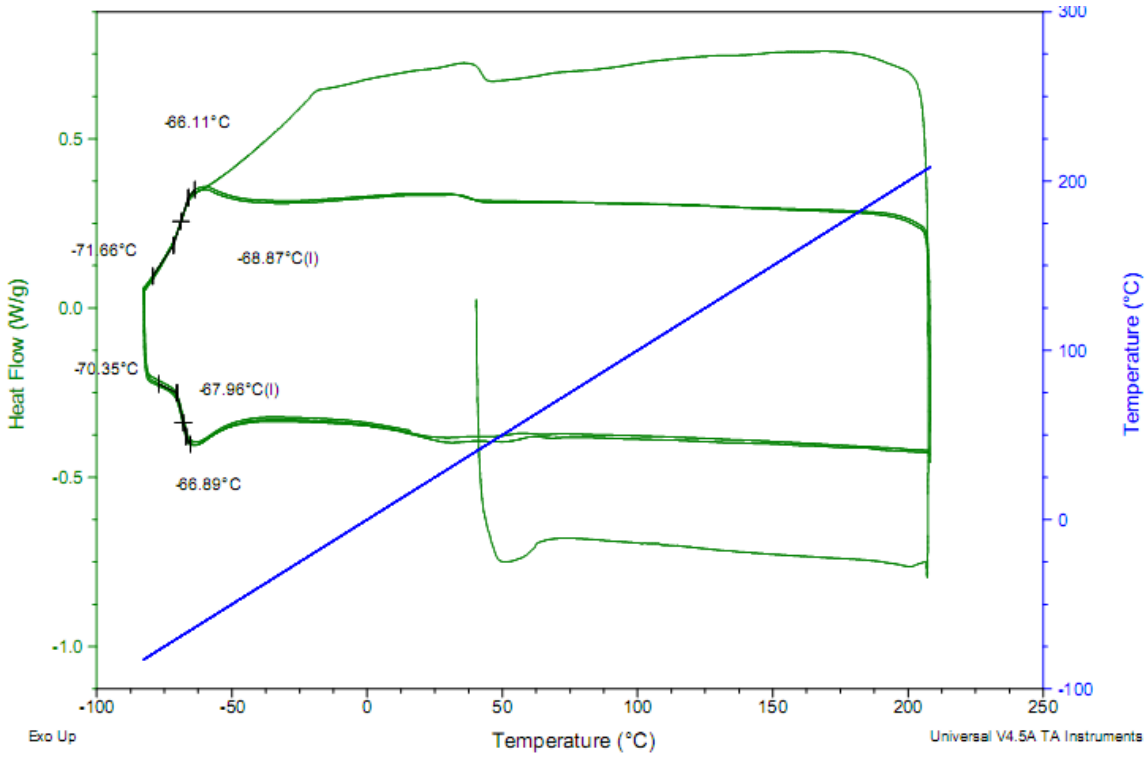


Representative DSC Traces

A typical DSC trace of PSE (1):

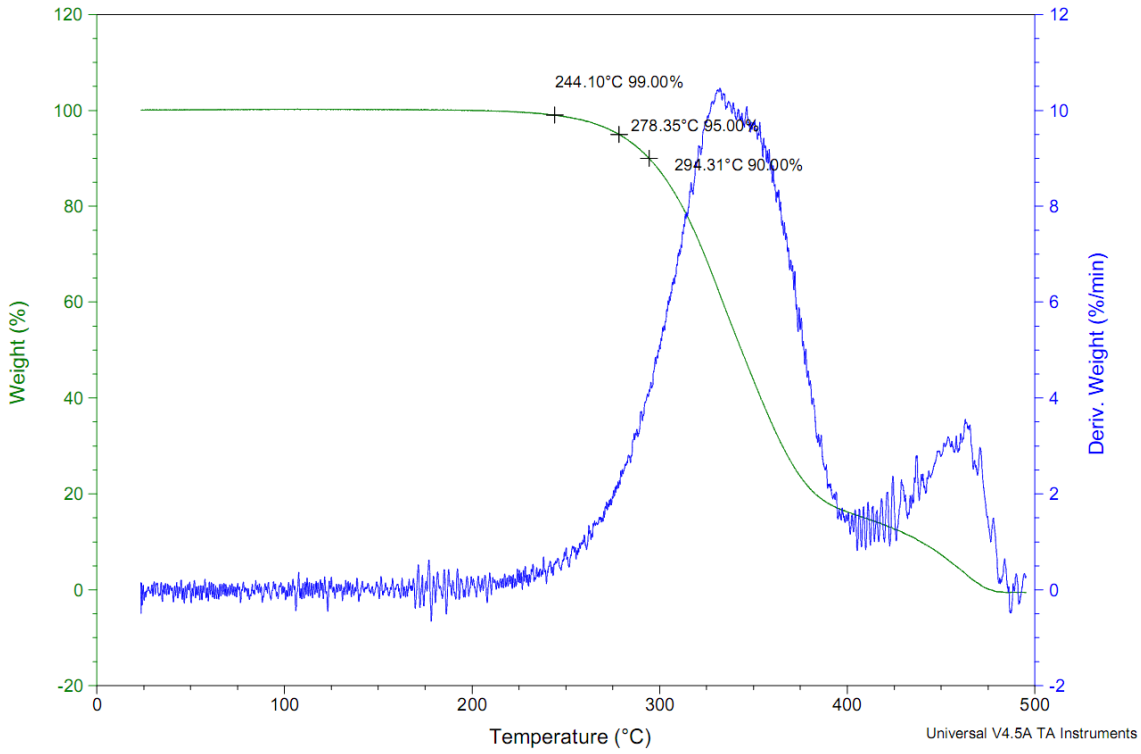


A typical DSC trace of PU:

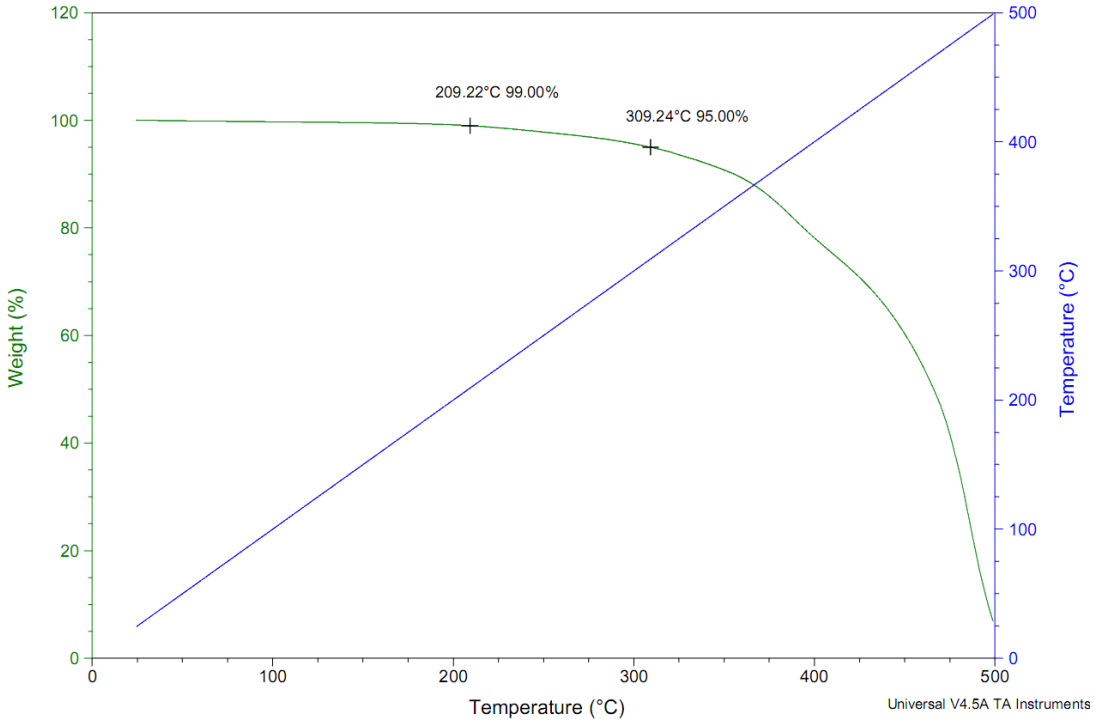


Representative TGA Traces

A typical TGA trace of PSE (1):



A typical TGA trace of PU:



7.5 References and Notes

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"Polysilylether: A Degradable Polymer from Biorenewable Feedstocks".
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Chapter 8: Synthesis of New Degradable Polymers from Biorenewable Sources

8.1 Introduction

After we reported the synthesis of polysilylethers (PSEs) described in Chapter 7,[1] several limitations of the polymer as well as the process for making the monomer became apparent. First**,** although the current synthetic route can be used to prepare decagrams of monomer **1**, stoichiometric amounts of $LiAlH_4$ and Al byproducts render the process unsustainable on a large scale. In addition, alkene isomerization during the hydrosilylation step generates internal alkenes that are difficult to separate from the desired product and that require labor-intensive separation (Figure 1). We envisioned to address these two problems by finding alternative methods for the reduction of the ester and hydrosilylation of the alkene. Specifically, we proposed to reduce the ester to the corresponding alcohol by catalytic hydrogenation. In addition, the use of more well-defined Fe-PDI complexes to catalyze the hydrosilylation could minimize alkene isomerization.[2] Furthermore, the Fe-PDI complex is known to catalyze alkene hydrosilylation with Et_2SiH_2,[3] thereby avoiding the reduction of the SiCl to SiH by metal hydrides.

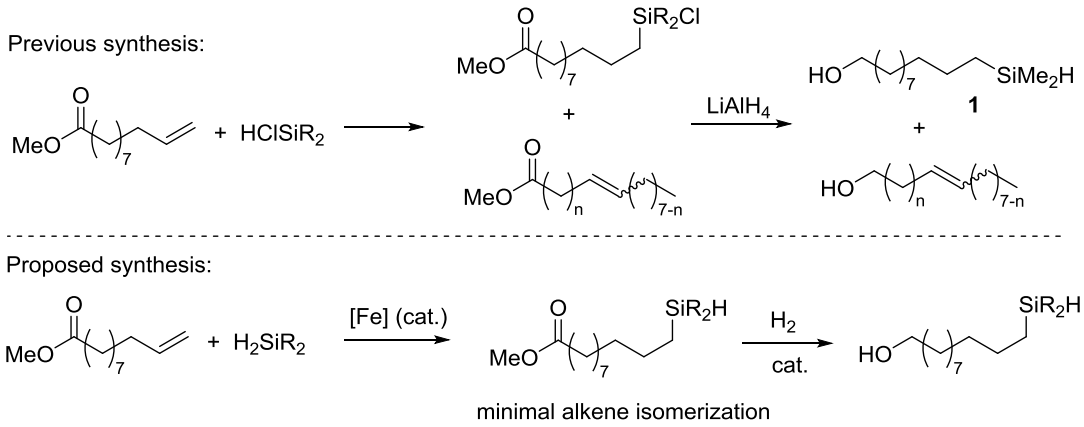


Figure 1. Proposed improved synthesis of the monomer for polysilylethers.

Second, the current route to monomer **1** only allows for the functionalization of fatty esters containing terminal alkene units, which limits the number of monomers accessible from bio feedstocks. There is a wide range of unsaturated fatty acid esters that contain internal double bonds. If a method can be developed for the tandem isomerization and hydrosilylation of internal double bonds, many monomers containing an alcohol and a silyl hydride ends can be accessed from naturally occurring unsaturated fatty acids (Figure 2).

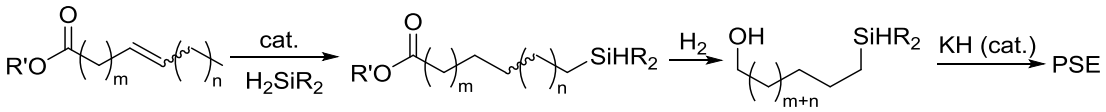


Figure 2. Proposed isomerization and hydrosilylation of fatty esters containing internal unsaturation.

Third, the silyl ether linkages in the PSEs are susceptible to hydrolysis under ambient conditions, as evident from the decrease in molecular weight of the polymers measured by SEC. Even the cleavage of a small portion of the silyl ether linkages causes a sharp drop in the molecular weight and increases the molecular weight distribution of the polymer, thereby altering material properties. Although the silyl ether linkages were incorporated to impart degradability, it appears that the high-sensitivity of those linkages to moisture renders them unsuitable for practical applications. Thus, we envisioned that by replacing the silyl ether linkages with siloxane (Si-O-Si) linkages (Figure 3), the hydrolytic stability of the materials would increase significantly.

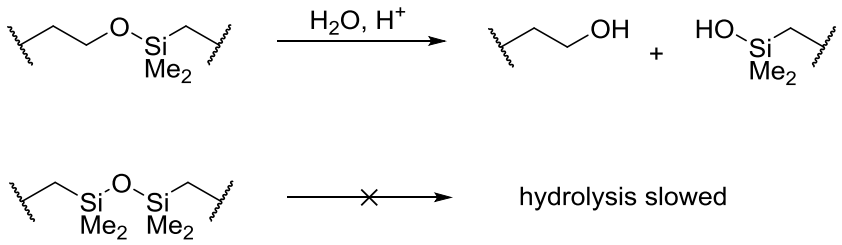


Figure 3. Replacing the silyl ether linkages with siloxane linkages to improve the hydrolytic stability.

8.2 Results and Discussion

Both the improved synthesis of monomer **1** and the conversion of fatty esters containing internal double bonds rely on finding a catalyst for the isomerization and hydrosilylation of internal double bonds to afford terminal alkyl silanes. Specifically, the catalyst needs to be compatible with secondary silanes ($R^1R^2SiH_2$) and a methyl ester group, to catalyze isomerizative hydrosilylation, and to be highly active for use at a low catalyst loading (e.g. < 1 mol %).

Several complexes have been reported to catalyze the isomerizative hydrosilylation of internal alkenes (Figure 4).[4-7] Catalyst **2** was demonstrated to be compatible with one secondary silane (Ph_2SiH_2) and substrates containing ester groups,[6] thus representing our best choice of catalyst.

Catalyst **3** was used by the Huang group for tandem dehydrogenation and hydrosilylation,[3] although compatibility with ester groups was not demonstrated. Catalyst **4** was shown to be active for the hydrosilylation of ester-containing internal alkenes with primary and tertiary silanes.[7] Finally, catalyst **5** is a known chain-walking catalyst and was shown to be compatible with tertiary silanes.[5]

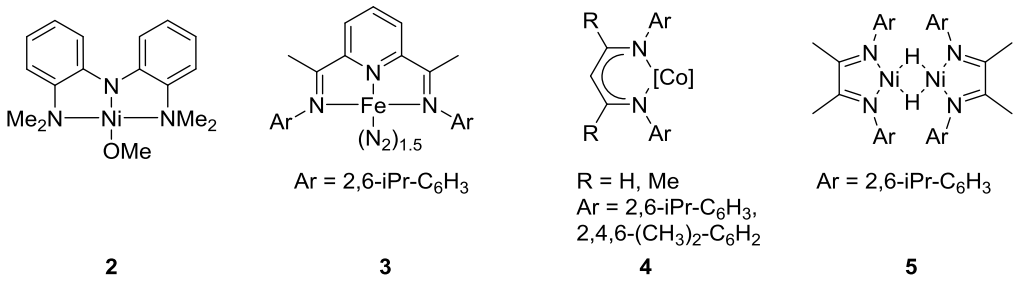


Figure 4. Reported catalyst for the isomerizative hydrosilylation of internal alkenes.

Catalysts **3-5** were prepared according to the literature procedures. Catalyst **2** was not obtained, because several attempts to synthesize it by following the literature procedure did not afford the desired Ni-methoxide complex. Specifically, treating the Ni chloride precursor **7** did not generate a species that contained an OMe group, as determined by NMR spectroscopy (Figure 5). However, we were able to contact the authors of the paper and asked them to conduct a test reaction of methyl oleate with Et_2SiH_2 with both **2** and a heterogeneous Ni catalyst they reported in 2016.[8] No conversion of the substrate was observed with **2**, suggesting that the ester group poisoned the catalyst. Only alkene isomerization and reduction of the ester group were observed with the heterogeneous Ni catalyst.

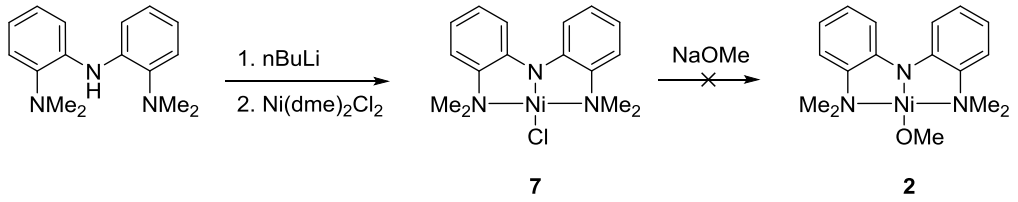


Figure 5. Attempted synthesis of **2**.

Results from hydrosilylation with catalysts **3-5** are summarized in Table 1. Catalyst **3** was inactive for substrates containing esters, which is in agreement with observations made by the Huang group (Zheng Huang, personal communication). Similarly, even though catalysts **4** and **5**

are active for the hydrosilylation of unfunctionalized internal alkenes, no isomerizative hydrosilylation took place when an ester-containing alkene or Et_2SiH_2 was used.

Table 1. Hydrosilylation with catalysts **3-5**.

Substrate	Catalyst (mol%)	Silane	Solvent	Yield (%)
trans-3-octene	**5** (5%)	$HSi(OEt)_3$	Neat	~50
trans-3-octene	**5** (5%)	H_2SiEt_2	Neat	0
$C_{10}H_{19}CO_2Me$	**5** (5%)	$HSi(OEt)_3$	Neat	0
$C_{10}H_{19}CO_2Me$	**3** (2%)	H_2SiEt_2	Neat	0
$C_{10}H_{19}CO_2Me$	**4** (2%)	H_2SiEt_2	Neat	0

In light of the poor results obtained, several challenges of isomerizative hydrosilylation of internal alkenes led us to question the practicality of this process. Specifically, most naturally occurring unsaturated fatty ester have internal double bonds that are more than 8 carbons from the alkyl terminus; thus, isomerization of the internal metal alkyl intermediate to the terminal metal alkyl species that would form the terminal alkylsilane would be very slow. In addition, if the isomerization occurs toward the ester, the eventual product, an alpha-beta unsaturated ester, is thermodynamically more stable than the ω_{-1}-alkenyl ester. Finally, most first-row transition metal based hydrosilylation catalysts are not thermally stable, so the slow reaction rate cannot be accelerated by elevating the reaction temperature.

With those considerations in mind, we decided to redirect our effort on the preparation of diol monomers from biorenewable materials.

During the degradation studies of PSEs reported in Chapter 7, we determined that the degradation product is a diol containing a siloxane linkage (Figure 6), which could be an valuable monomer for polyesters and polyurethanes, etc.. Diol **6** can be accessed through double hydrosilylation of methyl 10-undecenoate with tetramethyldisiloxane, followed by reduction of the ester groups to alcohols. For environmental and practical reasons, catalytic hydrogenation was preferred to reduction with stoichiometric metal hydride reagents, such as $LiAlH_4$.

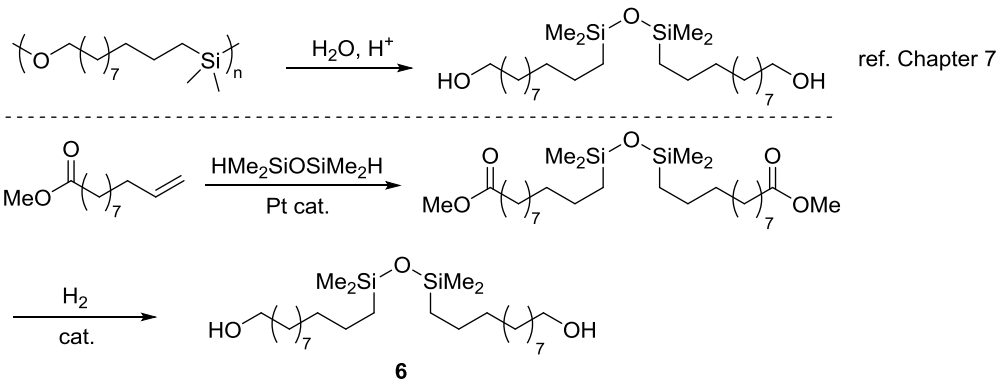
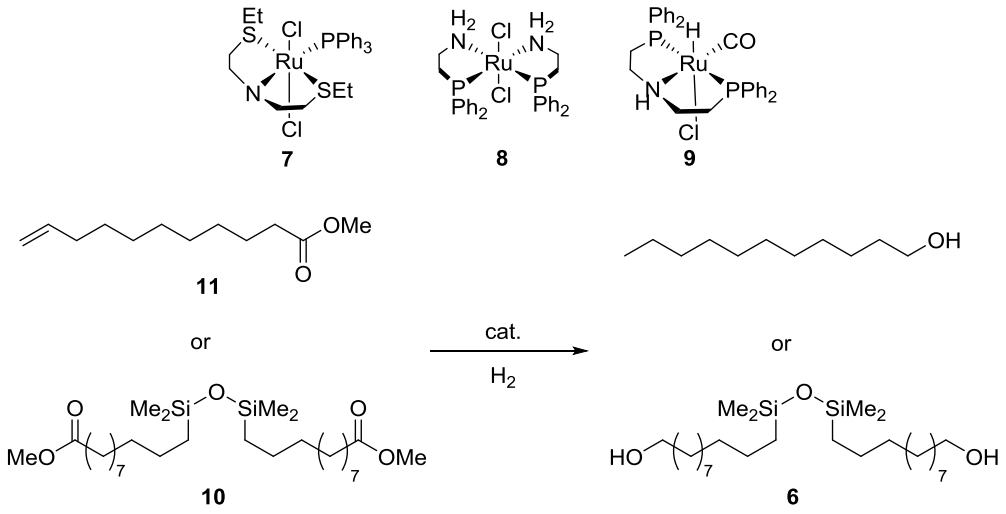


Figure 6. Synthetic design for the diol monomer **6**.

The hydrosilylation of methyl 10-undecenoate with tetramethyldisiloxane proceeded with 10 ppm of Karstedt's catalyst to afford the siloxane containing two ester termini. The crude material was directly subjected to hydrogenation with several commercial ester hydrogenation catalysts, and the results were summarized in **Table 2**. While the Gusev's catalyst[9] and the Firmenich catalyst[10] were not active for the catalytic hydrogenation of 10-undecenoate, Ru-MACHO[11] was found to be active for the hydrogenation of both methyl 10-undecenoate (**11**) and diester **10**. Ru-MACHO-BH_3 was also tested as a simple, single component catalyst, but was found to be insoluble in THF.

Table 2. Hydrogenation of esters.



Substrate	catalyst (mol%)	base (mol%)	solvent	time (h)	conversation (%)	yield (%)
11	**7** (0.1)	MeOK (1)	THF	2	0	0
11	**8** (0.1)	NaOMe (1)	THF	3	0	0
11	**9** (0.1)	NaOMe (10)	MeOH	16	60	nd
11	**9** (1)	NaOMe (1)	THF	16	60	nd
10	**9** (1)	NaOMe (10)	MeOH	16	<5	nd
10	**9** (1)	KOtBu (4)	THF	16	>95%	90%

Conditions: 0.2 mmol of substrate, 100 ℃, 0.3 mL solvent, reactions conducted in a Parr reactor with ~10 mL headspace.

Diol **6** was synthesized on a multi hundred milligram scale following purification by column chromatography. Major by-products of the reaction include isomerized starting material (with the ester group reduced to an alcohol after hydrogenation), the diester intermediate, and products resulting from the transesterification between a methyl ester and the reduced product (Figure 7).

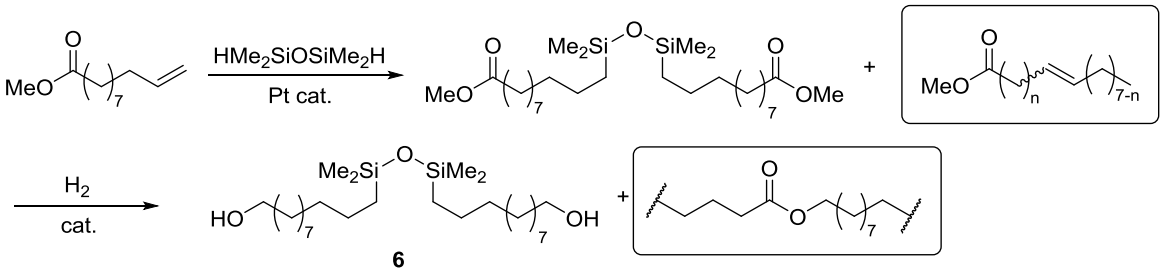


Figure 7. By-product analysis of the synthesis of **6**, with major by-products circled.

Diol **6** was subjected to polymerization with methylenediphenylisocyante (MDI) to construct polyurethane **12** with 1 mol% Sn(2-ethylhexanoate)$_2$ (Sn(oct)$_2$) as the catalyst. Following precipitation of the reaction mixture into MeCN, a white solid was obtained. Thermogravimetric analysis (TGA) indicated a 1% decomposition temperature of 250 ℃ and a 5% decomposition temperature of 279 ℃. The decomposition profile of the polymer clearly exhibits a two-stage decomposition: the first stage has an onset temperature at ~250 ℃ and the second stage has an onset temperature at ~400 ℃, corresponding to the decomposition of the alkyl chains and the aryl moieties (Figure 8). Differential scanning calorimetry (DSC) revealed a Tm of 100 ℃ (Figure 9), suggesting that polyurethane **12** is a crystalline polymer due to the large presence of arylurethane linkages. The molecular weight of the polymer determined by NMR spectroscopy is 38 kg·mol^{-1}, and the molecular weights determined by SEC (RI detector, PS standards) are 35 and 69 kg·mol^{-1} (M_n and M_w) with a Đ of 1.98.

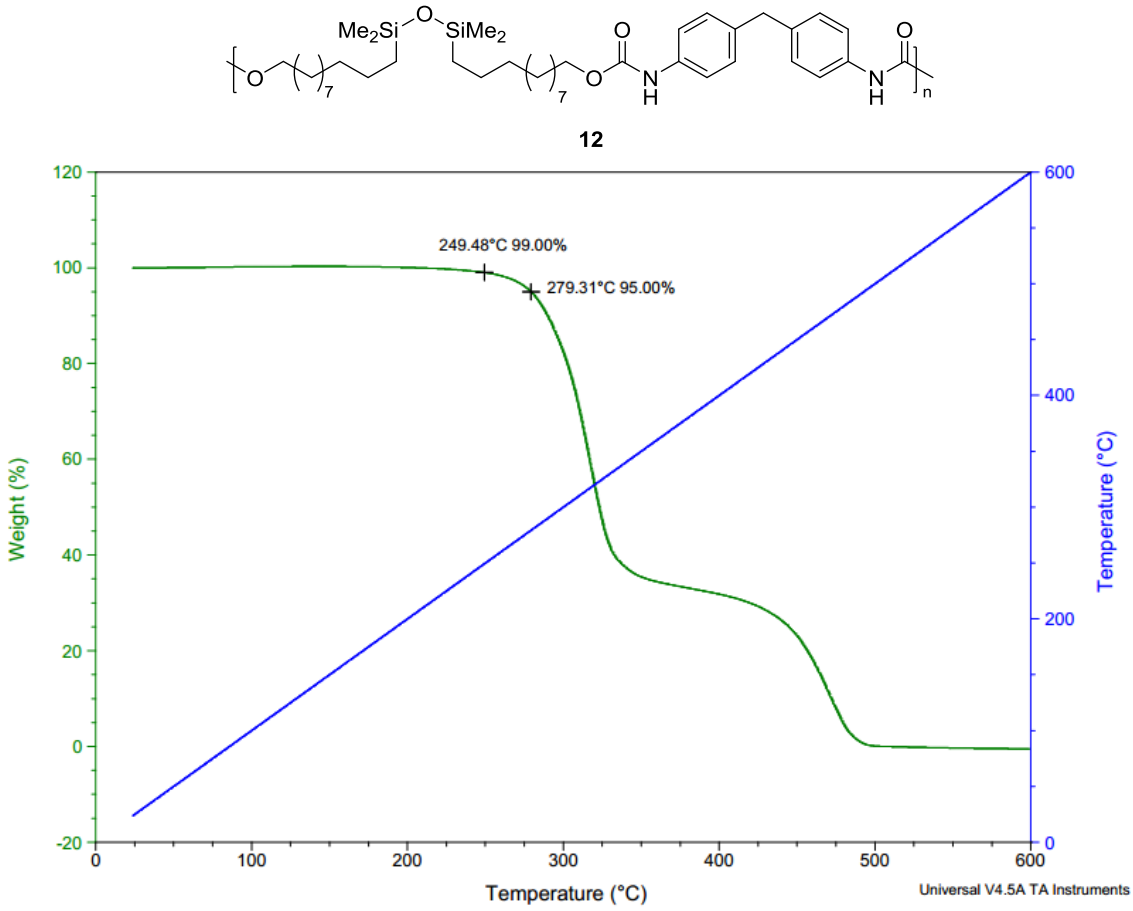


Figure 8. TGA graph of polyurethane **12** from 40 - 600 ℃ with a 10 °C·min^{-1}ramp rate under N_2.

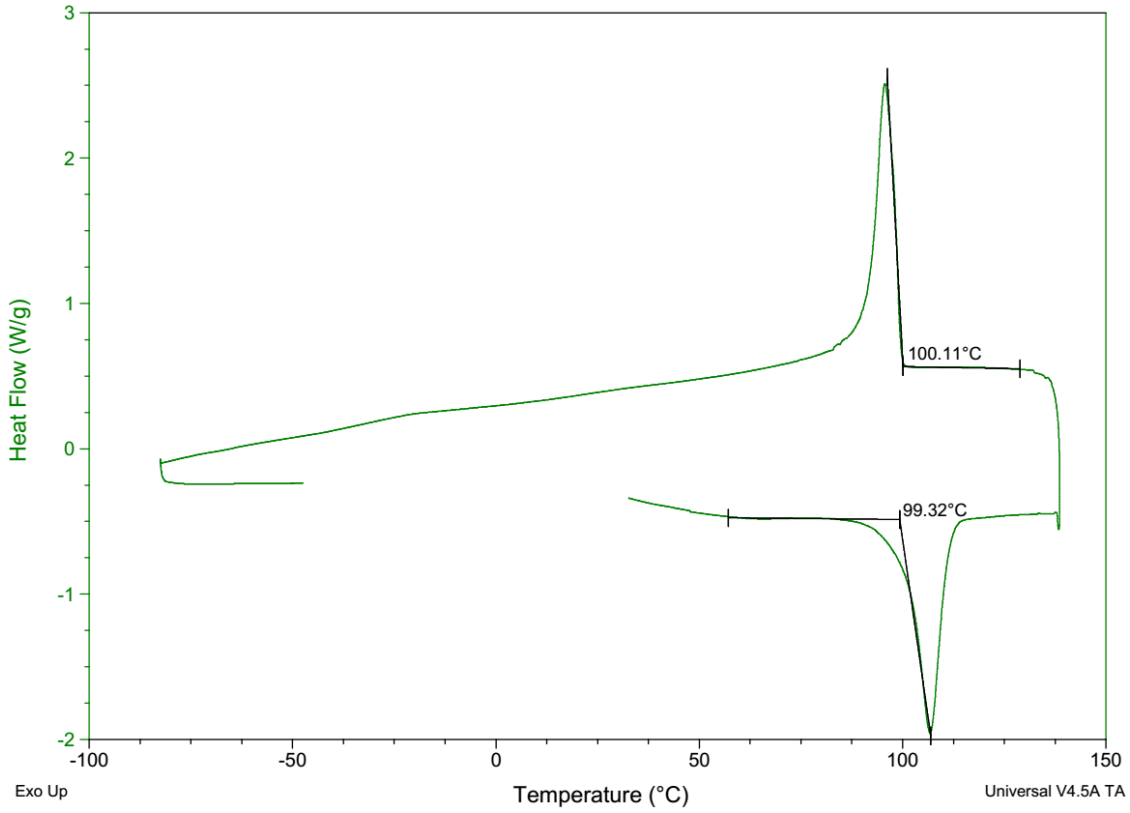
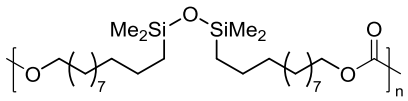


Figure 9. DSC graph of polyurethane **12** with a ramp rate of 10 °C·min^{-1}.

Diol **6** was also used for the synthesis of polycarbonates. While attempts to react **6** with 1/3 equivalent of triphosgene led to a mixture of products, presumably due to the hydrolysis of the siloxane linkage in **6** by the HCl by-product, reaction of **6** with 1 equivalent of carbonyldiimidazole (CDI) led to a viscous liquid **13** with a M_n of 27 kg·mol^{-1} and M_w of 52 kg·mol^{-1} (Đ = 1.93), as determined by SEC using a refractive index (RI) detector with PS references.



13

Because of the two methyl ester termini, diester **10** was also subjected to polymerization with diols and diamines to furnish polyesters and polyamides containing siloxane linkages. The polymerization reactions were conducted with $Sn(Oct)_2$ or $Ti(OBu)_4$ as the catalyst under a flow of N_2 to remove the MeOH by-product. The molecular weight (determined by SEC using an RI detector and PS standards) and thermal properties of the polymers are summarized in Table 4. All polyesters and polyamides are crystalline and exhibit high thermal stability. The polyamides

16 and **17** were poorly soluble in THF or chloroform at 20 ℃, and their molecular weights were not determined. In theory, their molecular weights could be determined by high temperature SEC.

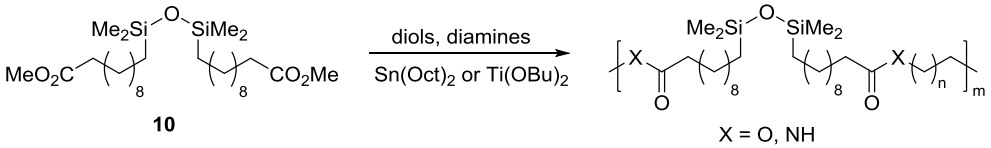
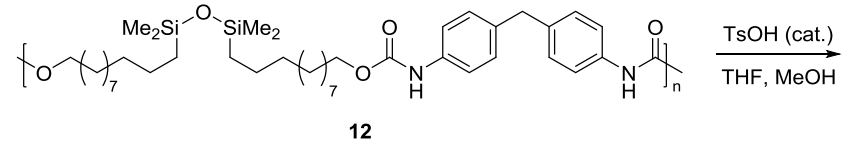


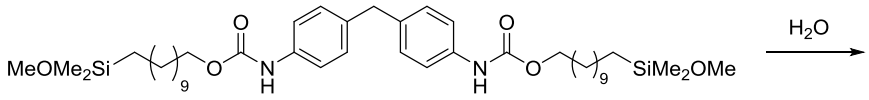
Table 4. Molecular weight and thermal properties of polyesters and polyamides derived from **10**.

Polymer	Monomer	catalyst	M_n (kg·mol^{-1})	M_w (kg·mol^{-1})	$Đ$	Tm (℃)	5% weight loss (℃)
14	$HO(CH_2)_{12}OH$	$Sn(Oct)_2$	22.4	57.0	2.54	23	348
15	$HO(CH_2)_{10}OH$		20.6	44.8	2.18	17	352
16	$H_2N(CH_2)_5NH_2$		nd	nd	nd	92	388
17	$H_2N(CH_2)_{12}NH_2$		nd	nd	nd	99	381
18	**6**	$Ti(OBu)_4$	58	144	2.48	-10	386

nd: not determined.

To probe the degradability of the polyurethanes containing siloxane linkages, the polymer was subjected to various acidic and basic conditions, either in water or a mixture of water and organic solvents. The reaction of polyurethane **12** in a mixture of THF and MeOH with toluenesulfonic acid (TsOH) as the catalyst afforded the corresponding silyl methyl ether at 20 ℃ in 1 d, and subsequent addition of H_2O led to the desired silanol (Figure 10). Silanol **19** underwent self-condensation to form oligomers during the workup (12% conversion of **19**, see Experimental section for more details).





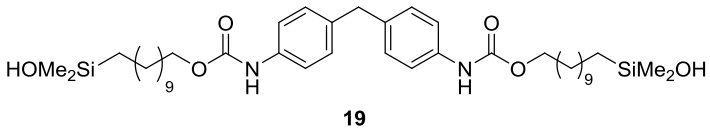


Figure 10. Degradation of polyurethane 12.

8.3 Conclusions

A new diol monomer was prepared from a two-step synthesis by hydrosilylation and hydrogenation of methyl 10-undecenoate, and this monomer was used to synthesis polyurethanes with MDI and polycarbonates with CDI. The monomer synthesis requires low catalyst loading, is highly atom-economic, and produces a minimum amount of waste. The polyurethanes exhibit good thermal stability and a melting temperature of 100 ℃. In addition, the precursor to the diol monomer, the diester, was directly subjected to transesterification or transamidation to afford crystalline polyesters and polyamides with good thermal stability.

Polyurethane **12** containing tetramethyldisiloxane linkages was degraded under mild conditions to a molecule containing two silanol termini, which can be further functionalized or allowed to self-condense to reform the siloxane linkages and thus the polymer **12**. Future efforts shall focus on studying the material properties of the new polymers, as well as exploring the reversibility of the siloxane hydrolysis to make self-healing materials.

Attempts to improve the synthesis of monomer **1** (Chapter 7) and to conduct isomerizative hydrosilylation of fatty acid esters with internal double bonds (e.g. methyl oleate) were met with challenges including incompatibility of the catalysts with secondary silanes or ester functionalities, slow reaction rate, low thermal stability of the catalyst, and thermodynamic favorability of isomerization of alkene in the undesired direction (i.e. toward the ester group rather than toward the alkane end). So far, it was tentatively concluded that conducting isomerizative hydrosilylation on unsaturated fatty esters to produce terminal alkyl silanes is not practical.

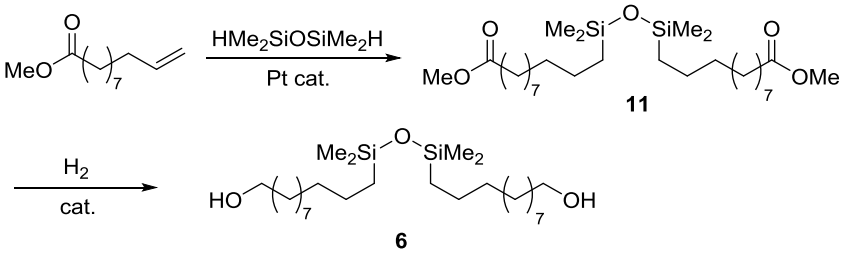
8.4 Experimental

Reagents and instrumentation

All chemicals were purchased from commercial sources unless otherwise stated. Metal catalyst used for hydrosilylation were prepared according to literature procedures.[4-7] Solvents were dried by an Innovative Technology Pure-Solv solvent purification system and stored over molecular sieves.

NMR spectra were acquired on Bruker AVQ-400, AVB-400, DRX 500, and AV-600 spectrometers. Chemical shifts were reported in ppm relative to residual solvent peaks ($CDCl_3$ = 7.26 ppm for ^1H and 77.16 ppm for ^{13}C). Coupling constants were reported in Hz. SEC was performed on a Malvern Viscotek TDAMax chromatography system equipped with TGuard T2000, T3000, T4000, and T5000 columns using THF as the eluent (30 ℃, 1 mL/min). DSC was performed on a TA Instruments Q200 calorimeter (purge gas: He, flow rate: 25 mL/min, ramp rate: 20 ℃/min, temperature range: -90 - 200 ℃). TGA was performed on a TA instrument Q500 thermogravimetric analyzer under nitrogen from 25 to 500 ℃ at a ramp rate of 10 ℃·min^{-1}.

Synthesis of Monomer 6

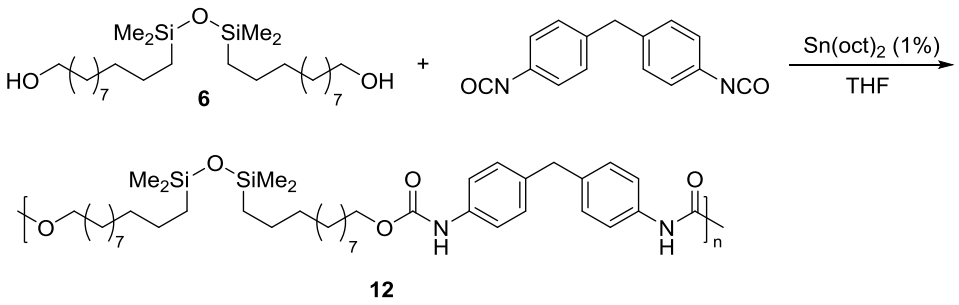


To a mixture of methyl 10-undecenoate (2.0 g, 10 mmol) and 1,1,3,3-tetramethyldisiloxane (0.67 g, 5.0 mmol) in a 4-mL vial was added Karstedt's catalyst (1 μL of 2 wt % xylene solution, 10 ppm relative to the alkene), and the vial was capped with a Teflon-lined cap and heated at 50 ℃ (stirring is optional) for 72 h to obtain **11** as a colorless (sometimes light yellow) liquid. ^1H NMR (500 MHz, $CDCl_3$) δ 3.66 (s, 6H), 2.30 (t, *J* = 7.6 Hz, 4H), 1.66 – 1.56 (m, 4H), 1.34 – 1.20 (m, 28H), 0.48 (t, *J* = 7.4 Hz, 4H), 0.02 (s, 12H). Signals corresponding to internal alkenes were observed at 5.45 - 5.35 ppm and account for 2-3% of the starting material, as determined by NMR spectroscopy. The crude mixture was used directly for the next step.

Representative hydrogenation of 11

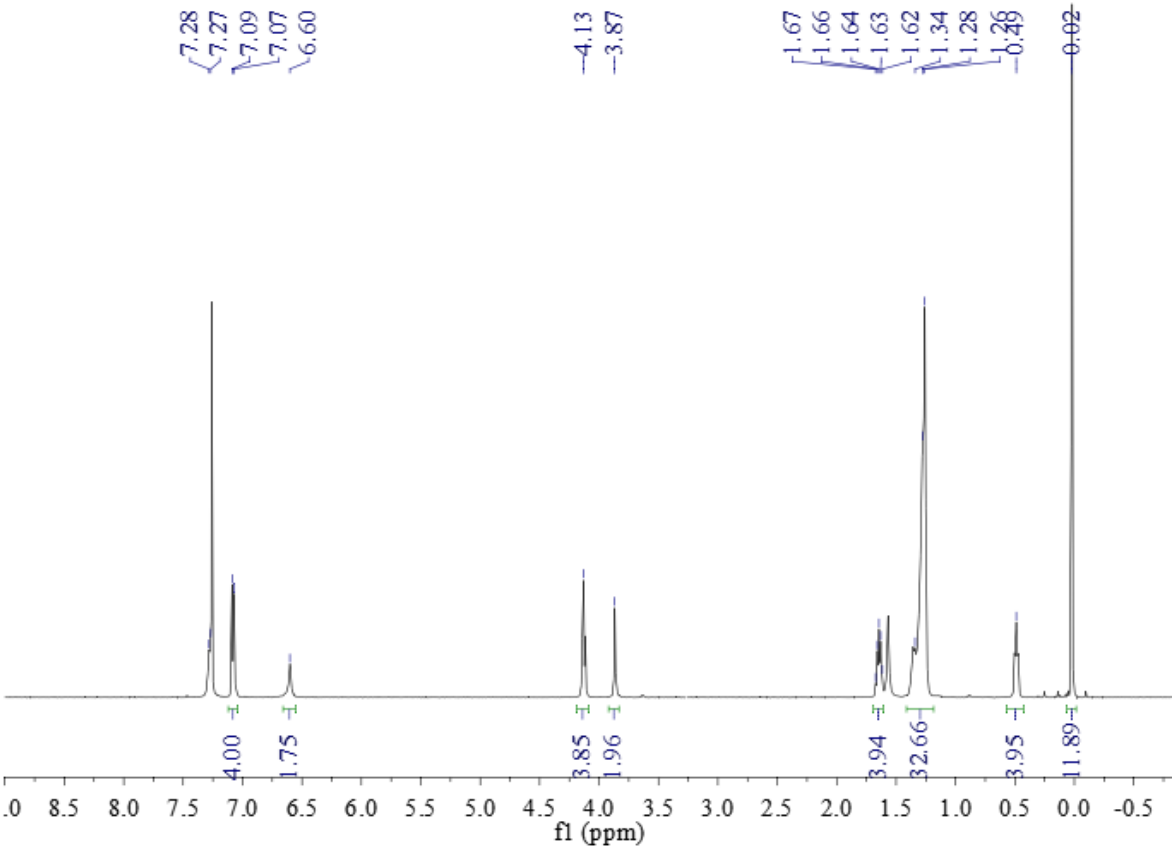
A Parr reactor (internal volume ~10 mL) was charged with Ru-MACHO (24 mg, 0.040 mmol), KO^{t}Bu (16 mg, 0.14 mmol), THF (6 mL), and diester **11** (2.00 mg, 3.77 mmol), in that order, under N_2, and the reactor was pressurized to 60 bar with H_2 and heated in a Al heating block set at 120 ℃ for 3 days. The reactor was then cooled to 23 ℃ and depressurized, and the reaction mixture was purified by silica gel column chromatography (0:10 to 3:7 ethyl acetate:hexanes) to afford **6** as a colorless liquid (1.1 g, 62% yield). The yield by NMR spectroscopy was ~90%. The low isolated yield is mostly due to difficulties in separating **6** from the by-products (Figure 7). The ^1H-NMR spectrum of **6** agrees with the reported data.[1]

Typical procedure for the synthesis of polyurethane 12

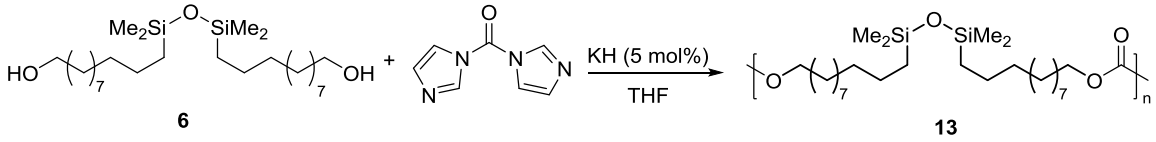


To a mixture of **6** (241 mg, 0.507 mmol) and MDI (127 mg, 0.507 mmol) dissolved in dry THF (5 mL) in a 20-mL vial under N_2 was added $Sn(oct)_2$ (1.7 μL, 0.010 mmol), and the vial was capped with a Teflon-lined cap and heated to 65 ℃ for 4 h with stirring. The mixture was cooled to 23 ℃ and added dropwise to MeCN (250 mL) under vigorous stirring. The precipitated polymer was collected by filtration, washed with a small portion of MeCN, and dried under vacuum. The resulting polymer was a colorless solid (291 mg, 79% yield). ^{1}H NMR (500 MHz, C_6D_6) δ 7.28 (d, J = 7.3 Hz, 4H), 7.08 (d, J = 8.3 Hz, 4H), 6.60 (s, 2H), 4.13 (t, J = 6.7 Hz, 4H), 3.87 (s, 2H), 1.70 – 1.61 (m, 4H), 1.40 - 1.20 (m, 28H), 0.49 (t, J = 7.4 Hz, 4H), 0.02 (s, 12H).

^{1}H-NMR spectrum of polyurethane 12



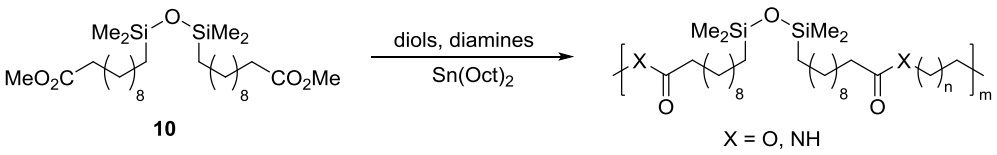
Synthesis of polycarbonate 13



6 **13**

To a mixture of **6** (196 mg, 0.413 mmol) and carbonyldiimidazole (67.9 mg, 0.413 mmol) in THF (2 mL) was added KH (0.8 mg, 0.02 mmol), and the mixture was stirred at 20 ℃ for 2 d. The THF solution was then poured into MeCN (200 mL) under vigorous stirring, and polymer **13** was obtained after washing with MeCN as a viscous gel (95 mg, 46% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.11 (t, *J* = 6.8 Hz, 4H), 1.71 – 1.59 (m, 4H), 1.42 – 1.17 (m, 28H), 0.49 (t, *J* = 7.4 Hz, 4H), 0.02 (s, 12H).

Typical procedure for the synthesis of polyesters and polyamides 14-17

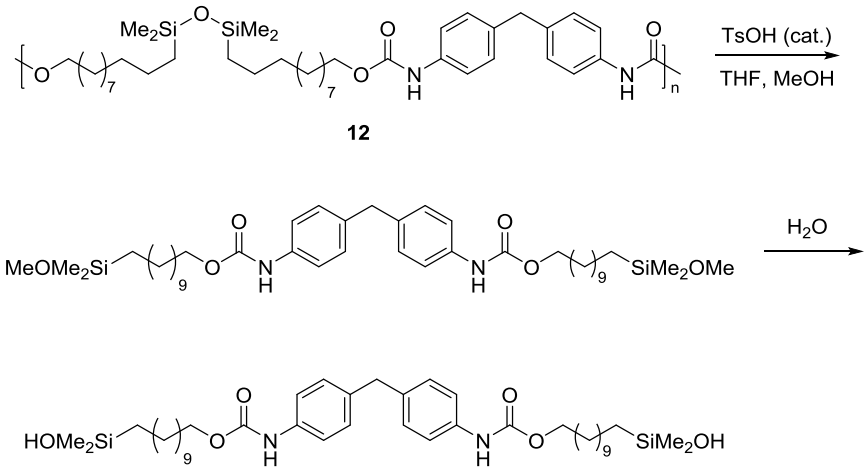


To a mixture of **10** (0.30 mmol) and diol or diamine (0.36 mmol, 20% excess) was added $Sn(oct)_2$ (1.0 μL, 1.0 mol%) under N_2, and the mixture was stirred at 130 ℃ for 2 h while being purged by a stream of N_2, then at 150 ℃ for 2 h while being purged by a stream of N_2, then finally at 150 ℃ under high vacuum (~50 mTorr) for 3 h. Then, the mixtures were diluted with $CHCl_3$ (0.5 - 1 mL) and added dropwise to MeOH (20 mL, for polyesters) or acetone (20 mL, for polyamides) under vigorous stirring. The products were obtained after decanting the solvents and drying under high vacuum.

Synthesis of polyester 18

To a mixture of **10** (107 mg, 0.202 mmol) and **6** (96.6 mg, 0.203 mmol) was added $Ti(OBu)_4$ (0.10 μL, ~0.13 mol%) under N_2, and the mixture was stirred at 100 ℃ for 20 h while being purged by a stream of N_2, then at 130 ℃ under high vacuum (~50 mTorr) for 5 h, and finally at 140 ℃ under high vacuum for 24 h. The mixture was diluted in CH_2Cl_2 (0.5 mL) and added dropwise to acetone (20 mL) under vigorous stirring. The product was obtained as a colorless gum after decanting the solvents and drying under high vacuum (135 mg, 71.7% yield).

Degradation of polyurethane 12



To a solution of **12** (30 mg) in THF (3 mL) and MeOH (2 mL) was added $TsOH \cdot H_2O$ (3 mg), and the mixture was stirred at 20 ℃ for 16 h until all the starting material had converted, as determined by TLC. Then, H_2O (15 mL) was added, and the mixture was stirred vigorously for 1 h until all of the silyl methyl ether was converted (as determined by TLC). Then, H_2O (10 mL) was added, and the organic products were extracted with Et_2O (20 mL). The organic fraction was washed with $NaHCO_3$ (saturated aqueous, 20 mL) and brine (20 mL), and dried over Na_2SO_4. The solvents were evaporated under reduced pressure. The crude material was purified by flash silica gel chromatography to afford the product as a colorless solid (15 mg, 49% yield). NMR analysis indicates that 12% of the silanol groups underwent self-condensation to form siloxane linkages during the evaporation of the solvents from pure column fractions. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.28 (d, *J* = 6.4 Hz, 4H), 7.09 (d, *J* = 8.4 Hz, 4H), 4.14 (t, *J* = 6.6 Hz, 4H), 3.88 (s, 2H), 1.69 – 1.60 (m, 4H), 1.39 – 1.22 (m, 36H), 0.61 – 0.56 (m, 4H), 0.12 (s, 12H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 153.94 (bs), 136.38 (bs), 136.17 (bs), 129.55 (s), 118.95 (bs), 65.54 (s), 40.67 (s), 33.52 (s), 29.68 (s), 29.62 (s, two peaks overlapping), 29.45 (s), 29.37 (s), 29.07 (s), 25.98 (s), 23.28 (s), 17.96 (s), -0.10 (s).

8.5 References and Notes

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Chapter 9: Ring-Opening Polymerization of a Macrolactone Derived from Undecenoic Acid

9.1 Introduction

Chapters 7 and 8 presented the synthesis of silyl ether- or siloxane-containing polymers by step-growth polymerization. Si-O-C and Si-O-Si linkages were incorporated into our polymers as handles for hydrolysis. Such hydrolysis would enable controlled degradation of polymers under mild conditions. Even though polymers with high molecular weight (on the orders of 10^4 g·mol^{-1}) have been obtained, step-growth polymerization suffers from several disadvantages: 1) High molecular weight is only achieved at very high conversion of the monomer, and because the molecular weight increase non-linearly with conversion, achieving specific molecular weight by halting the polymerization at certain monomer conversion is difficult. In the work reported in Chapter 7 on polysilylethers,[1] molecular weights were controlled by adding various amounts of an A-A type molecule (1,10-decanediol) and allowing the polymerization to run to completion. 2) Constructing well-defined chain ends is difficult, because trace amounts of impurity can lead to multiple types of chain ends. In Chapter 7 on the synthesis of PU with telechelic polysilylether (PSE) (Mn = 3 kg·mol^{-1}), some portion of the PSE contains only zero or one hydroxyl groups at the chain end, leading to material containing inactive chain ends.[1] 3) The molecular weight distribution (Đ) is often large (>2, see Chapter 8) and uncontrollable, especially for polymerization by reversible reactions, such as transesterification. Being able to control the Đ value has a profound influence on processability[2-3] and properties of block copolymers.[4-6]

To overcome the disadvantages of step-growth polymerization, we sought to construct renewable and degradable siloxane-containing polymers through living chain-growth polymerization. The advantages include: 1) The molecular weight increases linearly with conversion, and the molecular weight can be controlled by stopping the reaction at the desired conversion. 2) Chain ends can be controlled by choosing the appropriate initiator. For example, a di-functional initiator leads to polymers with the same functionality as the initiator on both polymer chain ends, which allows for functionalization of the chain ends. Although a living chain-growth polymerization is required to obtain a narrow polydispersity (Đ), this mode of polymerization does not guarantee a small Đ value. Control of the Đ value depends on several factors: 1) the rate of initiation versus the rate of propagation: if the rate of initiation is much faster than the rate of propagation, it is possible to achieve narrow molar mass distribution (Đ value close to 1); 2) the rate of chain transfer versus the rate of propagation: if the rate of propagation is not much faster than that of chain transfer, then chain transfer events would increase molar mass distribution. Chain transfer events are especially relevant for polymerization through reversible reactions, such as transesterification or alkene metathesis.

Monomers for chain-growth polymerization are either molecules containing double bonds (alkenes or dienes) or cyclic molecules. To incorporate siloxane linkages into the main polymer backbone through chain-growth polymerization, we considered the ring-opening polymerization (ROP) of a cyclic molecule containing a siloxane group the appropriate route.

The propagation step in ring-opening polymerization involves the cleavage of a functional group in the cyclic monomer and the addition of the catalyst and the emerging chain end across that functional group. ROP of lactides to produce poly(lactic acid) (PLA) or of ε-caprolactone to produce poly(ε-caprolactone) (PCL) with well-defined single site catalysts is well documented.[7-9] The Đ value can be low (<1.10) due to the fast initiation of the catalyst and the fast propagation rate relative to chain transfer. The large rate of propagation, compared to the rate of chain transfer, is due to the strain of the monomer. It is paradoxical, however, that a monomer that undergoes rapid ring-opening polymerization is usually difficult to be synthesized via cyclization and usually requires an indirect synthesis. For example, ε-caprolactone is produced from oxidation of cyclohexanone, not from cyclization of the corresponding ω-hydroxyacid. In addition, lactide is produced from depolymerization of poly- and oligolactic acid, with constant product (lactide) removal by distillation as the driving force.[10]

In Chapter 7 we described the synthesis of polysilylethers (PSEs) by step-growth polymerization of a linear ω-hydroxyhydrosilane. To achieve a high degree of control over the molecular weight, chain ends, and potentially Đ of the silicon-containing degradable polymers made from biorenewable sources, we sought to synthesize a cyclic silicon-containing monomer amenable to ROP. However, unlike the polymerization of PSEs described in chapter 7, we do not necessarily want to form the polymer by Si-O bond formation, because well-controlled polymerization by formation of the Si-O bonds in silicones is not well-documented.[11] Instead, we sought to synthesize a lactone using the existing ester functionality in the readily available methyl 10-undecenoate (**1**) (Figure 11). The siloxane unit can be incorporated using the alkene functionality in **1** by hydrosilylation. The ROP can be conducted by cleaving the ester linkage, and the same catalyst can be used to propagate the siloxane-containing monomers and then lactides to form block copolymers in one-pot. The construction of hard-soft-hard triblock copolymers from siloxane-containing monomers can lead to renewable and degradable thermoplastic elastomers.[12] Compared to the polysilylether-based block copolymers reported in Chapter 7, the siloxane linkages are much more resistant to spontaneous hydrolysis, which is a problem for the PSEs described in Chapter 8.

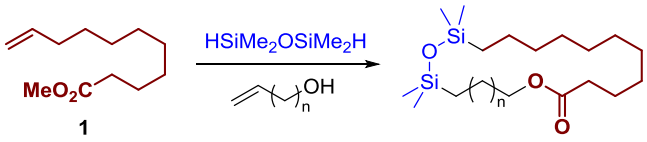


Figure 11. Proposed Si-containing cyclic monomers for ROP.

9.2 Results and Discussion

Monomer Synthesis

To synthesize a siloxane-containing lactone from methyl 10-undecenoate, two routes are possible: 1) initial mono-hydrosilylation, followed by transesterification with an alkene-containing alcohol and cyclization by hydrosilylation, and 2) initial mono-hydrosilylation, followed by hydrosilylation with an ene-ol and cyclization by macrolactonization (Figure 12). The first route was chosen for several reasons: 1) cyclization by an irreversible reaction (hydrosilylation) removes the issue of ring-opening under the cyclization conditions, as would be a problem for cyclization by transesterification; 2) the ω-alkenyl alcohol needed for route 2 must be protected during hydrosilylation and de-protected for the transesterification, and these two reactions add to the step count; 3) macrocyclization by hydrosilylation has not been explored, and our studies would assess the feasibility and practicality of using this reaction as a novel method to form macrolactones.

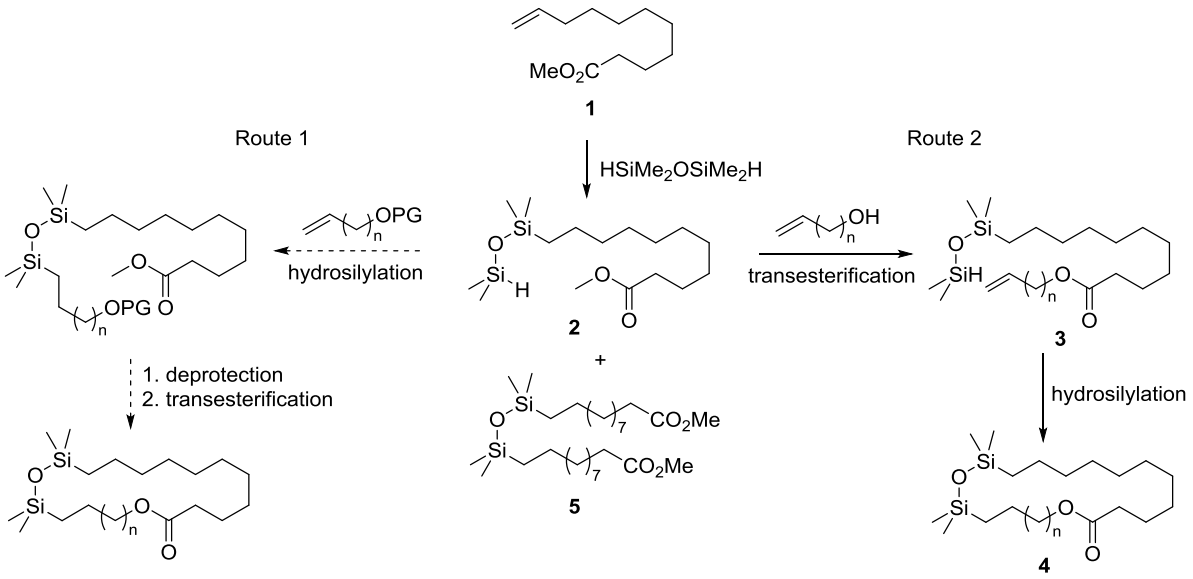


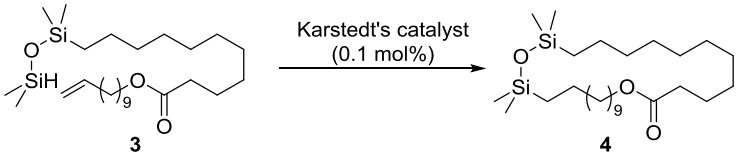
Figure 12. Synthesis of siloxane-containing monomer **4**.

To initiate our synthesis of the desired siloxane-containing lactone, mono-hydrosilylation of 1,1,3,3-tetramethyldisiloxane with methyl 10-undecenoate (**1**) was conducted (Figure 12). To minimize the formation of the double hydrosilylation product **5**, the silane was used in an excess. With three equivalents of the silane, the mono-hydrosilylation product **2** was obtained in 80% yield after distillation. If necessary, the excess disiloxane also could be recovered by distillation.

10-Undecenol was selected as the ω-alkenyl alcohol for transesterification because it is derived from castor oil and has a high boiling point (245-248 ℃). In fact, it can be prepared by the reduction of the ester in **1** with polymethylhydrosilane (PMHS).[13] Allyl alcohol, another biorenewable ω-alkenyl alcohol, was not selected, because the transesterification was conducted at 80 ℃ with a constant stream of nitrogen purging over the reaction mixture to remove the methanol by-product. Under those conditions, allyl alcohol soon evaporated. The transesterification catalyzed by $Ti(OBu)_4$ (0.2 mol%) formed compound **3** in 86% isolated yield after column chromatography.

Finally, for the cyclization step, various concentrations and solvents were tested. Reactions run in toluene gave a higher yield of the desired monocyclic product than did reactions run in other solvents, such as THF, CH_2Cl_2, or heptane (Table 5). With slow addition of **3** into a toluene solution of Karstedt's catalyst, the cyclization step was conducted on a multi-gram scale. Analysis of the crude product mixture revealed the presence of mono-, di-, and tricyclic products, as well as linear and cyclic oligomers, and compounds with internal alkenes resulting from alkene isomerization. While the crude mixtures did not separate well on normal silica column, especially because the desired product and the isomerized alkene tend to coelute, they separated well on $AgNO_3$ treated silica, presumably because the alkene-containing products bind to Ag and remain at the base line under the conditions required to elute the desired monocyclic product. By this procedure, monomer **4** was obtained in 36% yield. In addition, the dicyclic lactone was obtained in ~5% yield.

Table 5. Effect of concentration and solvent on the yield of the desired monocyclic product.



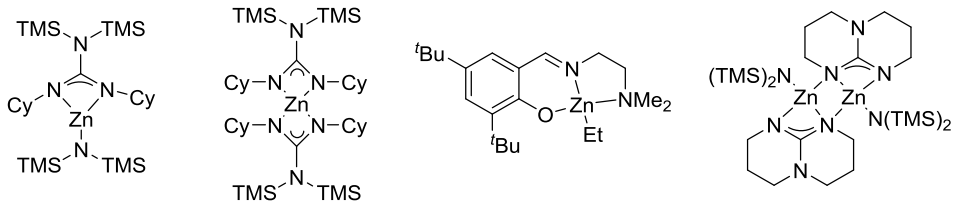
Solvent	Concentration (M)	Yield of **4** (determined by NMR spectroscopy)
THF	0.01	25%
	0.0025	27%
	0.001	28%
	0.00007	30%
toluene	0.001	**34%**
heptane		31%
CH_2Cl_2		30%
Et_2O		29%
1,4-dioxane		30%

We postulated that the rest of the crude product mixture (dimer, trimer, oligomers) from the cyclization step could be recycled to the monocyclic product by transesterification during active removal of the monocyclic product by distillation. This procedure would be analogous to that used to prepare lactide.[10] However, the distillation will likely require much higher temperatures or lower pressures than are needed for the preparation of lactide because the molecular weight of **4** is much higher than that of lactide.

Polymerization

The ROP of macrolactones is usually slower than the ROP of lactide or ε-caprolactone because of the lack of ring strain in large cycles.[14] As a result, chain transfer tends to compete with chain propagation, leading to broad molar mass distributions[15],[16]. Organic compounds,[17], organometallic species,[15-16, 18-21] and enzymes[22-24] have been reported to catalyze the ROP of pentadecalactone (PDL) and several 17-membered lactones.[24] However, no ROP of macrolactones of ring size beyond 20 have been reported, and our monomer **4** is a 26-membered ring. In addition, metal alkoxide transesterification catalysts, such as $Ti(OBu)_4$ or $Al(OiPr)_3$, should be avoided as catalyst for this reaction because the alkoxide ligands on the metals can act as initiators, diminishing the extent of end-group control.

Duchateau and co-workers recently reported the ROP of PDL with Zn-based catalysts **6** and **7** to afford polyesters with high molecular weights (on the order of 10 $kg \cdot mol^{-1}$) with Đ values between 1.2 and 1.7, suggesting that competitive transesterification that would lead to a high Đ value was suppressed.[19] Interestingly, the original reference for compound **6** described it as a zinc-*bisguanidinate* complex,[25] not the zinc-*monoguanidinate* complex drawn by Duchateau and co-workers.[19] In addition, another complex (**8**) reported in the same paper as complex **6**, containing TBD as the ligand, was described as a zinc-monoguanidinate dimer. Importantly, **8**, not **6**, was described to be active for the ROP of lactide.



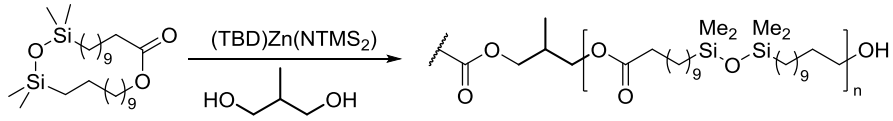
6 **6** (as drawn in ref. 25) **7** **8**

Complexes **7**[26] and **8**[25] were synthesized according to the literature procedures. The synthesis of complex **6** was not successful.[25] Attempted recrystallization of the crude product from hexanes or toluene did not afford any notable amount of crystals.

To construct a polyester containing two OH ends amenable to chain extension with lactide, 2-methyl-1,3-propanediol was selected as the initiator because of its relatively high solubility (for an alkanediol) in toluene and because the ^{1}H NMR chemical shift of the methyl group (0.85 ppm) is distinct from those of the monomer **4**. This distinct chemical shift allows for quantification of the polymer chain length by NMR spectroscopy.

The polymerization of **4** was conducted with **7** and **8** as the catalyst. Interestingly, reactions catalyzed by **7** did not occur at temperatures up to 120 ℃, whereas reactions with **8** (1 mol%) and 1 mol% of 2-methyl-1,3-propanediol proceeded to ~85% conversion after heating at 100 ℃ for 21 h. The ROP of **4** catalyzed by **8** (1 mol%) with a higher 2 mol% of 2-methyl-1,3-propanediol as the initiator proceeded to ~88% conversion after 12 h at 100 ℃. The polyester was isolated by diluting the reaction mixture with $CHCl_3$, quenching the Zn catalyst with iPrOH, and precipitation from an iPrOH/MeOH/acetone (1:1:0.2) mixture. The molecular weight data of the polymers are summarized in Table 6. The M_n was determined by NMR spectroscopy by comparing the integration of the CH_2 group alpha to the ester O to that of the CH_3 group of the initiator. The SEC data were obtained using an RI detector and referenced to PS standards. The Đ values are comparable to that of poly-PDL prepared by the same Zn catalyst.[19]

Table 6. Molecular weight data of poly-4.



monomer:Zn	monomer:initiator	M_n (calc) (kg·mol^{-1})	M_n (NMR) (kg·mol^{-1})	M_n (SEC) (kg·mol^{-1})	M_w (SEC) (kg·mol^{-1})	Đ
100:1	100:1	40.0	63.0	55.6	89.0	1.60
100:1	50:1	20.7	36.2	43.4	62.3	1.44

Notable features in the NMR spectrum of the polymer include a doublet at 0.98 ppm (J = 7.0 Hz) and two doublets at 4.01 ppm (J = 2.3 Hz) and 4.00 ppm (J = 2.0 Hz), corresponding to the chain initiator derived from 2-methyl-1,3-propanediol, a triplet at 3.63 ppm (J = 6.6 Hz) corresponding to the CH_2OH of the polymer chain ends, and a triplet at 4.05 ppm (J = 6.8 Hz) corresponding to the CH_2OC(O) methylene unit in the polymer backbone that resonantes upfield of the methylene unit in monomer **4** (4.11 ppm, t, J = 5.7 Hz). In addition to the signals from the polyester, two signals at 3.30 and 3.24 ppm (1:1 integration) corresponding to trace amounts of a TBD-Zn species were observed. Further optimization of the polymer precipitation conditions is needed to remove any residue Zn species completely.

The TGA of poly-**4** showed that 1% weight loss occurred at 168 ℃ and 5% at 255 ℃. These temperatures are much lower than those of a polymer with similar structure described in Chapter 8 (Table 4, polymer **18**). A trace amount of residual Zn species could be catalyzing

depolymerization and decomposition. Thus, we hypothesize that the Zn catalyst must be completely removed to maximize the thermal stability of the resulting polymer. DSC analysis showed that the melting temperature of the polymer is -10 ℃ and that the material lacks a glass transition down to -85 ℃. The melting temperature is much lower than that of polyPDL (~ 100 ℃),[18] despite the absence of branching in the polymer chain, suggesting that the siloxane units in poly-**4** significantly disrupt the packing of the molecule. In addition, a melting temperature below room temperature renders poly-**4** a potentially useful midblock for ABA triblock thermoplastic elastomers.

Because the Zn catalyst **8** is bound to the chain end as a Zn-alkoxide species during the ROP of **4**, an ABA triblock copolymer with PLA as the A-blocks and poly-**4** as the B-block was constructed without isolating the midblock. After the polymerization of **4** had proceeded to ~90% conversion, the solution containing poly-**4** was diluted in CH_2Cl_2, L-lactide (18-25 wt % relative to the poly-**4**) was added to the reaction mixture, and the system was allowed to react at 25 ℃ for 2 h. Analysis by NMR spectroscopy indicated that full conversion of lactide occurred, while the unreacted **4** remained. This material balance reflects the large rate difference in rate of the ROP of lactide vs that of ROP of **4** and ensures the homogeneity of the A-blocks.

The triblock copolymer was isolated by quenching the crude mixture with iPrOH (~10 vol %) and precipitation from a 1:1:0.2 mixture of MeOH:iPrOH:acetone. Notable features in the NMR spectrum of the resulting polymer include a doublet at 0.99 ppm (J = 6.9 Hz) and two doublets at 4.01 ppm (J = 2.4 Hz) and 4.00 ppm (J = 2.0 Hz), corresponding to the chain initiator derived from 2-methyl-1,3-propanediol, a multiplet at 4.11 ppm corresponding to the methylene protons at the junctions between PLA and poly-**4**, and a multiplet at 4.36 ppm corresponding to the methine protons at the end of the PLA chains. In contrast to the NMR spectrum of poly-**4** obtained from precipitation from iPrOH, signals corresponding to a TBD-Zn species at 3.29 and 3.25 ppm were not observed in the NMR spectrum of the block copolymer.

The molecular weights of two PLLA-*co*-poly-4-*co*-PLLA samples are summarized in Table 7. The M_n measured by NMR spectroscopy was determined by comparing the integration of the CH and CH_2 groups alpha to the ester O to that of the CH_3 group of the initiator. The SEC data were obtained using an RI detector and referenced to PS standards.

The TGA of the copolymer showed that 1% weight loss occurred at 142 ℃ and 5% at 228 ℃. DSC showed that the metalting temperature of poly-**4**, the ABA triblock copolymer, is -13 ℃. No melting transition for the PLLA segments was observed up to 200 ℃; this upper limit was limited by the 5% decomposition temperature. Studies on the mechanical properties of the ABA triblock copolymers are underway.

Table 7. Molecular weight data of PLLA-*co*-poly-**4**-*co*-PLLA (monomer:Zn = 100:1)

monomer:initiator	PLA content (wt %)	M_n (calc) ($kg \cdot mol^{-1}$)	M_n (NMR) ($kg \cdot mol^{-1}$)	M_n (SEC) ($kg \cdot mol^{-1}$)	M_w (SEC) ($kg \cdot mol^{-1}$)	$Đ$
100:1	19	50.7	58.0	nd	nd	nd
50:1	22	26.4	29.7	31.4	48.5	1.54

nd: not determined

9.3 Conclusions

We synthesized a 26-membered macrolactone containing a tetramethyldisiloxane unit from methyl 10-undecenoate by a reaction sequence that can be conducted on large scale. The combined yield was 25% over 3 steps. The macrolactone was subjected to ROP with a diol initiator and a Zn catalyst to give a polymer containing two OH ends and a molecular weight that is tunable by varying the monomer-to-initiator ratio. The melting temperature of the resulting polymer (Poly-**4**) is low (-10 ℃) for polyesters lacking branching in the alkyl chains of the monomers, suggesting that the siloxane units significantly disrupt the packing of the polymer chain. ABA triblock copolymers with PLA as the end blocks were prepared in a one-pot synthesis. The melting temperature of the triblock copolymers was also low (-13 ℃). Potential elastomeric properties of the copolymers are under investigation.

9.4 Experimental

Reagents and instrumentation

All chemicals were purchased from commercial sources unless otherwise stated. Complexes **7**[26] and **8**[25] were synthesized according to literature procedures. Solvents were dried by an Innovative Technology Pure-Solv solvent purification system and stored over molecular sieves.

NMR spectra were acquired on Bruker AVQ-400, AVB-400, DRX 500, and AV-600 spectrometers. Chemical shifts were reported in ppm, relative to residual solvent peaks ($CDCl_3$ = 7.26 ppm for ^1H and 77.16 ppm for ^{13}C). Coupling constants were reported in Hz. SEC was performed on a Malvern Viscotek TDAMax chromatography system equipped with Waters HSPgel columns using THF as the eluent (35 ℃, 1 mL/min). DSC was performed on a TA Instruments Q200 calorimeter (purge gas: He, flow rate: 25 mL/min, ramp rate: 10-20 ℃/min, temperature range: -90 - 200 ℃). TGA was performed on a TA instrument Q500 thermogravimetric analyzer under nitrogen from 25 to 500 ℃ at a ramp rate of 10 ℃/min.

Synthesis of 2

To a mixture of **1** (10.3 g, 52.0 mmol) and 1,1,3,3-tetramethyldisiloxane (21.0 g, 156 mmol) under N_2 was added Karstedt's catalyst (10 μL of 2 wt % xylene solution), and the mixture was heated under N_2 at 50 ℃ for 2 d. The conversion was 85% at this point (monitored by NMR spectroscopy). Then another batch of Karstedt's catalyst (2 μL of 2 wt % xylene solution) was added, and the mixture was heated for another 2 d until all of **1** had been converted (as determined by NMR spectroscopy). Silane **2** was obtained by vacuum distillation (20 mTorr, 130 ℃) as a colorless liquid (13.9 g, 80.6% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 4.67 (p, *J* = 2.6 Hz, 1H), 3.66 (s, 3H), 2.30 (t, *J* = 7.6 Hz, 2H), 1.70 – 1.53 (m, 2H), 1.34 - 1.21 (m, 14H), 0.56 – 0.43 (m, 2H), 0.16 (d, *J* = 2.5 Hz, 6H), 0.05 (s, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 174.49 (s), 51.57 (s), 34.27 (s), 33.52 (s), 29.65 (s), 29.62 (s), 29.47 (s), 29.40 (s), 29.31 (s), 25.11 (s), 23.32 (s), 18.27 (s), 1.05 (s), 0.19 (s). HRMS (EI+) cald for $C_{16}H_{35}O_3Si_2^+$: 331.2119, found: 331.2126.

Synthesis of 3

To a mixture of silane **2** (4.0 g, 12 mmol) and 10-undecenol (3.1 g, 18 mmol) in a 20-mL vial under N_2 was added $Ti(OBu)_4$ (8.1 mg, 0.024 mmol), and the mixture was heated at 80 ℃ while being purged by a constant stream of N_2 for 3 d. The conversion of **2** was monitored by NMR spectroscopy. After full conversion of **2**, the vial was opened under air, Et_3N (15 μL) was added to the mixture, and the mixture was stirred at 25 ℃ for 1 h. The mixture was then purified by column chromatography (0 → 5% Et_2O in hexanes) to afford **3** as a colorless liquid (4.9 g, 86% yield). ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.81 (ddt, *J* = 16.9, 10.2, 6.7 Hz, 1H), 5.06 – 4.87 (m, 2H), 4.67 (hept, *J* = 2.8 Hz, 1H), 4.05 (t, *J* = 6.7 Hz, 2H), 2.29 (t, *J* = 7.5 Hz, 2H), 2.04 (q, *J* = 6.9 Hz, 2H), 1.65 – 1.58 (m, 4H), 1.44 - 1.17 (m, 26H), 0.52 (t, *J* = 7.5 Hz, 2H), 0.16 (d, *J* = 2.8 Hz, 6H), 0.05 (s, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 174.15 (s), 139.33 (s), 114.28 (s), 64.53 (s), 34.57 (s), 33.94 (s), 33.53 (s), 29.67 (s), 29.65 (s), 29.61 (s), 29.54 (s), 29.49 (s), 29.43 (s), 29.38 (s), 29.33 (s), 29.24 (s), 29.07 (s), 28.81 (s), 26.08 (s), 25.19 (s), 23.33 (s), 18.28 (s), 1.05 (s), 0.19 (s). HRMS (EI+) calcd for $C_{26}H_{53}O_3Si_2^+$: 469.3528, found: 469.3517.

Synthesis of 4

To a solution of Karstedt's catalyst (80 μL of 2 wt % xylene solution) in toluene (140 mL) under N_2 at 25 ℃ was added dropwise a solution of **3** (5.90 g, 12.5 mmol) in toluene (140 mL) over 24 h. After the addition had finished, the solution was stirred for 2 h at 25 ℃, and the volatile materials were evaporated. The crude mixture was purified by column chromatography

(0 → 5% Et_2O in hexanes over silica treated with 3 wt % $AgNO_3$) to afford **4** as a colorless liquid that spontaneously solidified after several days of storage at 25 ℃ (2.09 g, 35% yield). ^1H NMR (600 MHz, $CDCl_3$) δ 4.11 (t, *J* = 5.7 Hz, 2H), 2.31 (t, *J* = 7.0 Hz, 2H), 1.67 – 1.58 (m, 4H), 1.42 – 1.21 (m, 30H), 0.53 – 0.45 (m, 4H), 0.02 (s, 12H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 174.19 (s), 64.39 (s), 34.93 (s), 33.62 (s), 33.60 (s), 29.85 (s), 29.77 (s, three peaks overlapping), 29.74 (s), 29.66 (s), 29.63 (s), 29.43 (s), 29.40 (s), 29.15 (s), 28.78 (s), 26.36 (s), 25.48 (s), 23.46 (s), 23.43 (s), 18.60 (s), 18.58 (s), 0.64 (s), 0.60 (s). HRMS (EI+) calcd for $C_{26}H_{54}O_3Si_2^+$: 470.3611, found: 470.3615.

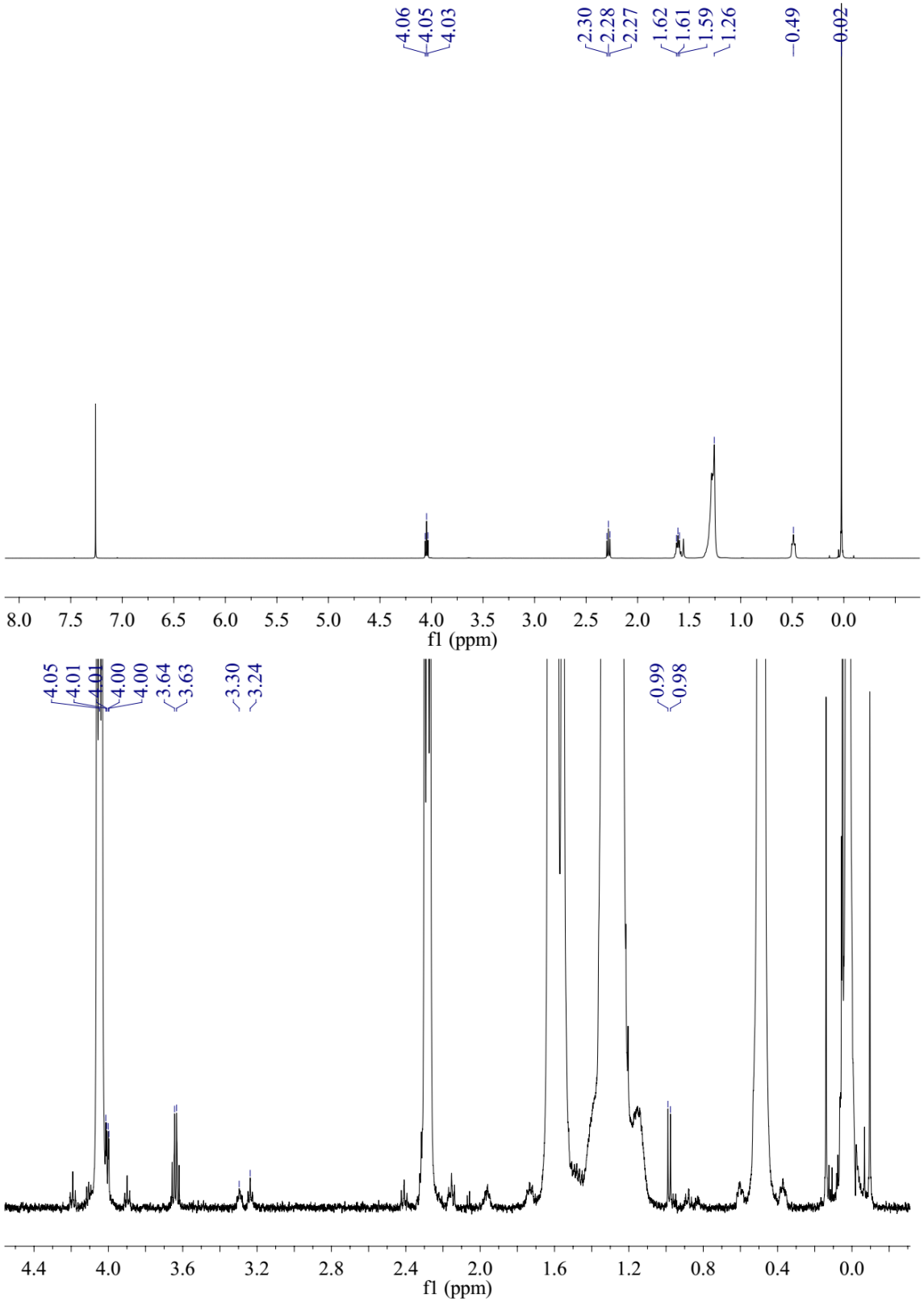
Representative procedure for the ROP of 4

A 4-mL vial under N_2 was charged with $\{(TBD)Zn[N(TMS)_2]\}_2$ (0.7 mg, 0.002 mmol), 2-methyl-1,3-propanediol (0.18 mg, 0.0020 mmol) in toluene (60 μL), and **4** (94 mg, 0.20 mmol), and the mixture was stirred under N_2 at 100 ℃ for 21 h. The conversion of **4** was monitored by NMR spectroscopy. After 21 h, the conversion was ~85%. The vial was opened under air, and the sample was diluted with $CHCl_3$ (0.4 mL) and iPrOH (0.1 mL) before being added dropwise to a stirring mixture of iPrOH and acetone (20:1). The precipitated polymer was washed with iPrOH and dried at 40 ℃ under vacuum. A colorless viscous liquid was obtained (60 mg, 64% yield).

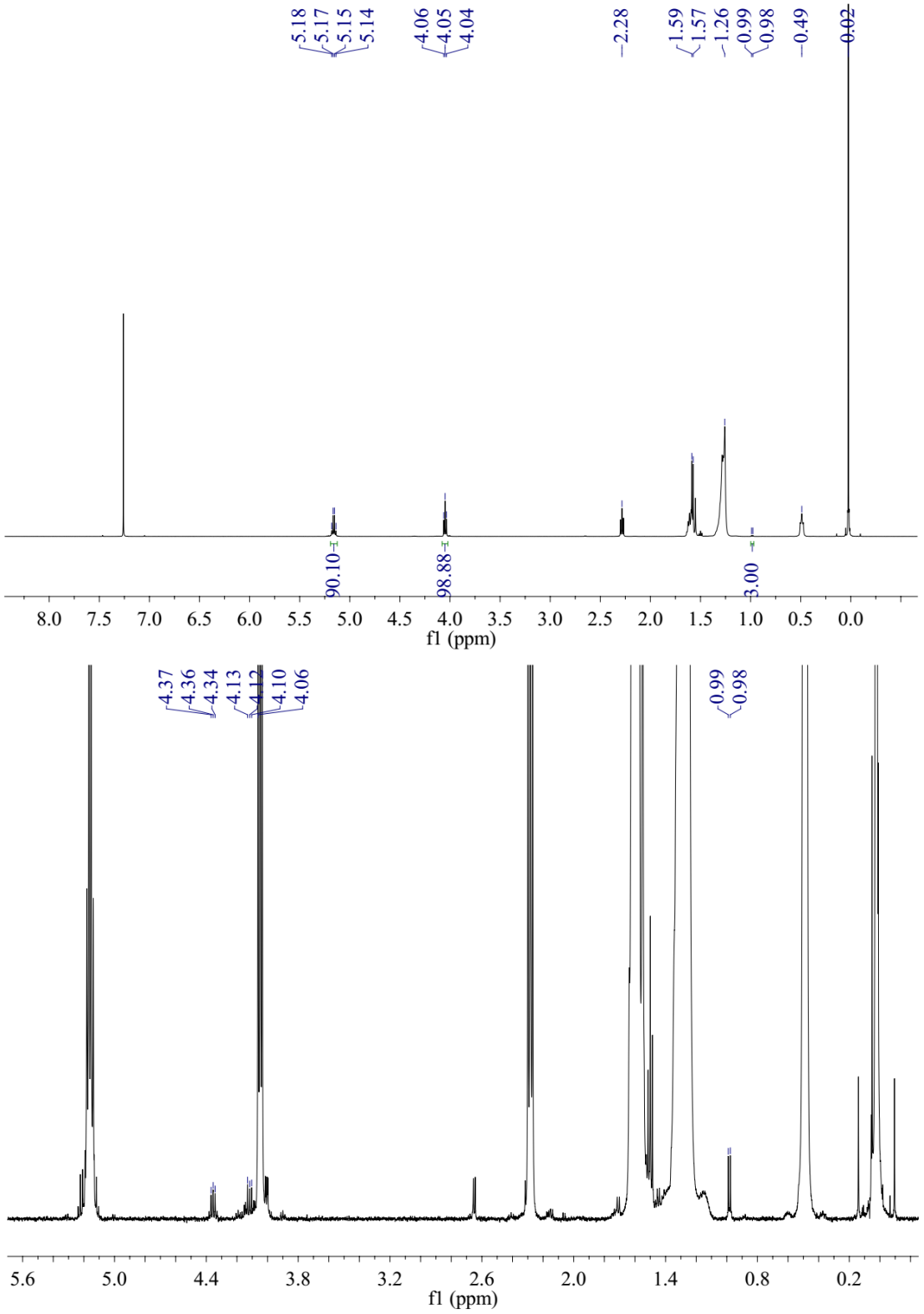
Representative procedure for the one-pot synthesis of PLLA-*co*-poly-4-*co*-PLLA

A 4-mL vial under N_2 was charged with $\{(TBD)Zn[N(TMS)_2]\}_2$ (2.3 mg, 0.0063 mmol), 2-methyl-1,3-propanediol (1.2 mg, 0.013 mmol) in toluene (380 μL), and **4** (300 mg, 0.638 mmol), and the mixture was stirred under N_2 at 100 ℃ for 30 h. The conversion of **4** at this point was 88%, as determined by NMR spectroscopy. The mixture was diluted with CH_2Cl_2 (1 mL), and to the mixture was added L-lactide (80 mg, 0.56 mmol). The resulting mixture was stirred at 25 ℃ for 2 h. All lactide had been converted at this point, as determined by NMR spectroscopy. The vial was opened under air, and to it was added iPrOH (0.3 mL). The mixture was stirred at 25 ℃ for 1 h before being added dropwise to a stirring mixture of MeOH (100 mL), iPrOH (100 mL), and acetone (20 mL). A white fiberous solid was obtained after decanting the solvents and was rinsed with iPrOH and dried under vacuum at 40 ℃ (237 mg, 62% yield).

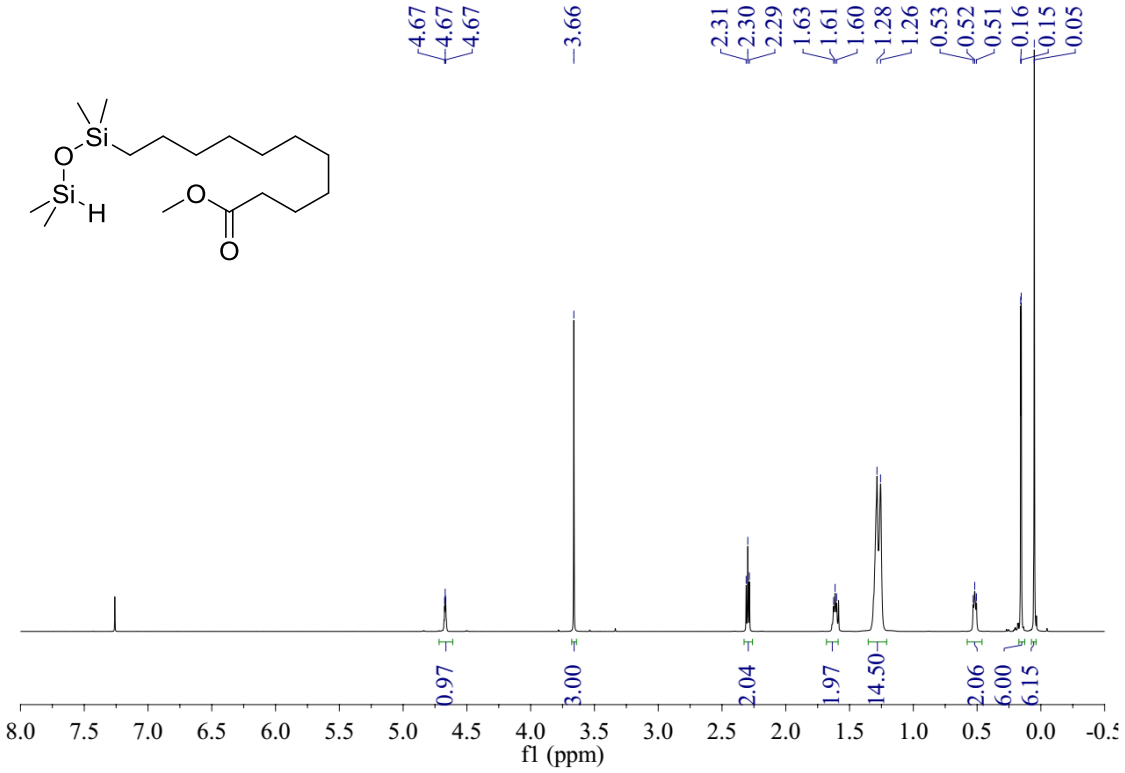
Representative NMR spectrum of poly-4 (with the spectrum expanded along the y axis)

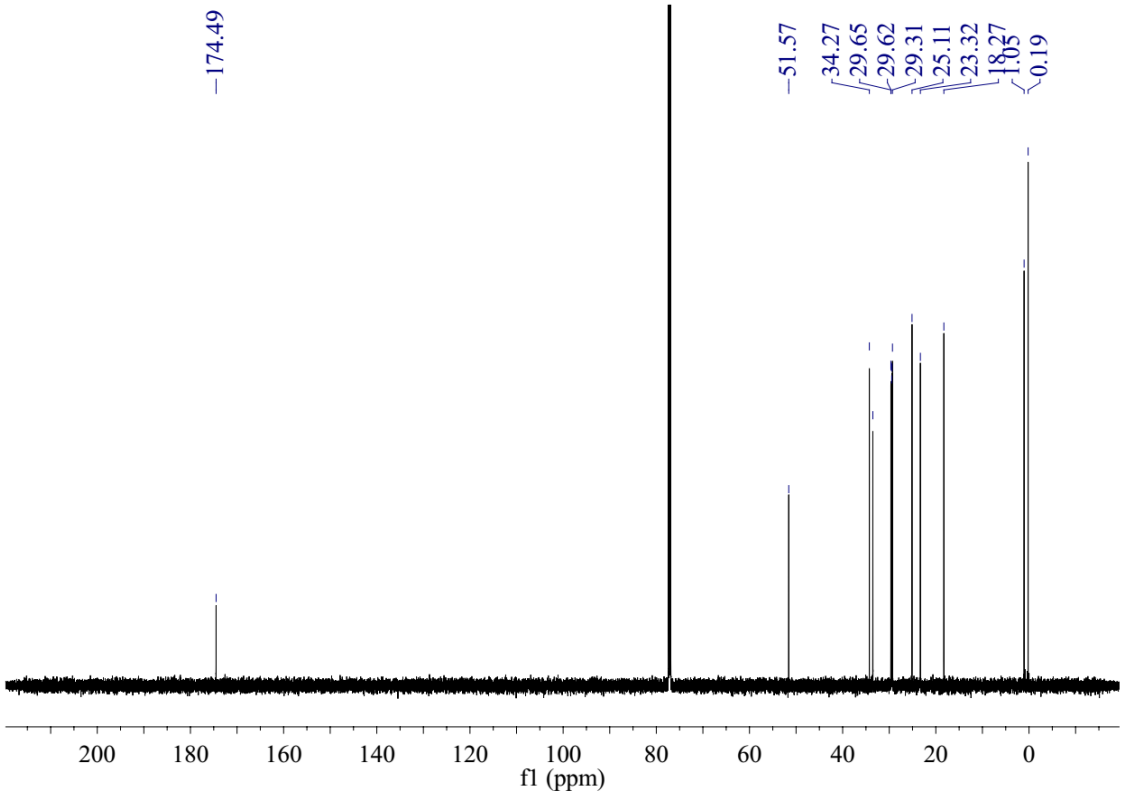


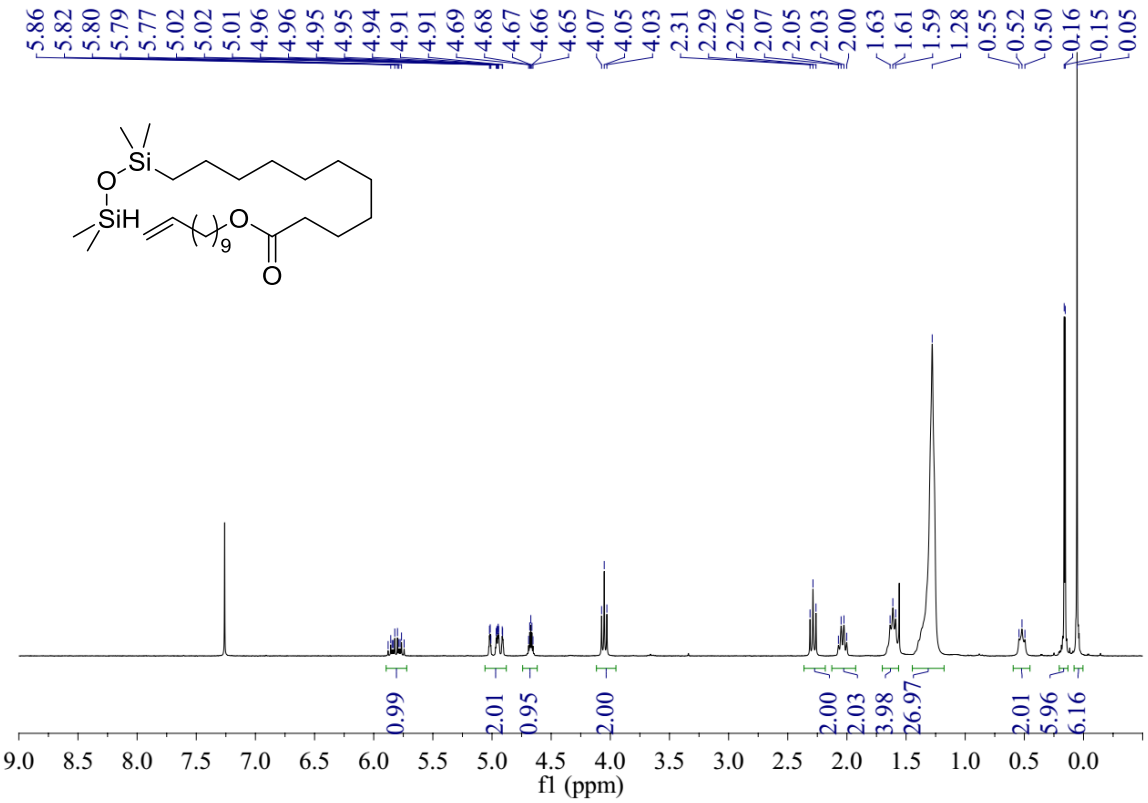
Representative NMR spectrum of PLLA-*co*-poly-4-*co*-PLLA (with the spectrum expanded along the y axis)

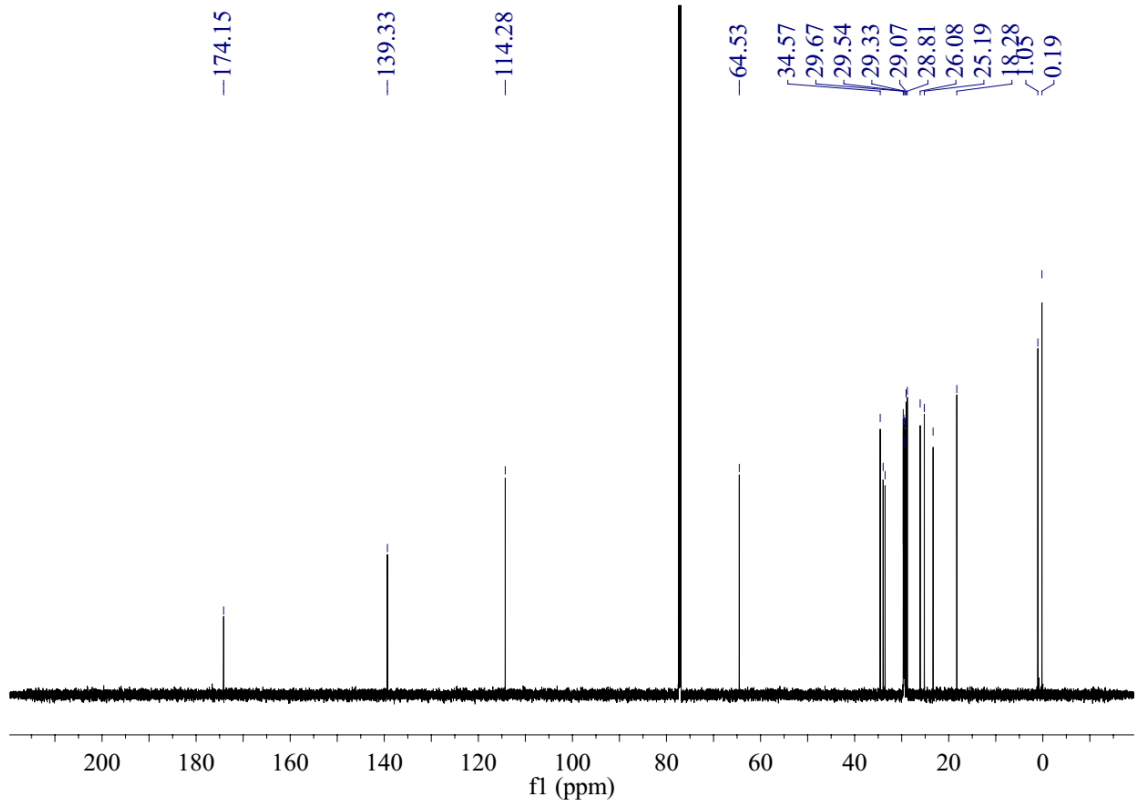


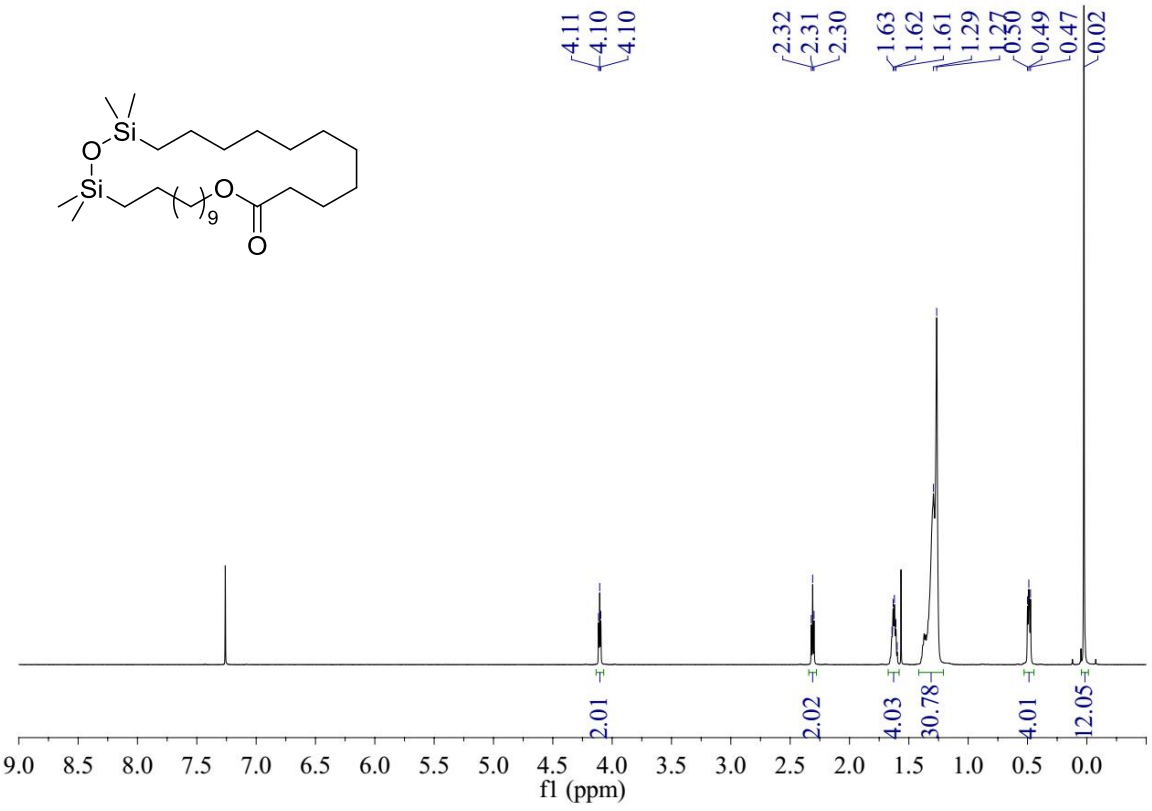
NMR spectra of new compounds

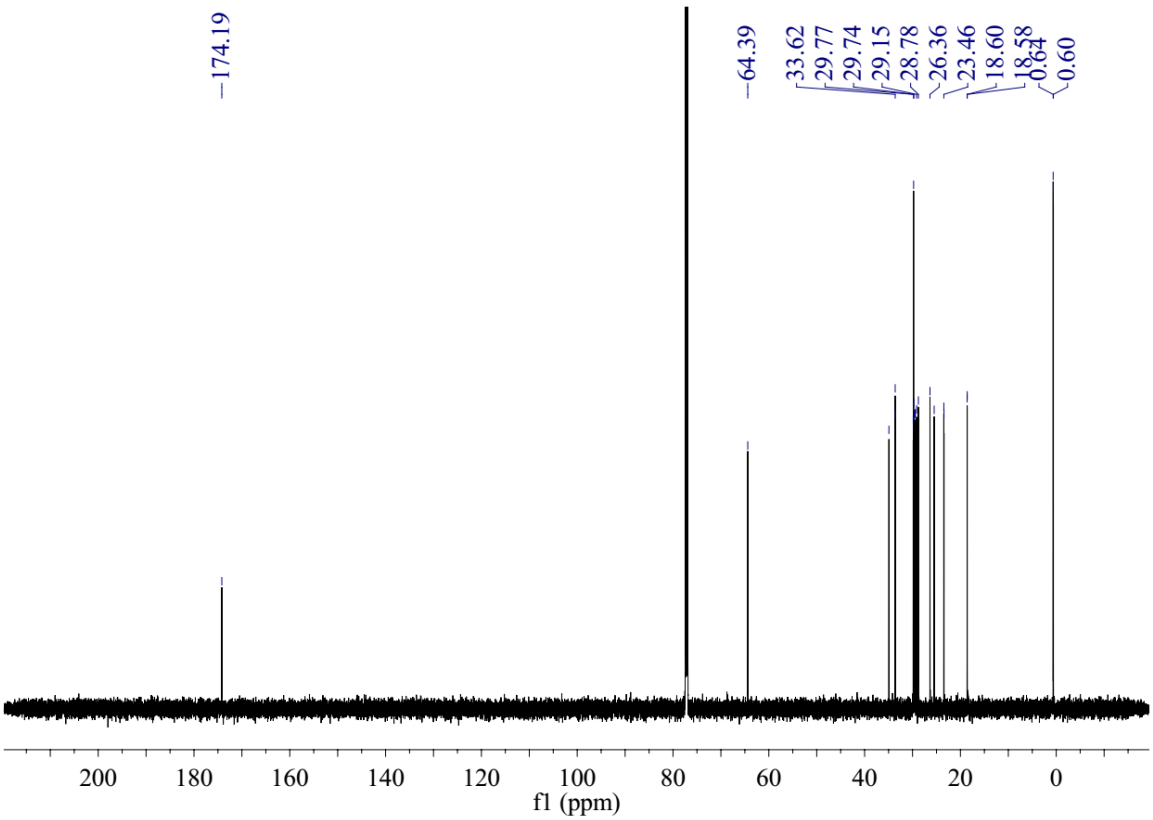





5.86 5.82 5.80 5.79 5.77 5.02 5.02 5.01 4.96 4.96 4.95 4.95 4.94 4.91 4.91 4.69 4.68 4.67 4.66 4.65 4.07 4.05 4.03 2.31 2.29 2.26 2.07 2.05 2.03 2.00 1.63 1.61 1.59 1.28 0.55 0.52 0.50 0.16 0.15 0.05
Si
O
SiH
O
9
O
0.99 2.01 0.95 2.00 2.00 2.03 3.98 26.97 2.01 5.96 6.16
9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)


174.15 139.33 114.28 64.53 34.57 29.67 29.54 29.33 29.07 28.81 26.08 25.19 18.28 1.05 0.19
200 180 160 140 120 100 80 60 40 20 0
f1 (ppm)


4.11
4.10
4.10
2.32
2.31
2.30
1.63
1.62
1.61
1.29
1.27
0.50
0.49
0.47
0.02
2.01
2.02
4.03
30.78
4.01
12.05
9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0
f1 (ppm)


174.19
64.39
33.62
29.77
29.74
29.15
28.78
26.36
23.46
18.60
18.58
0.64
0.60
200 180 160 140 120 100 80 60 40 20 0
f1 (ppm)

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