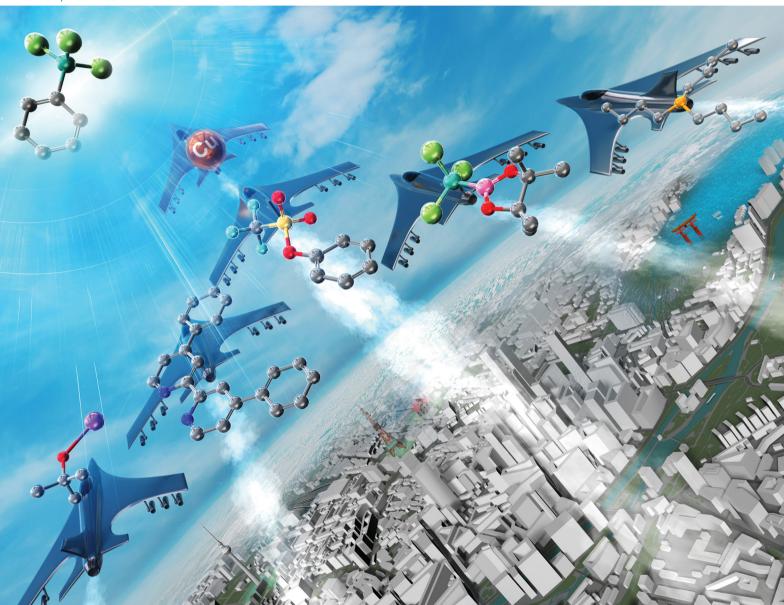
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Copper-catalyzed silvlation of aryl and alkenyl triflates with silylboronic esters avoiding basemediated borylation†

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Silylation of aryl and alkenyl triflates is found to occur readily with silylboronic esters as a silicon source under copper catalysis. The silyl moieties are exclusively installed into the organic frameworks through the preferential generation of a silylcopper species, wherein base-mediated direct borylation is totally suppressed. The combined use of tri-n-butylphosphine and 4,4'-diphenyl-2,2'bipyridine as a ligand combination turned out to be indispensable for achieving the high catalytic activity.

Silylboronic esters, versatile unsymmetrical bimetal reagents, play a pivotal role in modern synthetic organic chemistry, and have been demonstrated to be convertible into a variety of synthetically important organosilicon and -boron compounds.¹ The Si-B σ-bond is readily activated by transition metal catalysts; for instance, copper alkoxides undergo σ-bond metathesis to produce silylcopper species (Cu-Si), where the selective interaction between the Lewis acidic boryl group and the alkoxy moiety determines the chemoselectivity. The Cu-Si species thus generated serves as a silicon nucleophile for addition reactions across C-C multiple bonds³ as well as C=X bonds⁴ and is a coupling partner in ionic and radical reactions with alkyl (pseudo)halides.⁵ While the Cu-Si species have been well established to be coupled with sp³ carbon electrophiles, ^{6,7} their coupling reaction with sp² counterparts, especially aryl/alkenyl halides, has continued to be a challenging subject. We inferred that the difficulties in the copper-catalyzed silylation of aryl/ alkenyl halides with silylboronic esters should be mainly due to inevitable borylation that concomitantly takes place in the presence of a metal alkoxide, commonly used as a base in the

Trialkylsilylboronic esters employed in this study could readily be prepared according to our gram-scale synthesis, in which key trialkylsilyl lithium reagents were generated with the aid of less toxic tris(N,N-tetramethylene)phosphoric acid triamide (TPPA) (Scheme 3).10 With Et₃Si-B(pin) thus prepared, our effort was initially focused on the investigation of a proper leaving group on the C(sp²) electrophiles that can avoid the

$$\begin{bmatrix} Me_2PhSi - B(pin) \\ I \\ OMe \end{bmatrix} K^+ \xrightarrow{Ar-Br} \begin{bmatrix} Ar-Br-SiMe_2Ph \\ + \\ MeO-B(pin) \end{bmatrix} K^+$$

$$Ar^-K^+ \qquad Ar-Br(pin) \\ + \\ + \\ MeO-B(pin) \qquad + \\ + \\ + \\ Br-SiMe_2Ph \qquad KBr \end{bmatrix}$$

Scheme 1 Base-mediated, metal catalyst-free direct borylation of aryl bromides

above Cu-catalyzed silylations, giving aryl/alkenyl boron sideproducts as reported by the Ito group.8 Because the basemediated borylation was reported to facilely proceed even at 30 °C under transition metal-free conditions through a halogen-metal exchange pathway, where a halogenate-type intermediate is generated as a key intermediate (Scheme 1), 8 C(sp²)-Br/I that can easily be converted into the respective hypervalent forms are basically unsuitable electrophiles for the selective silvlation. Under these circumstances, aryl carboxylic acid derivatives and aryl aldehydes were reported to serve as C(sp²) electrophiles by use of Ni/Cu cooperative catalysts, undergoing decarbonylative silylation with silylboronic esters to give arylsilanes selectively (Scheme 2).9 Herein, we disclose for the first time that silvlboronic esters selectively act as silvl-installing reagents into C(sp2) frameworks under Cu-only catalysis by utilizing aryl and alkenyl triflates as electrophiles.

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Communication ChemComm

Scheme 2 Cooperative catalytic silylation of aryl electrophiles.

R₃Si—SiR₃
$$\xrightarrow{\text{MeLi (1 equiv.)}}$$
 R₃Si—Li $\xrightarrow{\text{TPPA/TMEDA}}$ R₃Si—Li $\xrightarrow{\text{NN-P-N}}$ $\xrightarrow{\text{NN-P-N}}$ $\xrightarrow{\text{PrO-B(pin) (1 equiv.)}}$ R= Me: 46% Et: 45%

Scheme 3 Synthesis of trialkylsilylboronic esters via TPPA-assisted generation of trialkylsilyl lithium reagents.

base-mediated borylation while exhibiting enough reactivity toward a Cu-Si species. As was expected, the reactions of p-tolyl bromide/iodide with Et₃Si-B(pin) in the presence of $CuI-P(n-Bu)_3$ as a catalyst afforded p-tolyl-B(pin) (2a) as the major product, showing that chemoselective installation of a silicon functionality is indeed difficult with $C(sp^2)$ -Br/I bonds even under copper catalysis (Table 1, entries 1 and 2). On the other hand, the borylation was completely suppressed with N-hydroxyphthalimide ester (COONPth) or such pseudohalides as mesvlate (OMs) and chloromethane sulfonate (OMc: OSO₂- CH_2Cl), but the silylation did not take place either (entries 3–5).

Table 1 Investigation of a leaving group

Entry	LG	$\mathbf{1a}^{a}$ (%)	$2\mathbf{a}^{a}$ (%)
1	I	13	28
2	Br	15	38
3	COONPth	0	0
4	OMs	0	0
5	OMc	0	0
6	OTs	18	0
7	OTf	34^b	0

^a GC yield. ^b Isolated yield. Conditions: substrate (0.3 mmol), Et₃Si-B(pin) (0.6 mmol), CuI (0.03 mmol), P(n-Bu)₃ (0.06 mmol), t-BuOK (0.36 mmol), THF (1 mL), rt, 1 h.

Finally, the desired silvlation was found to proceed exclusively by employing tosylate (OTs) or triflate (OTf) as leaving groups to provide 1a in 18% and 34% yield, respectively (entries 6 and 7).

Using an OTf moiety as the better leaving group, we next carried out the silvlation with various copper salts in the presence of t-BuOK (base) and $P(n-Bu)_3$ (ligand) and found that CuI was optimal (Table 2, entries 1-7). The use of t-BuOK turned out to be indispensable for the silvlation, and thus reactions with other alkoxides of lower basicity were totally unsuccessful (entries 8-11). Among the ligands surveyed, the combined use of $P(n-Bu)_3$ (10 mol%) and 4,4'-diphenyl-2,2'bipyridine (4,4'-Phbpy) (10 mol%) proved to be the most effective as was the case of our previously reported Cu-catalyzed silylation of C(sp³)-COONPth (entry 12).^{7b,11} No desired product was obtained in the absence of the ligands and/ or CuI, verifying the necessity of the copper catalysis together with the ligand system for the smooth silylation (entries 13 and 14).

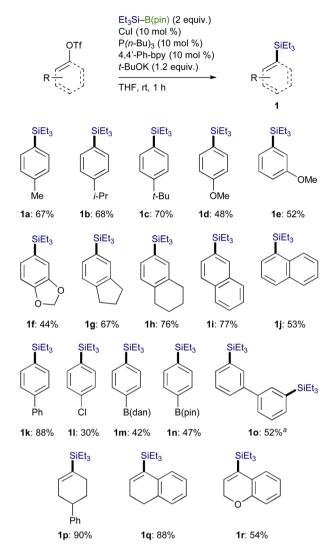
A variety of aryl triflates bearing an electron-donating group could facilely undergo the silvlation under the optimum conditions to furnish the respective aryl silanes (1a-1h) with exclusive chemoselectivity, and borylation-based side-products were not generated at all (Scheme 4). In addition, the reaction of naphthyl and biphenyl triflates also took place to afford the corresponding arylsilanes (1i-1k) in moderate to good yields. Although the silvlation of functionalized aryl triflates with Cl, B(dan) (dan: naphthalene-1,8-diaminato), and B(pin) (pin: pinacolato) also proceeded under the present reaction conditions, the yield became somewhat lower (11-1n). The reaction was applicable to a bis-triflate, whose C-OTf bonds could both be transformed into C-SiEt₃ bonds to give 10. Furthermore,

Table 2 Optimization of the reaction conditions

Entry	[Cu]	Ligand	Base	GC yield (%)
1	CuI	P(<i>n</i> -Bu) ₃	t-BuOK	34^a
2	CuCl	$P(n-Bu)_3$	t-BuOK	29
3	$CuBr \cdot SMe_2$	$P(n-Bu)_3$	t-BuOK	27
4	CuTc	$P(n-Bu)_3$	t-BuOK	9
5	CuSCN	$P(n-Bu)_3$	t-BuOK	10
6	Cu(MeCN) ₄ ·PF ₆	$P(n-Bu)_3$	t-BuOK	7
7	Cu(MeCN) ₄ ·BF ₄	$P(n-Bu)_3$	t-BuOK	26
8	CuI	$P(n-Bu)_3$	MeONa	0
9	CuI	$P(n-Bu)_3$	MeOK	0
10	CuI	$P(n-Bu)_3$	t-BuOLi	0
11	CuI	$P(n-Bu)_3$	t-BuONa	Trace
12	CuI	$P(n-Bu)_3/4,4'-Phbpy$	t-BuOK	67 ^a
13	CuI	None	t-BuOK	0
14	None	None	t-BuOK	0

^a Isolated yield. Conditions: p-tolyl-OTf (0.3 mmol), Et₃Si-B(pin) (0.6 mmol), copper salt (0.03 mmol), ligand (0.06 mmol), base (0.36 mmol), THF (1 mL), rt, 1 h.

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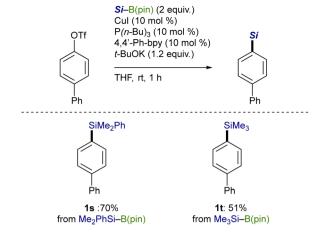


Scheme 4 Substrate scope on triflates. Conditions: triflate (0.3 mmol), Et₃Si-B(pin) (0.6 mmol), CuI (0.03 mmol), P(n-Bu)₃ (0.03 mmol), 4,4'-Phbpy (0.03 mmol), t-BuOK (0.36 mmol), THF (1 mL), rt, 1 h. a Reaction was carried out with a ditriflate (0.15 mmol)

alkenyl triflates, readily prepared from the respective ketones, could also participate in the present reaction, providing good yields of various alkenylsilanes (1p-1r).

The catalytic silvlation was also applicable to Me₂PhSi-B(pin), giving an arylsilane (1s) in 70% yield (Scheme 5). It should be noted that Me₃Si-B(pin), which can practically be prepared by our method (Scheme 3, vide supra), has proven to be convertible into the corresponding product (1t) in a straightforward manner, providing an alternative approach for the Me₃Si-installing process.¹²

As depicted in Scheme 6, control experiments were conducted to gain mechanistic insights into the C(sp²)-Si bondforming process. The stereochemical outcome with an acyclic alkenyl triflate (isomeric ratio = 58:42) indicates that a radical pathway would be operative in the present substitution: (E)-alkenylsilane (1u) became enriched through a stereoconvergent pathway, where an alkenyl radical intermediate rapidly



Scheme 5 Silylation with other silylboronic esters. Conditions: biphenyl-OTf (0.3 mmol), silylboronic ester (0.6 mmol), CuI (0.03 mmol), $P(n-Bu)_3$ (0.03 mmol), 4,4'-Phbpy (0.03 mmol), t-BuOK (0.36 mmol), THF (1 mL), rt, 1 h.

Stereochemistry with an alkenyl triflate

Radical trap experiment

X	Yield of 1i (%)	
0	77	
1.5	52	
3.0	39	

Scheme 6 Control experiments

isomerized before the silvlation. 13 Besides, the addition of 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO), a radical scavenger, to the reaction of 2-naphthyl triflate reduced the yields of 1i as the amount of TEMPO increased, which also supports the possibility of the radical pathway.14

Based on the above results, the silvlation would be triggered by the generation of a Cu^I-Si species via σ-bond metathesis between a copper alkoxide [Cu^I-Ot-Bu] and a silyboronic ester (Scheme 7). 7a Then t-BuO coordinates to CuI-Si to provide an Communication ChemComm

R-Si
$$Cu^{II}-Si$$

$$O-t-Bu$$

$$3c$$

$$Cu^{II}-Ot-Bu$$

$$3c$$

$$Cu^{II}-Si$$

$$O-t-Bu$$

$$3c$$

$$Cu^{II}-Si$$

$$O-t-Bu$$

$$3b$$

$$R-OTf$$

$$Cu^{II}-Si$$

$$O-t-Bu$$

$$3b$$

$$R-OTf$$

$$Cu^{II}-Si$$

$$O-t-Bu$$

$$3a$$

Scheme 7 A proposed catalytic cycle

electron-rich silvlcuprate species [t-BuO-Cu^I-Si]⁻ (3a), which may serve as a single-electron reductant for an aryl/alkenyl triflate. The resulting radical anion then releases TfO of good leaving ability to generate an isomerizable free radical (cf. Scheme 6), which readily recombines with [t-BuO-Cu^{II}-Si] (3b), affording a Cu^{III} complex (3c). Finally, 3c undergoes reductive elimination to provide a C(sp²)-Si product with the regeneration of the copper alkoxide.

In conclusion, we have demonstrated for the first time that C(sp²) electrophiles undergo selective silylation with silylboronic esters under copper-only catalysis by using a triflate moiety as an optimal leaving group, which leads to the exclusive formation of various aryl/alkenyl-silanes with complete suppression of undesired base-mediated borylation. Moreover, the mechanistic studies suggested that the present silylation may involve a radical pathway. A similar silylation of aryl and alkenyl carbamates under iron catalysis was reported by the Feng group; 12e however, the present silvlation is a meaningful expansion of the reactivity as this proceeds under milder conditions and permits the use of easily accessible triflates as substrates. Further studies on the catalytic utilization of silylboronic esters as well as on details of the reaction mechanism are in progress.

S. K., M. O, and H. Y. designed the study. M. N. and T. Y. aided in interpreting the results. H. Y. supervised the project. S. K. collected all data and wrote the manuscript with support from M. O. and H. Y. All authors have approved the final version of the manuscript.

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Conflicts of interest

There are no conflicts to declare.

Notes and references

1 For reviews on the chemistry of silylboranes, see: (a) J. Feng, W. Mao., L. Zhang and M. Oestreich, Chem. Soc. Rev., 2021,

- 50, 2010; (b) M. Oestreich, E. Hartmann and M. Mewald, Chem. Rev., 2013, 113, 402; (c) T. Ohmura and M. Suginome, Bull. Chem. Soc. Jpn., 2009, 82, 29.
- 2 For a review on the reactions of silvlcopper species, see: W. Xue and M. Oestreich, ACS Cent. Sci., 2020, 6, 1070.
- 3 For the seminal works with alkynes, see: (a) T. Fujihara, Y. Tani, K. Semba, J. Terao and Y. Tsuji, Angew. Chem., Int. Ed., 2012, 51, 11487; (b) F. Meng, H. Jang and A. H. Hoveyda, Chem. - Eur. J., 2013, 19, 3204.
- 4 For the seminal works with carbonyl compounds, (a) C. Kleeberg, E. Feldmann, E. Hartmann, D. J. Vvas and M. Oestreich, Chem. - Eur. J., 2011, 17, 13538; (b) J. Plotzitzka and C. Kleeberg, Inorg. Chem., 2017, 56, 667.
- 5 For the seminal works with allylic electrophiles, see: (a) D. J. Vyas and M. Oestreich, Angew. Chem., Int. Ed., 2010, 49, 8513; (b) L. B. Delvos, D. J. Vyas and M. Oestreich, Angew. Chem., Int. Ed., 2013, 52, 465; (c) C. K. Hazra, E. Irran and M. Oestreich, Eur. J. Org. Chem., 2013, 4903; (d) M. Takeda, R. Shintani and T. Hayashi, J. Org. Chem., 2013, 78, 5007; for the seminal works with propargylic electrophiles, see: (e) D. J. Vyas, C. K. Hazra and M. Oestreich, Org. Lett., 2011, 13, 4462.
- 6 For ionic reactions with alkyl electrophiles, see: (a) J. Scharfbier and M. Oestreich, Synlett, 2016, 127; (b) J. Scharfbier, H. Hazrati and M. Oestreich, Org. Lett., 2017, 19, 656; (c) J. Scharfbier, B. M. Gross and M. Oestreich, Angew. Chem., Int. Ed., 2020, 59, 1577.
- 7 For radical reactions with alkyl electrophiles, see: (a) W. Xue, Z.-W. Qu, S. Grimme and M. Oestreich, J. Am. Chem. Soc., 2016, 138, 14222; (b) W. Xue and M. Oestreich, Angew. Chem., Int. Ed., 2017, 56, 1164; for a review, see: (c) S. Bähr, W. Xue and M. Oestreich, ACS Catal., 2019, 9, 16.
- 8 (a) E. Yamamoto, K. Izumi, Y. Horita and H. Ito, J. Am. Chem. Soc., 2012, 134, 19997; (b) E. Yamamoto, K. Izumi, Y. Horita, S. Ukigai and H. Ito, Top. Catal., 2014, 57, 940; (c) E. Yamamoto, S. Ukigai and H. Ito, Chem. Sci., 2015, 6, 2943; (d) R. Uematsu, E. Yamamoto, S. Maeda, H. Ito and T. Taketsugu, J. Am. Chem. Soc., 2015, 137, 409; (e) E. Yamamoto, K. Izumi, R. Shishido, T. Seki, N. Tokodai and H. Ito, Chem. - Eur. J., 2016, 22, 17547; for a review, see: (f) E. Yamamoto, S. Maeda, T. Taketsugu and H. Ito, Synlett, 2017, 1258.
- 9 (a) L. Guo, A. Chatupheeraphat and M. Rueping, Angew. Chem., Int. Ed., 2016, 55, 11810; (b) X. Pu, J. Hu, Y. Zhao and Z. Shi, ACS Catal., 2016, **6**, 6692; (c) S.-C. Lee, L. Guo, H. Yue, H.-H. Li and M. Rueping, Synlett, 2017, 2594; (d) X. Wang, Z. Wang and Y. Nishihara, Chem. Commun., 2019, 55, 10507; (e) W. Srimontree, L. Guo and M. Rueping, Chem. - Eur. J., 2020, 26, 423.
- 10 S. Kamio, T. Imagawa, M. Nakamoto, M. Oestreich and H. Yoshida, Synthesis, 2021, 4678.
- 11 For the effects of other ligands and full optimization of the reaction conditions, see ESI† for details.
- 12 For the seminal works on catalytic Me₃Si-installation reactions, see: (a) H. Matsumoto, S. Nagashima, K. Yoshihiro and Y. Nagai, J. Organomet. Chem., 1975, 85, C1; (b) D. Azarian, S. S. Dua, C. Eaborn and D. R. M. Walton, *J. Organomet. Chem.*, 1976, 117, C55; (c) H. Matsumoto, K. Yoshihiro, S. Nagashima, H. Watanabe and Y. Nagai, J. Organomet. Chem., 1977, 128, 409; (d) L. J. Gooßen and A. S. Ferwan, Synlett, 2000, 1801; for recent works on constructing $C(sp^2)$ -SiEt₃ bonds with Et₃Si-B(pin), see: (e) J. Zhang, Y. Zhang, S. Geng, S. Chen, Z. Liu, X. Zeng, Y. He and Z. Feng, Org. Lett., 2020, 22, 2669; (f) J. Jia, X. Zeng, Z. Liu, L. Zhao, C.-Y. He, X.-F. Li and Z. Feng, Org. Lett., 2020, 22, 2816.
- 13 Less steric repulsion between a Ph group of the cis-alkenyl radical and an incoming 3b may determine the stereoselectivity.
- 14 The naphthyl moiety was not trapped by TEMPO while a Et₃Si-TEMPO adduct was generated as a side-product. In sharp contrast to the results obtained with TEMPO, the addition of 9,10dihydroanthracene, a known radical scavenger, hardly influenced the course of the silylation, implying that an ionic mechanism involving direct σ-bond metathesis between Cu-SiEt₃ and aryl/ alkenyl triflates might still be conceivable.
- 15 For our previous reports on similar copper-catalyzed bolylations of alkyl, alkenyl and aryl halides with diborons, see: (a) H. Yoshida, Y. Takemoto, S. Kamio, I. Osaka and K. Takaki, Org. Chem. Front., 2017, 4, 1215; (b) H. Yoshida, S. Kamio and I. Osaka, Chem. Lett., 2018, 47, 957.