

Palladium(0)-Catalyzed Silylation of Aryl Halides with Triorganosilanes: Synthesis of Aryl(2-furyl)silanes

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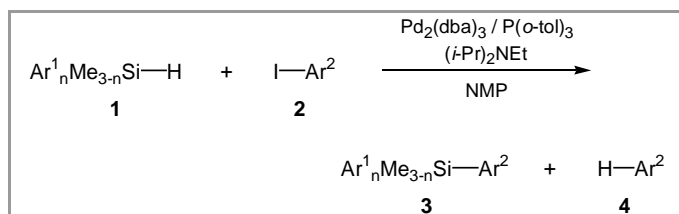
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Abstract: Triorganosilanes, which possess two aryl groups on the silicon atom, undergo the palladium-catalyzed silylation of aryl iodides. Aryl(2-furyl)silanes thus obtained are potentially useful starting materials for carbon-carbon bond-formation reactions in the presence of transition metal catalysts and tetrabutylammonium fluoride.

Key words: Silicon, Palladium, Catalysis, Cross-Coupling, Halides

Recently, much attention has been focused on the coupling reaction of metalloid hydride with organic electrophiles as an atom-economical method for the synthesis of organometalloids. The metalations of aryl halides using various metalloid hydrides, including boron,¹ silicon,² germanium,³ and tin compounds,⁴ have been extensively studied; however, the scope of metalloid hydrides used as metalating reagents is still limited. In fact, examples of the silylation using hydrosilanes other than triethoxysilane are rare.⁵ Therefore, it was of interest to expand the scope of palladium-catalyzed silylation to another hydrosilane as a silicon source. We report herein that triorganosilanes **1** couple with aryl halides Ar²-X **2** in the presence of palladium catalyst to give all-carbon-substituted arylsilanes **3**; the selective silylation requires two aryl groups Ar¹ on the silicon atom of triorganosilanes **1** (Equation 1). During the completion of this work, Yamanoi reported a similar palladium-catalyzed method for the combination triorganosilanes with aryl iodides.⁶

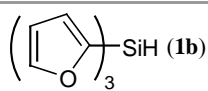
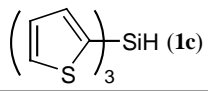
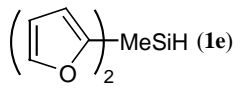
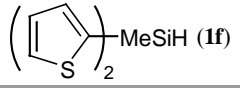


Equation 1 Palladium-catalyzed silylation of aryl halides using triorganosilanes

An initial screen was performed using several triorganosilanes **1** for the silylation of 4-iodoanisole (**2a**). The results are summarized in Table 1. Treatment of **2a** (1 equiv) with **1** (1.5 equiv) and (*i*-Pr)₂NEt (3 equiv) in the presence of 1.5 mol% of Pd₂(dba)₃·CHCl₃ and 6 mol% of P(*o*-tol)₃ in NMP at room temperature was found to lead to the corresponding arylsilane **3aa-3ha**. The formation of anisole (**4a**) by reduction of the starting **2a** was the major side reaction. Under our conditions, the ratio of **3:4a** was strongly influenced by substituents on

the silicon atom of **1**. Among the hydrosilanes **1a-1h** examined, diarylmethylhydrosilanes **1d-1f** (Equation 1, n=2) exhibited the highest product selectivity to produce the corresponding arylsilanes **3da-3fa** in 75-82% yields (entries 4-6). The use of diarylhydrosilanes was suitable for the silylation, as the differences in the yields and on the selectivity among **1d** (Ar¹=Ph, entry 4), **1e** (Ar¹=2-furyl, entry 5), or **1f** (Ar¹=2-thienyl, entry 6) were not particularly large. Unfortunately, the use of triarylhydrosilanes **1a-1c** (n=3) produced lower ratios of **3:4a** (entries 1-3). For dimethylphenylsilane (**1g**) and triethylsilane (**1h**), no product selectivity was observed (entries 7 and 8).

Table 1 Reaction of 4-Iodoanisole (**2a**) with Representative Hydrosilanes **1**^a

Entry	1	3	Yield (%) ^b	
			3	4a
1	Ph ₃ SiH (1a)	3aa	64	(33)
2	 SiH (1b)	3ba	71	(29)
3	 SiH (1c)	3ca	68	(31)
4	Ph ₂ MeSiH (1d)	3da	79	(18)
5	 MeSiH (1e)	3ea	82	(12)
6	 MeSiH (1f)	3fa	75	(14)
7	PhMe ₂ SiH (1g)	3ga	34	(57)
8	Et ₃ SiH (1h)	3ha	(44)	(46)

^a Reaction conditions: **2a** (1.0 mmol), **1** (1.5 mmol), (*i*-Pr)₂NEt (3 mmol), Pd₂(dba)₃·CHCl₃ (15 μmol), P(*o*-tol)₃ (60 μmol), in NMP (4 mL) at room temperature for 2 h.

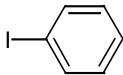
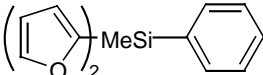
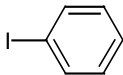
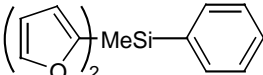
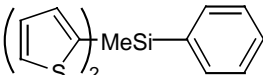
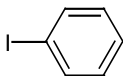
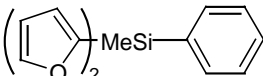
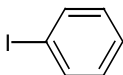
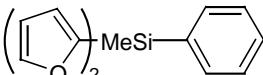
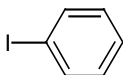
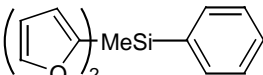
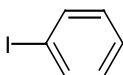
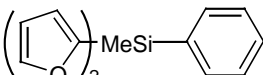
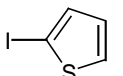
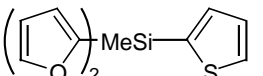
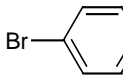
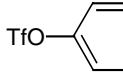
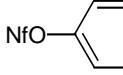
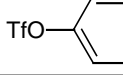
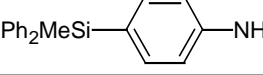
^b Isolated yields are based on **2a**. Yields in parentheses are GC yields.

The results obtained with representative aryl halides **2**, giving arylsilanes **3** similarly as above, are listed in Table 2. As a whole, the desired products **3** were contaminated with small amounts of the reduced byproducts **4**, but their isolation was very easy. The present process was extremely tolerant of a variety of common functional groups. Thus, **2** containing free anilino NH₂ (entry 4) and phenolic OH moieties (entry 5), an amide (entry 12) and acetoxy group (entry 6), and halogen atom (entry 7) were all efficiently converted to the corresponding

products **3**. In contrast, the traditional methods via Grignard reagents or organolithiums require the protection of functional groups frequently.⁷ Although aryl iodides were significantly reactive, replacing the leaving group of aryl halides with the corresponding bromide or triflate gave lower yield under our normal conditions. Gratifyingly, by using a treatment with an additional excess

amount of iodide anion, the silylation of aryl bromide, triflate, and nonaflate afforded moderate to good product yields (entries 9-12).⁸ In such cases, KOAc was more favorable base for selective silylation. Unfortunately, all attempts at the silylation of *ortho*-substituted or electron-deficient aryl halides were unsuccessful.^{2,6}

Table 2 Reaction of Representative Aryl Halides^a

Entry	Hydrosilane 1	Aryl Halide 2	Product 3	Yield (%) ^b
1	1e	 (2b)	 (3eb)	67 ^c
2	1e	 (2c)	 (3ec)	80
3	1f	2c	 (3fc)	90
4	1e	 (2d)	 (3ed)	71
5	1e	 (2e)	 (3ee)	55
6	1e	 (2f)	 (3ef)	79
7	1e	 (2g)	 (3eg)	77
8	1e	 (2h)	 (3eh)	88
9 ^d	1d	 (2i)	3da	69
10 ^d	1d	 (2j)	3da	84
11 ^d	1d	 (2k)	3da	83
12 ^d	1d	 (2l)	 (3la)	72

^a Reaction conditions: **2** (1.0 mmol), **1** (1.5 mmol), (*i*-Pr)₂NEt (3 mmol), Pd(dba)₃·CHCl₃ (15 μmol), P(*o*-tol)₃ (60 μmol), in NMP (4 mL) at room temperature for 2 h.

^b Isolated yields are based on **2**.

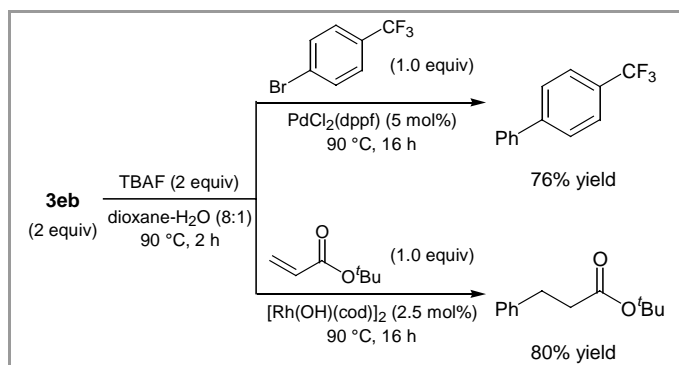
^c GC yield.

^d KI (3 mmol) was used as an additive, and KOAc (3 mmol) was used instead of (*i*-Pr)₂NEt.

We then turned our attention toward a synthetic application of aryl(2-furyl)silanes **3** thus obtained via the transition-metal-catalyzed coupling reaction. Recently, several groups have demonstrated the palladium-catalyzed

cross-coupling reactions of all-carbon-substituted organosilanes, such as 2-pyridyl⁹ and 2-thienyl(alkenyl)silanes.^{10,11} In these reactions, the heteroaryl group acts as a good dummy group upon treatment with fluoride ion to form possibly organosilanols. We found

that 2-furyl group on silicon atom worked in a manner similar to those heteroaryl groups (Scheme 1).¹² For example, after treatment of di(2-furyl)(methyl)phenylsilane **3eb** (2 equiv) with TBAF (2 equiv) in dioxane–H₂O (8:1) at 90 °C, the palladium-catalyzed cross-coupling reaction with 4-bromobenzotrifluoride (1.0 equiv) took place to produce the corresponding unsymmetrical biaryl in 76% yield. Also, **3eb** participated in rhodium-catalyzed 1,4-addition to α,β -unsaturated ester to give the desired adduct in good yield.¹³



Scheme 1 Synthetic utility of aryl(2-furyl)silanes

In conclusion, triorganosilanes, which possess two aryl groups on the silicon atom, were found to undergo the palladium-catalyzed silylation of aryl iodides; however, the mechanism for this silylation is unclear at the present stage.¹⁴ In addition, we have demonstrated that aryl(2-furyl)silanes can be coupled with electrophiles, such as aryl halides and α,β -unsaturated carbonyl compounds.

Silylation of Aryl Iodides; General Procedure (Table 2).

$\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (0.015 mmol) and $\text{P}(o\text{-tol})_3$ (0.06 mmol) were placed in a test tube capped with a septum rubber. The test tube was flushed with nitrogen and then charged with NMP (4 mL). Aryl iodide **2** (1.0 mmol), (*i*-Pr)₂N₂Et (3 mmol), and hydrosilane **1** (1.5 mmol) were added successively. The reaction mixture was then stirred at room temperature for 2 h. After the reaction, the mixture was diluted with ether, washed three times with H₂O to remove NMP, and dried over Na₂SO₄. The solvent was removed under reduced pressure and the residue was purified by flash column chromatography to give the desired arylsilane **3**.

3ea

¹H NMR (CDCl₃): δ = 0.78 (s, 3 H), 3.81 (s, 3H), 6.42 (dd, J = 1.8, 3.0 Hz, 2 H), 6.76 (d, J = 3.0 Hz, 2 H), 6.93 (d, J = 8.5 Hz, 2 H), 7.54 (d, J = 8.5 Hz, 2 H), 7.72 (d, J = 1.8 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -4.24, 55.05, 109.61, 113.79, 122.79, 124.52, 136.24, 147.72, 155.38, 161.14.

HRMS (EI): m/z calcd for C₁₆H₁₆O₃Si [M⁺]: 284.0868; found: 284.0840.

3fa

¹H NMR (CDCl₃): δ = 0.88 (s, 3 H), 3.81 (s, 3H), 6.92 (d, J = 7.9 Hz, 2 H), 7.21 (dd, J = 3.6, 4.3 Hz, 2 H), 7.34 (d, J = 3.6 Hz, 2 H), 7.52 (d, J = 7.9 Hz, 2 H), 7.68 (d, J = 4.3 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -0.87, 55.03, 113.69, 128.26, 131.98, 135.77, 126.43, 136.26, 136.80, 161.05.

HRMS (EI): m/z calcd for C₁₆H₁₆O₂Si [M⁺]: 316.0412; found: 316.0443.

3eb

¹H NMR (CDCl₃): δ = 0.81 (s, 3 H), 6.43 (dd, J = 1.2, 3.0 Hz, 2 H), 6.78 (d, J = 3.0 Hz, 2 H), 7.3–7.5 (m, 3 H), 7.62 (d, J = 8.0 Hz, 2 H), 7.73 (d, J = 1.2 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -4.47, 109.65, 122.98, 127.97, 129.96, 133.84, 134.65, 147.82, 154.95.

HRMS (EI): m/z calcd for C₁₅H₁₄O₂Si [M⁺]: 254.0763; found: 254.0721.

3ec

¹H NMR (CDCl₃): δ = 0.78 (s, 3 H), 2.36 (s, 3H), 6.42 (dd, J = 1.8, 3.0 Hz, 2 H), 6.77 (d, J = 3.0 Hz, 2 H), 7.20 (d, J = 7.5 Hz, 2 H), 7.51 (d, J = 7.5 Hz, 2 H), 7.72 (d, J = 1.8 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -4.38, 21.57, 109.61, 122.84, 128.84, 130.11, 134.70, 140.01, 147.74, 155.22.

HRMS (EI): m/z calcd for C₁₆H₁₆O₂Si [M⁺]: 268.0919; found: 268.0912.

3fc

¹H NMR (CDCl₃): δ = 0.89 (s, 3 H), 2.36 (s, 3H), 7.2–7.3 (m, 4 H), 7.35 (d, J = 3.1 Hz, 2 H), 7.50 (d, J = 7.3 Hz, 2 H), 7.69 (d, J = 4.3 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -0.99, 21.55, 128.26, 128.77, 132.00, 133.02, 134.74, 135.55, 136.85, 139.92.

HRMS (EI): m/z calcd for C₁₆H₁₆S₂Si [M⁺]: 300.0463; found: 300.0442.

3ed

¹H NMR (CDCl₃): δ = 0.75 (s, 3 H), 3.78 (br s, 2H), 6.41 (dd, J = 1.2, 3.0 Hz, 2 H), 6.69 (d, J = 8.0 Hz, 2 H), 6.75 (d, J = 3.0 Hz, 2 H), 7.40 (d, J = 8.0 Hz, 2 H), 7.71 (d, J = 1.3 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -4.23, 109.54, 114.63, 122.58, 129.27, 136.08, 147.58, 148.13, 155.78.

HRMS (EI): m/z calcd for C₁₅H₁₅NO₂Si [M⁺]: 269.0872; found: 269.0834.

3ee

¹H NMR (CDCl₃): δ = 0.78 (s, 3 H), 4.85 (s, 1 H), 6.42 (dd, J = 1.8, 3.0 Hz, 2 H), 6.76 (d, J = 3.0 Hz, 2 H), 6.85 (d, J = 8.5 Hz, 2 H), 7.50 (d, J = 8.5 Hz, 2 H), 7.72 (d, J = 1.8 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -4.27, 109.61, 115.47, 122.81, 126.12, 136.49, 147.73, 155.28, 157.15.

HRMS (EI): m/z calcd for $C_{15}H_{14}O_3Si$ [M^+]: 270.0712; found: 270.0733.

3ef

1H NMR ($CDCl_3$): δ = 0.77 (s, 3 H), 2.30 (s, 3H), 6.43 (dd, J = 1.8, 3.0 Hz, 2 H), 6.79 (d, J = 3.0 Hz, 2 H), 7.10 (d, J = 8.0 Hz, 2 H), 7.62 (d, J = 8.0 Hz, 2 H), 7.73 (d, J = 1.8 Hz, 2 H).

^{13}C NMR ($CDCl_3$): δ = -4.41, 21.17, 109.68, 120.75, 122.78, 128.94, 131.44, 136.02, 147.88, 152.18, 169.30.

HRMS (EI): m/z calcd for $C_{17}H_{16}O_4Si$ [M^+]: 312.0818; found: 312.0845.

3eg

1H NMR ($CDCl_3$): δ = 0.79 (s, 3 H), 6.44 (dd, J = 1.2, 3.6 Hz, 2 H), 6.78 (d, J = 3.6 Hz, 2 H), 7.36 (d, J = 8.3 Hz, 2 H), 7.53 (d, J = 8.3 Hz, 2 H), 7.73 (d, J = 1.2 Hz, 2 H).

^{13}C NMR ($CDCl_3$): δ = -4.49, 109.71, 123.19, 128.25, 132.25, 136.02, 136.41, 147.98, 154.38.

HRMS (EI): m/z calcd for $C_{15}H_{13}O_2^{35}ClSi$ [M^+]: 288.0373; found: 288.0418.

3eh

1H NMR ($CDCl_3$): δ = 0.85 (s, 3H), 6.43 (dd, J = 1.2, 3.7 Hz, 2 H), 6.83 (d, J = 3.7 Hz, 2 H), 7.23 (dd, J = 3.1, 4.9 Hz, 1 H), 7.43 (d, J = 3.1 Hz, 1 H), 7.69 (d, J = 4.9 Hz, 1 H), 7.73 (d, J = 1.2 Hz, 2 H).

^{13}C NMR ($CDCl_3$): δ = -3.24, 109.47, 109.73, 123.07, 128.34, 132.32, 137.00, 147.90, 154.45.

HRMS (EI): m/z calcd for $C_{13}H_{12}O_2SiS$ [M^+]: 260.0327; found: 260.0368.

Palladium-Catalyzed Cross-Coupling of Aryl(2-furyl)silanes (Scheme 1).

A mixture of di(2-furyl)(methyl)phenylsilane (2 mmol) and TBAF·3H₂O (2 mmol) in dioxane–H₂O (8:1, 3.6 mL) was stirred at 90 °C for 2 h. To this were added PdCl₂(dppf) (0.05 mmol) and 4-bromobenzotrifluoride (1.0 mmol). After being stirred at 90 °C for 16 h, the GC analysis of the resulting mixture indicated the formation of 4-phenylbenzotrifluoride in 76% yield.

Rhodium-Catalyzed 1,4-Addition of Aryl(2-furyl)silanes to α,β -Unsaturated Esters (Scheme 1).

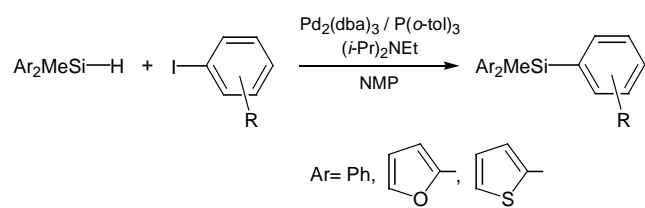
A mixture of di(2-furyl)(methyl)phenylsilane (2 mmol) and TBAF·3H₂O (2 mmol) in dioxane–H₂O (8:1, 3.6 mL) was stirred at 90 °C for 2 h. To this were added [Rh(OH)(cod)]₂ (0.025 mmol) and *tert*-butyl acrylate (1.0 mmol). After being stirred at 90 °C for 16 h, the GC analysis of the resulting mixture indicated the formation of *tert*-butyl 3-phenylpropionate in 80% yield.

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- (14) To some extent, a plausible mechanism for the case of triethoxysilane proposed by us (see reference 2a) would refer to the present situation. However, the role of KI (Table 2, entries 9-12) is not easily interpretable.

Graphical abstract:**Short title of the article:**

Palladium-Catalyzed Silylation of Aryl Halides with Triorganosilanes