

Boron-Catalyzed Aromatic C–H Bond Silylation with Hydrosilanes

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S Supporting Information

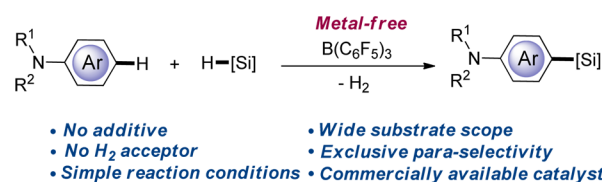
ABSTRACT: Metal-free catalytic C–H silylation of a series of aromatic compounds such as *N,N*-disubstituted anilines with various hydrosilanes has been achieved for the first time using commercially available $B(C_6F_5)_3$ as a catalyst. This protocol features simple and neutral reaction conditions, high regioselectivity, wide substrate scope (up to 40 examples), Si–Cl bond compatibility, and no requirement for a hydrogen acceptor.

Silyl-substituted aromatic compounds such as silylanilines are of great interest in various fields, such as organic electronics and photonics, pharmaceuticals, and molecular and materials synthesis.^{1–3} The catalytic C–H silylation of arenes with hydrosilanes through release of H_2 is the most efficient way to synthesize silyl-substituted aromatic compounds because this method does not require prefunctionalization of the reaction partners.⁴ To date, various metal-based catalysts^{4–6} have been reported for C–H silylation reactions between arenes and hydrosilanes in the presence of an excess amount of a hydrogen acceptor.^{6a,d–g} In contrast, metal-free catalytic C–H silylation has remained almost unexplored to date.^{7–9} In view of the concerns about the influences of trace metals on the efficiency of organic electronic devices and human consumption products as well as the costs associated with removing residual catalysts, the development of metal-free catalytic processes for efficient C–Si bond formation is of great interest and importance.

Boron Lewis acids have received much recent attention as powerful tools for activation of dihydrogen and hydrosilanes and related transformations.^{10,11} It was previously reported that intramolecular dehydrosilylation of hydrosilyl-substituted biphenyls could be achieved in the presence of a catalytic amount of $B(C_6F_5)_3$ together with a base such as dichloropyridine.⁷ However, attempts at the analogous intermolecular C–H silylation suffered from low activity and poor selectivity.⁸ Very recently, Oestreich and co-workers briefly noted the silylation of *N,N*-dimethylaniline with $PhMe_2SiH$ in the presence of a catalytic amount of $B(C_6F_5)_3$.⁶ⁱ

We have previously used boron compounds such as $[Ph_3C][B(C_6F_5)_4]$ and $B(C_6F_5)_3$ as cocatalysts for the rare-earth-catalyzed C–H alkylation of arenes.¹² In the course of studies on the use of such catalyst systems for C–H silylation reactions,¹³ we found that $B(C_6F_5)_3$ alone could serve as an excellent catalyst for C–H silylation of electron-rich arenes such as *N,N*-dimethylaniline (Scheme 1). The silylation reaction takes place exclusively at the para position, affording a wide range of silylated aromatic compounds under neutral

Scheme 1. Boron-Catalyzed Aromatic C–H Bond Silylation with Hydrosilanes



conditions without a hydrogen acceptor. In addition to a wide range of easily available mono-, di-, and trisubstituted hydrosilanes, metal-sensitive chlorohydrosilanes such as $PhSiH_2Cl$ and Ph_2SiHCl can also be used as efficient silylation agents through Si–H bond cleavage without observable dehalogenation. We report herein these discoveries.

On the basis of screening of various boron catalysts and other parameters (solvent, temperature, reaction time, and substrate ratio) for the C–H silylation of *N,N*-dimethylaniline (**1a**) with diphenylsilane (**2a**) (Table S1), we chose $B(C_6F_5)_3$ (1.0–2.5 mol %) as a catalyst to examine the scope of hydrosilanes for this transformation in chlorobenzene at 120 °C. Some representative results are summarized in Table 1 and Scheme 2.

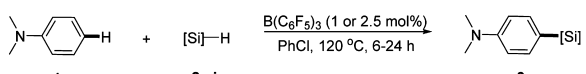
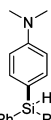
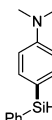
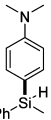
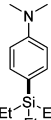
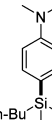
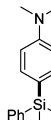
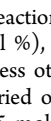
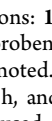
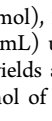
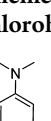

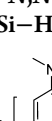
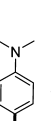
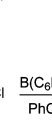
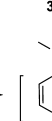
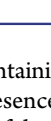
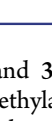
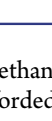
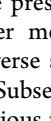
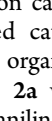
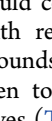
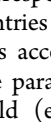
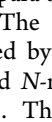
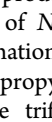
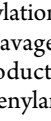
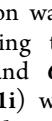
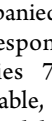



We found that a much wider range of hydrosilanes could be employed in comparison with metal-based catalyst systems.^{4–6} Either mono-, di-, or trisubstituted hydrosilanes with either alkyl or phenyl substituents could serve as efficient silicon sources for the present silylation reaction (Table 1). More remarkably, chlorohydrosilanes containing a highly reactive Si–Cl bond, such as Ph_2SiHCl (**2k**) and $PhSiH_2Cl$ (**2l**), could also selectively undergo the silylation reaction through Si–H cleavage, leaving the reactive chloride intact (Scheme 2). In all cases, the silylation took place exclusively at the para C–H bond of *N,N*-dimethylaniline, affording the corresponding para-silylated derivatives in moderate to high yields (Table 1). The reaction of *N,N*-dimethylaniline with Ph_2SiH_2 on a 5 mmol scale in the presence of 1.0 mol % $B(C_6F_5)_3$ easily afforded 1.09 g (72% yield) of the silylation product **3a** after chromatography, demonstrating the practicability of this protocol (Table 1).

The chlorosilylated products **3k** and **3l** formed by the reactions of *N,N*-dimethylaniline with **2k** and **2l**, respectively (Scheme 2), were confirmed by ¹H NMR and GC–MS analyses, although their isolation by chromatography was difficult because of the extremely high sensitivity of the Si–Cl bond to moisture. However, treatment of the reaction mixtures

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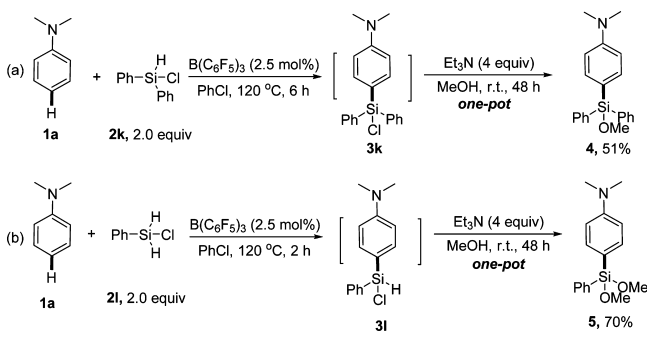
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Table 1. C–H Silylation of *N,N*-Dimethylaniline with Various Hydrosilanes^a

		
1a	2a-j	3
		
3a , 84% ^b (72%, 5 mmol scale)		
		
3b , 80% ^c		
		
3c , 82%		
		
3d , 65%		
		
3e , 68%		
		
3f , 60%		
		
3g , 61%		
		
3h , 85%		
		
3i , 80%		
		
3j , 67%		

^aReaction conditions: **1a** (0.25 mmol), **2** (0.75 mmol), B(C₆F₅)₃ (1.0 mol %), and chlorobenzene (0.5 mL) under N₂ at 120 °C for 24 h, unless otherwise noted. Isolated yields are shown. ^bThe reaction was carried out for 6 h, and 0.50 mmol of Ph₂SiH₂ was used. ^cB(C₆F₅)₃ (2.5 mol %) was used.

Scheme 2. C–H Silylation of *N,N*-Dimethylaniline with Chlorohydrosilanes through Si–H Cleavage



containing **3k** and **3l** with methanol (as the solvent) in the presence of triethylamine afforded the further synthetically useful methoxysilane derivatives **4** and **5** in a simple one-pot procedure (Scheme 2). The excellent Si–Cl compatibility of the present boron catalyst should constitute a great advantage over metal-based catalysts with respect to the synthesis of diverse silylated organic compounds.

Subsequently, **2a** was chosen to examine the silylation of various tertiary aniline derivatives (Table 2). Several *N*-methyl-*N*-alkylanilines (**1b–e**) smoothly reacted with **2a**, affording the corresponding para-silylation products **6a–d** in high yields (entries 1–4). The silylation of *N*-methyl-*N*-allylaniline (**1f**) was accompanied by hydrogenation of the allyl unit, yielding the para-silylated *N*-methyl-*N*-propylaniline product **7** in 75% yield (entry 5). The valuable trifluoromethyl group in **1g** survived in the present reaction with Ph₂SiH₂ (entry 6). In the case of substrates containing ether bonds (**1h** and **1o**), the silylation reaction was accompanied by reductive C–O bond cleavage,¹⁴ giving the corresponding ether-free silylated products **6a** and **6g** (entries 7 and 14). *N*-Methyl-*N*-phenylaniline (**1i**) was applicable, albeit with lower activity, selectively affording the monosilylated product **6f** (entry 8). Cyclic amines such as **11–n** could be easily transformed into the desired products **6i–k** in satisfactory yields (entries 11–

13). 4-Phenylpiperazine **1p**, which contains two nitrogen atoms, selectively afforded the expected product **6l** in 73% yield (entry 15), in contrast to what was observed in the case of its ether analogue **1o** (entry 14). *N,N*-Dimethylanilines bearing either electron-donating or electron-withdrawing groups on the phenyl ring (**1q–y**) all underwent the para-selective silylation in moderate to high yields (entries 16–24).¹⁵ The sterically demanding phenyl substituent at either the ortho (**1s**) or meta (**1y**) position did not significantly obstruct the reaction, and the desired para-silylation product **6o** or **6u**, respectively, was obtained. More importantly, synthetically valuable aromatic carbon–halogen (F, Cl, Br, I) bonds (**1r**, **1u–x**) are compatible with this catalytic system, thus affording more opportunities for further chemical transformations. The reaction of *N,N*-dimethyl-5,6,7,8-tetrahydronaphthalen-1-amine (**1z**) gave the desired product **6v** in 90% yield (entry 25), while *N,N*-dimethyl-1-naphthylamine (**1aa**) showed lower reactivity, affording the C4-silylated product **6w** in 45% yield under the same reaction conditions (entry 26). Triphenylamine (**1ab**) showed no reactivity under the same conditions, probably because of the lower electron density at the phenyl ring. When *N,N*-dimethyl-*p*-toluidine was used as a substrate, a small amount (<10% yield) of the ortho-silylation product **6y** was observed (entry 28).

This methodology could also be applied to disilylation reactions. Representatively, the reaction of 1,4-diphenylpiperazine (**8**) with Ph₂SiH₂ (5.0 equiv) in the presence of 5.0 mol % B(C₆F₅)₃ afforded exclusively the para-disilylated product **9** in 81% yield (Scheme 3a). The monosilylation product was not observed. It is also worth noting that in the case of *N*-methylindole (**10**), the unusual C5-silylation product **11** was isolated as the major product in 34% yield together with a small amount of the C3,C5-disilylation product (Scheme 3b). Generally, silylation at C5 of an indole derivative is difficult using metal-based catalysts.^{5,6,16}

Since arylsilanes are known to undergo versatile transformations, synthetic applications of some representative silylation products obtained in this work are demonstrated here (Scheme 4). For example, silylated tertiary aniline **6d** could be readily transformed into the corresponding secondary aniline derivative **12** bearing a methoxysilyl substituent through simultaneous removal of the benzyl group from the N atom and conversion of the Si–H bond to a Si–OMe group under Pd-catalyzed hydrogenolysis in MeOH (Scheme 4a). Triethylsilyl-substituted *N,N*-dimethylaniline **3f** smoothly underwent iodination, bromination, and chlorination, affording the corresponding halogenated products **13–15** in high yields under mild conditions (Scheme 4b). The functionalized biphenyl compound **18** could be constructed from **3d** through ruthenium-catalyzed oxidation of the Si–H bond¹⁷ (Scheme 4c) and subsequent Pd-catalyzed Hiyama–Denmark cross-coupling¹⁸ (Scheme 4d).

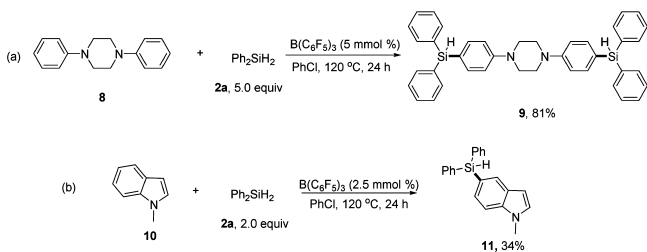
A possible reaction pathway for the present boron-catalyzed C–H silylation is proposed in Scheme 5 on the basis of previous studies of Si–H bond activation by boron compounds,^{7,8,10e,11f,19,20} although further studies are needed to clarify the details. The reaction could start with activation of the hydrosilane by B(C₆F₅)₃ through a B⋯H interaction to form the weak adduct A. Nucleophilic attack of the para carbon of electron-rich *N,N*-dimethylaniline at the electropositive silicon center in A from the back side would generate ion-pair intermediate B.²⁰ Release of one molecule of H₂ from B could yield the silylation product and regenerate B(C₆F₅)₃.²¹

Table 2. C–H Silylation of Various Substituted Aniline Derivatives with Diphenylsilane^a

Entry	Amine 1	Product	Entry	Amine 1	Product	Entry	Amine 1	Product
1			11			16		
2						17		
3						18		
4								
5			12			19		
6						20		
7			13			21		
8						22		
9			14			23		
10						24		
			15			25		
						26		
						27		
						28		

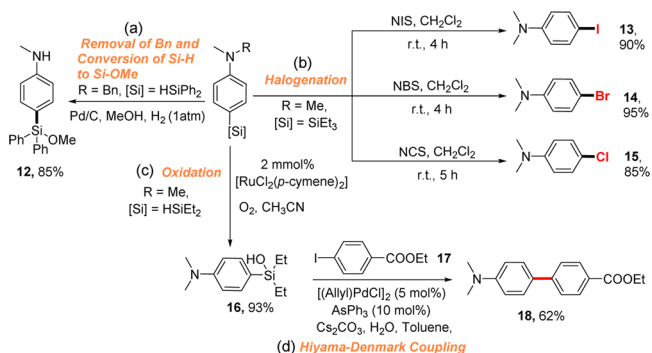
^aReaction conditions: **1** (0.25 mmol), **2a** (0.75 mmol), B(C₆F₅)₃ (2.5 mol %), and chlorobenzene (0.5 mL) under N₂ at 120 °C for 24 h, unless otherwise noted. Isolated yields are shown. N.D. = not detected. ^bB(C₆F₅)₃ (1.0 mol %) and Ph₂SiH₂ (0.50 mmol) were used. ^cThe reaction time was 48 h.

Scheme 3. C–H Silylation of 1,4-Diphenylpiperazine and *N*-Methylindole with Diphenylsilane



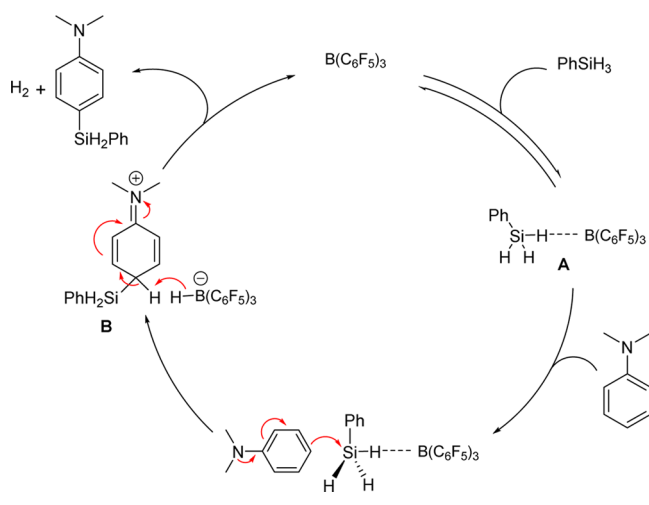
In conclusion, we have realized metal-free catalytic C–H silylation of a series of electron-rich aromatic compounds such as *N,N*-disubstituted anilines with a variety of hydrosilanes using B(C₆F₅)₃ as a catalyst. The reaction takes place under neutral conditions without the requirement of a hydrogen acceptor. Aromatic C–X (X = Cl, Br, I) bonds and even the

Scheme 4. Synthetic Applications of Some Representative Silylation Products



highly sensitive Si–Cl bond are compatible, thus affording a new family of silylated aromatic compounds that are difficult to

Scheme 5. Possible Mechanism for Boron-Catalyzed C–H Silylation



prepare by other means. This work has demonstrated for the first time that a boron-based Lewis acid can serve as a unique catalyst for the synthesis of valuable silylated aromatic compounds. Studies of other C–H functionalization reactions by boron catalysts are in progress.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b01349.

Experimental procedures, characterization data, and copies of NMR spectra (PDF)

Crystallographic data for **6s** (CIF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

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