Copper(I)-Catalyzed Allylic Substitution of Silyl Nucleophiles through Si-Si Bond Activation

Hajime Ito,^{a,*} Yuko Horita,^{a,b} and Masaya Sawamura^b

^a Division of Chemical Process Engineering, Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan Fax: (+81)-(0)11-706-6561; e-mail: hajito@eng.hokudai.ac.jp

^b Department of Chemistry, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan

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Abstract: We report the first copper(I)-catalyzed reaction between a disilane and allylic carbonates to produce allylsilanes. The silyl nucleophilic substitution proceeded primarily in a $S_N 2$ fashion whereas $S_N 2'$ products were also obtained through σ - π - σ isomerization of the copper(III) intermediate depending on the substrate's steric bulk.

Keywords: copper; homogeneous catalysis; metalation; silanes; synthetic methods

Reactions between silvl nucleophiles and carbon electrophiles provide indispensable synthetic procedures for organosilicon compounds. Trialkylsilylmetal compounds that are prepared from stoichiometric silyl halides and low-valent metals, typically lithium, have been extensively studied especially in combination with stoichiometric copper(I) salts.^[1] Recent studies have focused on more convenient procedures such as the catalytic generation of silvl nucleophiles through σ -bond metathesis reactions of transition metal complexes^[2] (Si-Si/Pd,^[3] Si-B/Rh,^[4] Si-B/Cu^[5] or Si-Si/ Cu^[6]). The practical advantage of these procedures is that they enable the use of easily storable and available precursors commercially such as PhMe₂Si-B(pin) and PhMe₂Si-SiMe₂Ph as silyl nucleophile sources. We have previously reported the first example of a copper(I)-catalyzed reaction between disilanes and α , β -unsaturated carbonyl compounds where the Si-Si bond is cleaved by σ-bond metathesis to form a silvlcopper(I) intermediate, which undergoes a formal nucleophilic addition to α , β -unsaturated carbonyl compounds [Scheme 1 (a)].^[6a]

Allylsilanes are particularly useful organosilane reagents because of their high stereo- and regioselective addition reactions with aldehydes using Lewis acid



Scheme 1. Copper(I)-catalyzed silvlation of α , β -unsaturated carbonyl compounds (a) and allylic esters (b) with disilanes.

catalysts (Hosomi–Sakurai allylation).^[7,8] The development of an efficient preparation method for allylsilanes has attracted significant interest for a long time.^[1–10] Many studies have been devoted to the reaction between stoichiometric silylmetal/copper(I) reagents and allylic electrophiles.^[9]

Oestreich and co-workers recently reported a copper(I)-catalyzed silylation using silylborane as well as silylzinc reagents.^[5c,9f] However, there have been no reports on the use of disilanes as the silyl group source in copper(I)-catalyzed allylsilane synthesis. We are interested in investigating disilane/copper(I) catalysis and thus report here the regioselective silylation of allylic carbonates with a disilane compound in the presence of CuCl catalyst and K(O-*t*-Bu). The regioselectivity was primarily $S_N 2$ but it also depended heavily on the steric nature of the substrates; the $S_N 2'$ product was found to be the major compound when the $S_N 2$ product had more steric congestion [Scheme 1 (b)].

We initially examined the silyl substitution of allylic carbonate (*E*)-**1a** using our previous catalyst system, CuOTf (5 mol%) and PBu₃ (5 mol%) in the presence of disilane **2** (Table 1, entry 1), which is the most ef-

Table 1. Copper(I)-catalyzed silyl substitution of allylic carbonate 1a.^[a]



Entry	Ligand	K(O- <i>t</i> Bu) [mol%]	CuX	<i>T</i> [°C]	Yield ^[b] [%]	3a/3a'
1	Bu ₃ P	-	CuOTf	100	0	_
2	none	10	CuCl	0	6	_
3	none	100	CuCl	0	60	90:10
4	none	100	CuCl	-30	37	94:6
5 ^[c]	none	200	CuCl	-30	44	95:5
6	none	0	CuCl	0	0	_
7	none	100	none	0	0	_
8	PPh ₃	100	CuCl	0	57	90:10
9	Xphos	100	CuCl	0	47	83:17
10	dppe	100	CuCl	0	53	86:14
11	dppp	100	CuCl	0	61	86:14
12	Xantphos	100	CuCl	0	43	86:14
13 ^[d]	_	100	CuCl/NHC	0	61	90:10
14	2,2'-bipy	100	CuCl	0	59	86:14

^[a] *Reaction conditions:* **1a** (0.25 mmol), **2** (0.25 mmol), CuCl (0.0125 mmol), ligand (0–0.125 mmol), K(O-*t*-Bu) (1.0M, 0.25 mL, 0.25 mmol), THF (0.5 mL).

^[b] Yield and regioisomeric ratio were determined by GC analysis. The starting material was consumed within 1 h in almost all cases and the main by-product was **4a**.

^[c] 10 mol% of CuCl was used.

^[d] Chloro[1,3-bis(2,6-diisopropylphenyl)-imidazole-2-ylidene]copper(I) was used.

fective catalyst for the silvlation of α,β -unsaturated carbonyl compounds.^[6a] However, no reaction occurred, even at 100 °C. We then examined another copper(I) catalyst, a combination of K(O-t-Bu) (10 mol%) and CuCl (5 mol%) but only found that the corresponding allylsilane product 3a had formed in low yield (entry 2, 6%). A reaction with a larger amount of K(O-t-Bu) (100 mol%) improved the yield (60%) in the presence of a catalytic amount of CuCl (5 mol%) (entry 3). The reaction was complete within 1 h at 0°C with a full conversion of the substrate. Silvl ether 4a was the only side product and no other products were detected. The $S_N 2$ product (E)-3a was the major product with high α/γ regioselectivity (3a/3a' = 90:10). The regioselectivity was improved in this reaction at -30 °C (3a/3a' = 94:6) but the yield decreased to 37% (entry 4). Additional K(O-t-Bu) did not significantly improve the yield (entry 5, 44%). Both K(O-t-Bu) and CuCl were necessary to promote this reaction indicating that the copper(I) species that was generated from disilane/CuCl/K(O-t-Bu) is most likely responsible for the silyl substitution reaction (entries 6 and 7). The desired product was scarcely obtained when other disilanes such as hexamethyldisilane were used instead of **2**. Allylic acetates or ethers gave lower yields than those for allylic carbonates **1a**.

We next examined the impact of the ligand and expected the reaction to be attenuated by the nature of the ligand. However, a notable improvement in the yield and regioselectivity was not found for the reactions with PPh₃, Xphos, dppe, dppp, Xantphos, an N-heterocyclic carbene ligand and 2,2'-bipyridine ligands (entries 7–14). In all these reactions the (*E*)-configuration stereoisomer was found to be the major product with high selectivity (>20:1).

We then examined the copper(I)-catalyzed silyl substitution of the disilane using various allylic substrates (Table 2).^[11] (*E*)-**1b**, which is a regioisomeric substrate of (*E*)-**1a** in terms of the allylic system, afforded the α -product (*E*)-**3b** in a moderate yield and regioselectivity (entry 1, 52%, $\alpha/\gamma = 79:21$). The reaction with excess carbonate resulted in a slight im-

Entry	Substrate	Product	Yield [%] ^[b]
	OCO ₂ Me	PhMe ₂ Si	
1 ^[c]	Ph (E)-1b	Ph (E)- 3b . <i>E/Z</i> >20:1	52 (α/γ, 79:21)
2 ^[c,d]	(E)-1b OCO₂Me	(E)- 3b SiMe ₂ Ph	75 (α/γ, 88:12)
3 ^[e]	(<i>E</i>)-1c	(<i>E</i>)- 3c , <i>E/Z</i> >20:1	72 (α/γ, 85:15)
4 ^[f]	Ph (<i>E</i>)-1d OCCo2Me	SiMe ₂ Ph Ph (<i>E</i>)-3d, <i>E/Z</i> = 88:12 SiMe ₂ Ph	66 (α/γ, 95:5)
5 ^[e]	Ph (<i>E</i>)-1e	Ph 3d, <i>E/Z</i> = 54:46	68 (α/γ, 0:100)
6 ^[e]	Ph (Z)-1d OCO ₂ Me	Ph SiMe ₂ Ph SiMe ₂ Ph Ph (Z) -3d, $E/Z = 4:96$ 3e	48% (α/γ, 58:42)
7 ^[e]	Ph 1f	PhMe ₂ Si Ph 3f	55 (α/γ, 99:1)
8 ^[e]	$\bigcirc CCO_2 - i - Pr \\ \frown C_5 H_{11} (E) - 1g$	$\bigcup_{C_5H_{11}}^{SiMe_2Ph} 3g$	39 (α/γ, 1:>99)
9 ^[e]		SiMe ₂ Ph SiMe ₂ Ph	48
10 ^[f]		3i SiMe2Ph	72
11 ^[f]		3j SiMo Dh	66
12 ^[e]	0 0 0 (<i>E</i>)-1k		66 (α/γ, 91:9)

Table 2. Copper(I)-catalyzed silyl substitution of allylic carbonates 1.^[a]

^[a] Reaction conditions: **1a** (0.5 mmol), **2** (0.5 mmol), CuCl (0.025 mmol), K(O-t-Bu) (1.0M, 0.5 mL, 0.5 mmol), additional THF (0.5 mL).

^[b] Yield and regioisomeric ratio were determined by NMR analysis after chromatographic purification. In almost all the cases, **1a** was fully consumed at 1 h and the main by-product was the silyl ether **4**.

^[d] 1a (0.25 mmol), 2 (0.168 mmol) were used. Yield was based on the disilane.

^[e] 1.2 mL of THF were added.

^[f] 1.0 mL of THF was added.

provement in the regioselectivity (75%, $\alpha/\gamma = 88:12$) (entry 2). A substrate with methyl and butyl groups around an internal allylic system [(*E*)-**1c**] gave the corresponding α -product (*E*)-**3c** with a similar regioselectivity ($\alpha/\gamma = 85:15$) compared to that of (*E*)-**1b** (entry 3). The reactions with the substrates containing a terminal allylic system [(*E*)-**1d** and (*E*)-**1e**] both resulted in the selective production of (*E*)-**3d** where the new Si–C bond formed at the terminal position of the product. This gave the typical regioselectivity often found in the reaction with a π -allyl copper(III) intermediate (entries 4 and 5).^[9] The reaction of (Z)-1d gave both the α -product [(Z)-3d] and the γ -product 3e with a very low regioselectivity ($\alpha/\gamma = 58:42$). It is noteworthy that the α -products retained the double bond configuration of the starting material [entries 4 and 6, (E)-3d], whereas the γ -product resulted in a mixture of E/Z isomers (entry 5). The more sterically demanding substrate 1f with dimethyl substitution at the γ -position of the leaving group resulted in very high regioselectivity (entry 7, $\alpha/\gamma = 99:1$). The substrate derived from the tertiary allylic alcohol [(E)-1g]

^[c] 0.25 mmol scale.



Scheme 2. A plausible reaction mechanism for the copper(I)-catalyzed silylation of allylic carbonate with disilane.

bearing two methyl groups at the α -position of the leaving group then afforded only the γ -product **3g** (entry 8, $\alpha/\gamma = 1.99$) avoiding steric congestion. The silylation of carbonates with cyclic structures gave the corresponding allylic silanes (entries 9–11). This catalysis has moderate functional group compatibility; the acetal group in (*E*)-**1k** can tolerate the silylation conditions (entry 12).

The reaction profile given in Table 2 indicates that the reaction involves allylic isomerization through the π -allyl copper(III) intermediate (Scheme 2). The silylcopper(I) species 5 was first formed through σ -bond metathesis between the disilane, CuCl and KOR.^[12] The oxidative addition of the C–O bond on the copper(I) center (A) gave a silvlcopper(III) intermediate. When the steric bulk between two substituents around the allylic system is similar ($R^1 \approx R^2$), a subsequent reductive elimination (**B**) occurs at the α -position to give the S_N^2 product **3a** at a much faster rate than that of σ - π - σ isomerization. On the other hand, when the difference in the steric demands of the α position is significantly larger than that of the γ -position, the Si-C bond forms at the sterically less congested γ -position (C) by the σ - π - σ isomerization of the allylic copper(III) species $(R^1 > R^2)$, producing the $S_N 2'$ product **3a'**. The erosion of E/Z isomeric purity that was observed in the $S_N 2'$ reaction product (Table 2, entry 5) is consistent with this explanation.

In summary, we report the first example of allylsilane synthesis by the copper(I)-catalyzed reaction of a disilane. Similar to other silylmetal/copper(I) systems the regioselectivity for the newly formed Si–C bond depends on the structure of the substrate. Although there is room for improvement in product yield as a synthetic method of allylsilanes, these results provide interesting insights into novel silyl copper species that are generated by the disilane/ Cu(I)/excess KOR system as well as provide a new convenient procedure for allylsilane synthesis with a copper(I) catalyst.

Experimental Section

General Remarks

Materials were obtained from commercial suppliers and purified by the standard procedure unless otherwise noted. Dry THF was purchased and used as received. NMR spectra were recorded on a JEOL JNM-ECX400P spectrometer (¹H: 400 MHz and ¹³C: 99.5 MHz) or a Varian Gemini 2000 (¹H: 300 MHz, ¹³C: 75.6 MHz). Tetramethylsilane (¹H) and CDCl₃ (¹³C) were employed as external standards, respectively. CuCl (ReagentPlus® grade, 224332–25G, \geq 99%) and K(O-*t*-Bu)/THF (1.0M, 328650–50ML) were purchased from Sigma–Aldrich Co. and used as received. Mesitylene was used as the internal standard for determining NMR yields. Recycle preparative gel permeation chromatography was conducted with a JAI LC-9101 using CHCl₃ as eluent. Low- and high-resolution mass spectra were recorded at the Center for Instrumental Analysis, Hokkaido University.

Representative Procedure for Copper(I)-Catalyzed Allylic Substitution with Disilane

Copper chloride (2.5 mg, 0.025 mmol) was placed in an oven-dried reaction vial. The vial was sealed with a screw cap containing a silicon-coated rubber septum. After the vial had been evacuated and backfilled with nitrogen, THF (1.0 mmol), disilane 2 (0.5 mmol), and K(O-t-Bu)/THF (1.0M, 0.5 mL, 0.5 mmol) were added through the rubber septum at 0°C. Then the allylic carbonate 1 (0.5 mmol) was added dropwise. After the reaction was complete, the reaction mixture was passed through a short silica column eluting with 1% Et₂O/hexane mixed solvent. The crude mixture was further purified by column chromatography (SiO₂, hexane). When the pure product was not obtained by several column chromatography purifications, the yield of the reaction was determined by ¹H NMR analysis of the crude material using an internal standard. The further purification of the product could be conducted with a recycle gel permeation chromatography.

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