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CpTiCl-Catalyzed Regio- and Chemoselective One-Step Synthesis of □-Substituted Allylsilanes from Terminal Alkenes Using Dianion-Type Zincate (SiSiNOL-Zn-ate)

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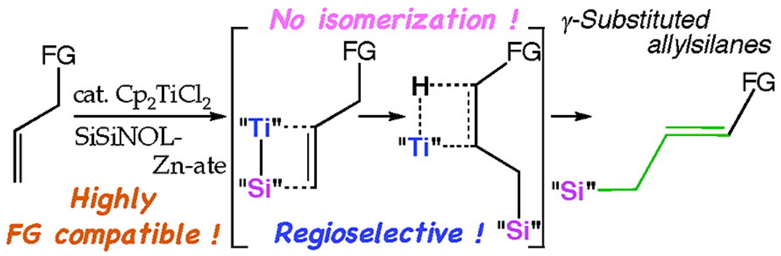

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Cp_2TiCl_2-Catalyzed Regio- and Chemoselective One-Step Synthesis of γ-Substituted Allylsilanes from Terminal Alkenes Using Dianion-Type Zincate (SiSiNOL-Zn-ate)

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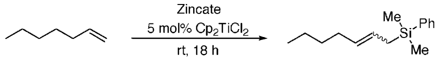
Allylsilanes are important intermediates for carbon−carbon and carbon−heteroatom bond formation in organic synthesis because of their easy handling, unique reactivities, and high regiocontrollability.[1] Methods currently available for their synthesis include transition-metal-catalyzed silylmetalation of 1,3-dienes or allenes and Wittig reactions.[2] Unfortunately, however, many of these reactions have significant disadvantages: low generality, low chemoselectivity, the requirement for tedious multistep synthesis of the precursor, and so on. We disclose here a chemo- and regioselective direct preparation method of γ-substituted allylsilanes from readily available terminal alkenes with various kinds of functional groups, using a newly developed silylzincate (SiSiNOL-Zn-ate) and catalytic Cp_2TiCl_2 system. We also demonstrate that the resultant functionalized allylsilanes can be versatile allylating reagents, providing basic architecture for functionalized materials.

Silylmetalation reaction of reactive unsaturated C−C bonds such as alkynes, allenes, or dienes has been extensively utilized in organic synthesis.[3] However, its application to alkenes has not been well developed due to low reactivity of the isolated C−C double bond.[4] We have recently developed a dianion-type zincate (SiBNOL-Zn-ate, Table 1 entry 6) that promotes chemo- and regioselective silylzincation of functionalized terminal alkynes without any transition-metal catalyst.[6a] To develop a new silylmetalation reaction of terminal alkenes, we started with the design and screening of suitable silylzincates by using 1-heptene (**1a**) as a model substrate. However, all initial attempts using various silylzincates without any catalyst were unsuccessful. Then, we focused on screening of catalysts for the addition of the silylzincate to functionalized olefins. After extensive experimentation, we found that the combination of 5 mol % of Cp_2TiCl_2 and SiSiNOL-Zn-ate (Table 1, entry 7) silylated **1a** in good yield under mild conditions. Interestingly, this silylation gave predominantly a γ-substituted allylsilane (**2a**, a Heck-type addition product), and neither regioisomers nor saturated alkylsilanes were observed at all.

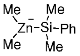
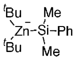
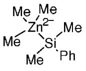
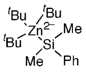
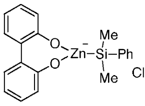
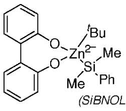
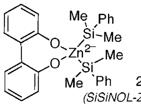
Tamao and co-workers reported some excellent silyltitanation reactions using a stoichiometric amount of Cp_2TiCl_2 and 2 equiv of DMPSLi to acetylenes or 1,3-dienes,[5] but no example using alkenes as substrates has been reported to date. A Ti(III)−Si-active species, $Cp_2TiSiMe_2Ph$, is proposed to be involved in those silyltitanation reactions. Although the silylation mechanism in our case is not clear yet, Zn-ate is essential for this catalytic silylation at terminal alkenes; the yield of the allylsilane was less than 1% when Zn(II) was omitted, and other metals such as Mg(II), Al(III), V(II), Cr(II), Mn(II/III), Fe(II/III), Co(II/III), and Cu(I) could not replace Zn(II). In addition, the coordination number and the nature of the countercations were also critical for this silylation reaction.[6]

With optimized conditions in hand, we studied the scope of this new protocol, and representative results are summarized in Table 2. In addition to terminal alkenes bearing simple alkyl chains, those possessing a range of functional groups could be used: suitably protected alcohols, amines, thiol, and ketones (entries 1−5, 14), as well as cyclohexyl and aryl substitution (entries 11−13), are tolerated in the reaction. A variety of electrophilic functional groups, including a carbamate, carbonate, and ester, also caused no problems

Table 1. Screening of Zincates for Cp_2TiCl_2-Catalyzed Silylation of 1-Heptene (**1a**)[a]

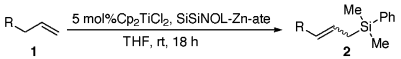


1a **2a**

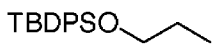
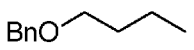
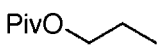
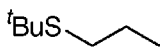
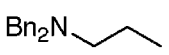
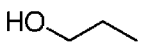
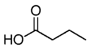
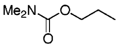
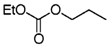
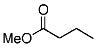
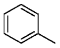
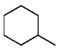
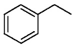
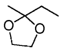
Entry	Zincate		E/Z	Yield (%)[b]
	Anion	*Cation*		
1		Li^+	—	0
		$ClMg^+$	22/77	38
2		Li^+	—	0
		$ClMg^+$	26/74	5
3		$2Li^+$	—	0
		$2ClMg^+$	26/74	12
4		$2Li^+$	—	0
		$2ClMg^+$	28/72	4
5		Li^+	—	0
		$ClMg^+$	28/72	37
6	 (SiBNOL-Zn-ate)	$2Li^+$	—	0
		$2ClMg^+$	24/76	54
7	 (SiSiNOL-Zn-ate)	$2Li^+$	—	0
		$2ClMg^+$	30/70	95

[a] The silylation was carried out using zincate (1.1 equiv), substrate (1.0 equiv), and Cp_2TiCl_2 (5 mol %) in THF at room temperature for 18 h. [b] Isolated yield.

Table 2. Silylation of Various Functionalized Terminal Alkenes[a]



1 **2**

Entry	R		E/Z	Yield (%)[b]
1		(**1b**)	24/76	95
2		(**1c**)	28/72	92
3[c]		(**1d**)	29/71	94
4		(**1e**)	26/74	88
5		(**1f**)	21/79	75
6[d]		(**1g**)	26/74	55
7[d]		(**1h**)	24/76	100
8		(**1i**)	24/76	95
9		(**1j**)	27/73	79
10		(**1k**)	23/77	80
11		(**1l**)	N.D.	84
12[e]		(**1m**)	49/51	47 [f]
13		(**1n**)	26/74	71[g]
14		(**1o**)	21/79	81[h]

[a] Unless otherwise noted, the silylzincation was carried out using zincate (1.1 equiv), substrate (1.0 equiv), and Cp_2TiCl_2 (5 mol %) in THF at room temperature for 18 h. [b] Isolated yield. [c] The reaction was carried out under reflux. [d] 3 equiv of zincate was used. [e] The reaction was carried out at 45 °C. [f] Vinylsilane was isolated in 18% yield (E/Z = 64/36). [g] Vinylsilane was isolated in 8% yield (E/Z = 58/42). [h] Vinylsilane was isolated in 19% yield (E/Z = 50/50).

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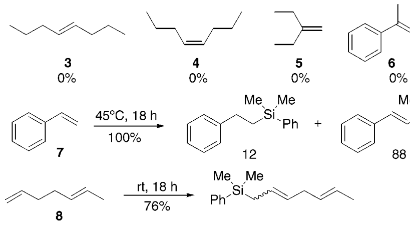
Scheme 1. Reactivity and Selectivity of the Present Silylation



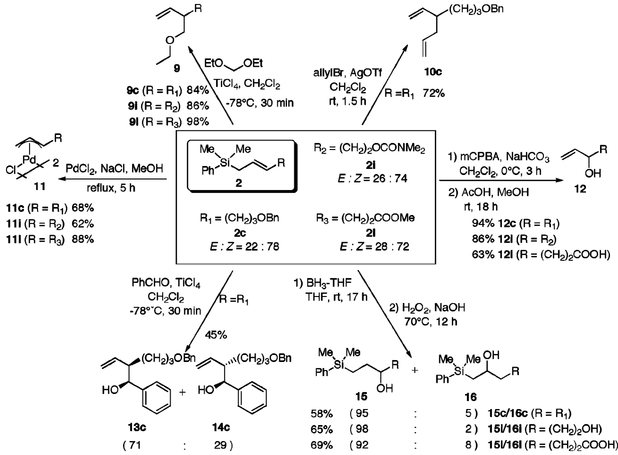
(entries 8−10). Substrates containing a free O−H moiety, such as aliphatic alcohols and carboxylic acid could also be utilized, and no self-condensation was observed (entries 6, 7). To our knowledge, this reaction is the first example of an efficient one-step synthesis of γ-substituted allylsilanes with wide substrate generality.

Some characteristic aspects of the regio- and stereoselectivity of this silylation can be drawn from the data in Table 2. (1) Regioselectivity of addition: the silylation reaction occurs with very high regiospecifically for monosubstituted alkenes (no regio isomer was detected), probably due to the steric effect. (2) Direction of β-elimination (allyl/vinyl selectivity): as evidenced by entries 1−10, the reactions with terminal alkenes containing any functional group distal from the reaction site (the double bond) gave the allylsilanes preferentially over the corresponding vinylsilanes. On the other hand, in the case of terminal alkenes containing bulky substituents, such as a cyclohexyl, benzyl, or cyclic ketal group, near the reaction site, the allyl/vinyl selectivity showed a declining trend. (3) Stereoselectivity: the *E*/*Z* ratios of the allylsilanes were almost constant (except for entry 12), with *Z* isomers as the major component. (4) Isomerization of double bond: no movement of the C−C double bond of allylsilanes was observed at all, even when a carbonyl or phenyl moiety was present. Isomerization to give conjugated products often occurs in Ru- and Pd-catalyzed reactions.[7]

To investigate the chemoselectivity of this silylation, the reactivities of this system with various alkenes were next examined (Scheme 1). The functional group specificity of this silylation is very high, and internal olefins (**3** or **4**) or 1,1′-disubstituted alkenes (**5** or **6**) did not react at all. On the other hand, the reaction of styrene (**7**) provides both alkylsilane and vinylsilane with a quantitative conversion yield. The alkyl/vinyl ratio depends on the reaction temperature to some extent, and when the reaction was carried out at 45 °C, the corresponding vinylsilane and alkylsilane were obtained in 88% and 12% yields, respectively. In the competitive reaction of internal alkenes in 1,5-heptadiene (**8**) using SiSiNOL-Zn-ate and 5 mol % of Cp_2TiCl_2, silylation at the terminal alkene proceeded with complete selectivity. In addition, no isomerization of olefins was observed at all.

Finally, the potential use of the functionalized allylsilanes produced in this work was examined (Scheme 2).[8] The resultant γ-substituted allylsilanes can be utilized as allylating agents in the presence of Lewis acids with high chemo- and regioselectivity. The allylsilanes also react with *m*-CPBA or BH_3•THF to give the corresponding oxidized products in moderate to high yields with high regioselectivities. These multifunctionalities can easily be further transformed in various ways, so that the synthetic value of γ-substituted allylsilanes would be greatly extended by the present approach.

Scheme 2. Reactivity of the Functionalized Allylsilanes



In conclusion, we have developed a new method for the chemo- and regioselective silylation reaction of functionalized terminal alkenes, utilizing a catalyst system comprising catalytic Cp_2TiCl_2 and a dianion-type Zn(II) ate complex (SiSiNOL-Zn-ate). The method provides a simple and direct route for the synthesis of regiocontrolled γ-substituted allylsilanes from various functionalized terminal alkene precursors. Efforts to expand the scope of the reaction and to elucidate the reaction pathway with the help of theoretical and spectroscopic studies are in progress in our laboratory.

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Supporting Information Available: Experimental procedures and characterizations. This material is available free of charge via the Internet at http://pubs.acs.org.

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