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Dedicated to our colleague and friend Professor *E. Peter Kündig* on the occasion of his 75th anniversary

The silyl- and germylzincation of terminal or internal propargylic alcohols by reaction with $(Me_3Si)_3SiH/Et_2Zn$, $[(Me_3Si)_3Si]_2Zn/Et_2Zn$ or Ph_3GeH/Et_2Zn is examined. These reactions proceed through the addition of silicon- or germanium-centered radicals across the carbon–carbon triple bond followed by the trapping by diethylzinc of the produced vinyl radical through homolytic substitution at the zinc atom. The influence of the hydroxy unit on the regio- and stereoselectivity of these reactions is discussed and compared to its role played in radical hydrosilylation and hydrogermylation reactions. Protocols developed to achieve the β-regioselective silylzincation of propargyl alcohol and the α-regioselective germylzincation of internal propargylic alcohols are particularly important, as they occur with *trans* stereoselectivity. For both procedures the C(sp^2)–Zn bond remains available for subsequent in-situ electrophilic substitution leading overall to net alkyne *trans* difunctionalization.

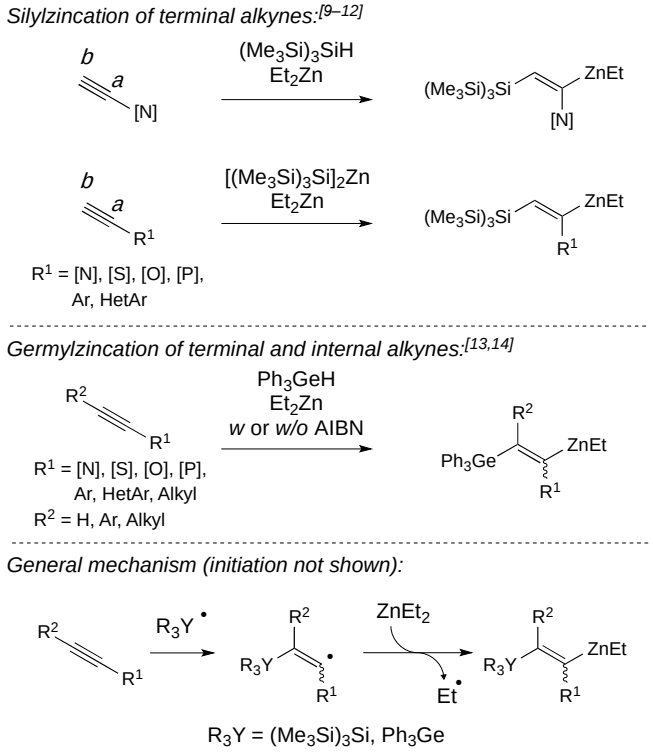
Keywords: Silylmetalation • Germylmetalation • Propargylic alcohols • Radical reactions • Zinc

Introduction

The prevalence of carbon-carbon double bonds in organic molecules makes the stereodefined construction of multi-substituted alkenes a central issue in organic synthesis.[1,2] In this context, the addition of element–metal bonds across carbon–carbon triple bonds, i.e. alkyne elementometalation reactions, as coined by Negishi,[3] is an area of intense on-going research as it offers the possibility to prepare in a single operation 1,2-difunctionalized alkenes ideally suited for the subsequent orthogonal introduction of two different substituents.[4–7] However, the success of this approach is heavily dependent on the regio- and the stereoselectivity of the addition reaction.

In this field, as part of our interest in dialkylzinc-mediated radical reactions for the functionalization of carbon–carbon multiple bonds,[8] we recently unveiled a radical approach to the silyl- and germylzincation of carbon–carbon triple bonds (Scheme 1). Suitable procedures relying on a combination of either $(Me_3Si)_3SiH/Et_2Zn$[9] or $[(Me_3Si)_3Si]_2Zn/Et_2Zn$[10–12] were developed to achieve the silylzincation of terminal α-heteroatom- or α-(het)aryl-substituted alkynes, delivering the corresponding β-silylated vinylzinc intermediates with excellent β regioselectivity (Scheme 1, top). The decisive feature of this approach is the uncommon *trans*-stereoselectivity. Equally, the (unprecedented) germylzincation of α-heteroatom substituted alkynes (terminal or internal),[13] as well as of internal aryl- or alkyl-substituted alkynes,[14] was achieved through the reaction with Ph_3GeH/Et_2Zn (Scheme 1, middle). The success of the developed radical approaches relies on the opportunity to combine two key steps: the addition of silicon- or germanium-centered radicals across carbon–carbon triple bonds and the subsequent trapping by diethylzinc of the produced vinyl radical through homolytic substitution at the zinc atom (Scheme 1, bottom).

Scheme 1. Radical silyl- and germylzincation of alkynes.



During our studies, we discovered that propargylic alcohols (without need of alcohol protection) can also be well-suited substrates for this chemistry. The silylmetalation of propargylic alcohols and ethers is a synthetically relevant transformation for which a number of procedures has been developed. The most popular rely on the addition of silylcopper intermediates, either generated in catalytic amounts from silylaluminium, silylzinc, [15,16] or silylboron[17,18] reagents, or used as stoichiometric silicon anion donors.[19–21] Direct silylalumination,[22] silylzincation,[23,24] dialkylzinc-catalyzed silylboration[25] and Pd-catalyzed silylstannylation[26] and silylboration[27] were also reported. With these procedures, the silicon unit is generally incorporated at the alkyne carbon distal to the oxygen group (*β* regioselectivity), with few exceptions.[23] Yet, regiocontrol, especially in the case of internal alkynes, is not always perfect. Regarding stereoselectivity, products arising from exclusive *syn* addition are customarily observed. By contrast with silylmetalation, to the best of our knowledge, there is no report on the germylmetalation of propargylic alcohols (or ethers) previous to our work.*

Hereafter, we thus discuss our results regarding the implementation of the protocols developed for radical silyl- and germylzincation to this important family of alkynes. As a prelude to our work and to gain understanding about the addition of $(Me_3Si)_3Si$ and Ph_3Ge radicals across the carbon–carbon triple bonds of propargylic alcohols, we survey radical hydrosilylation (with $(Me_3Si)_3SiH$) and hydrogermylation (with Ph_3GeH) reactions of the same substrates, combining literature precedents and new experimental results.

Results and Discussion

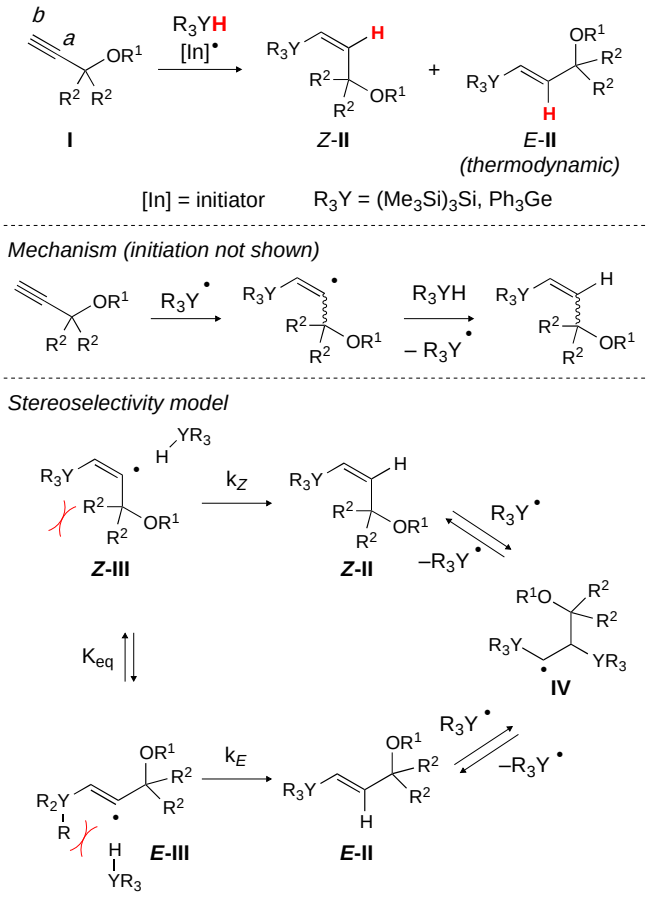
Radical Hydrosilylation and Hydrogermylation of Propargylic Alcohols

Terminal Propargylic Alcohols

Propargylic alcohols having a terminal alkyne (**I**) react readily with $(Me_3Si)_3SiH$[28,29] or Ph_3GeH[30] to provide the corresponding vinylsilanes or vinylgermanes **II** through a radical chain-reaction entailing radical addition and H-atom transfer to the vinylic radical adduct (Scheme 2, top and middle). Such reactions have been reported to occur with excellent *β* regioselectivity related to the fact that the adding radical reacts on the terminal carbon atom of the alkyne to avoid unfavorable steric interactions. Conversely, the stereoselectivity varies with the substrate and the reaction conditions.

It is conveniently rationalized according to the commonly accepted scenario depicted in Scheme 2, bottom. Vinyl radical **III** produced from the addition step is sp^2-hybridized, has a bent geometry, and exists as a rapidly interconverting mixture of *Z* and *E* isomers. The kinetic stereoselectivity of the process is related to a Curtin-Hammett-type situation wherein the *Z*/*E* ratio for the formation of **II** depends both on the relative stability of both isomers of radical **III** (K_{eq}), as well as the relative ease of each diastereomeric form to undergo H-atom transfer (k_Z vs k_E). The possibility to have *Z*-to-*E* interconversion of product **II** under the operating conditions through a radical addition/elimination process involving intermediate **IV** further complexifies the analysis.

Scheme 2. Radical hydrosilylation and hydrogermylation of propargylic alcohols having terminal alkynes.

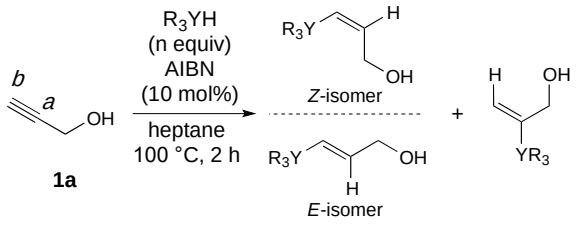


In the case of primary or secondary alcohol derivatives, the *Z*-isomer is the kinetic product for both hydrosilylation[29,31,32] and hydrogermylation[30] reactions: The reaction of the H-atom donor (R_3YH) with *Z*-**III**, for which the interaction with the bulky R_3Y group is avoided, is more favorable. At rt, the $(Me_3Si)_3Si$ radical does not induce alkene *Z*-to-*E* isomerization[29] and the *Z* isomer is recovered

* Our report on the germylzincation of aryl- and alkyl-substituted alkynes included propargylic alcohols having internal alkynes, see ref 14.

intact. At higher temperatures and in the case of hydrogermylation for which Ph_3Ge-radical-induced isomerization leading to the thermodynamically more stable *E*-isomer occurs even at rt,[33] mixtures of *E* and *Z* isomers are generally obtained. With tertiary alcohol derivatives, *E*-stereoselectivity was observed for hydrosilylation reactions,[32,34,35] but it was not established whether this preference for the *E* isomer was of kinetic or thermodynamic origin. For hydrogermylation reactions, the kinetic stereoselectivity was found to be in favor of the *Z*-isomer both at rt and at 100 °C.[30] On our side, we considered the hydrosilylation and hydrogermylation reactions of propargyl alcohol (**1a**) in heptane at 100 °C using AIBN as radical initiator (Table 1).

Table 1. Radical hydrosilylation and hydrogermylation of propargyl alcohol **1a** at 100 °C.



$R_3YH = (Me_3Si)_3SiH$ **2ab** **2aa**

$R_3YH = Ph_3GeH$ **3ab** **3aa**

Entry	R_3YH [equiv]	Product [β (*Z*/*E*)/α][a]	Yield (%)[b]
1	$(Me_3Si)_3SiH$ (0.8)	**2a**β/**2a**α [96(60:40):4]	80[c]
2	$(Me_3Si)_3SiH$ (1.5)	**2a**β/**2a**α [96(79:21):4]	82
3	Ph_3GeH (0.8)	**3a**β/**3a**α [94(80:20):6]	80[c]
4	Ph_3GeH (2.0)	**3a**β/**3a**α [96(15:85):4]	80

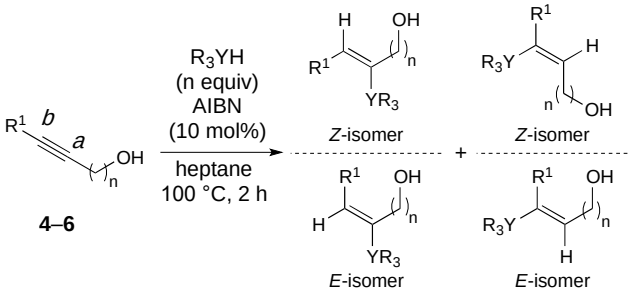
[a] Determined by ^1H NMR analysis of the crude reaction mixture. [b] Determined by ^1H NMR spectroscopy using butadiene sulfone as internal standard. [c] Based on $(Me_3Si)_3SiH$ or Ph_3GeH (limiting reagent).

The yields in vinylsilane **2a** or vinylgermane **3a** were consistently high. Excellent β regioselectivity was noted, though not perfect (β/α ~95:5) by contrast with the literature precedents. The stereoselectivities were in good agreement with the above-described scenario. In default of the hydride reagent, predominant formation of the kinetic *Z* isomer was obtained both for hydrosilylation (entry 1) and hydrogermylation (entry 3). Conversely, using excess hydride, formation of the *E* isomer prevailed in the case of hydrogermylation (entry 4). For the latter, such behavior can be easily ascribed to radical induced *Z*-to-*E* isomerization. For the hydrosilylation reaction, the *Z* isomer remained the major product and the *Z*/*E* ratio was somewhat higher (entry 2). These results lend clear evidence that under these conditions $(Me_3Si)_3Si$-radical-promoted *Z*-to-*E* isomerization occurs minorly, if at all, and thus that the observed stereoselectivity is of kinetic origin. The reason why the ratio varies with the amount of hydride still needs to be established.

Internal Propargylic Alcohols

By contrast with derivatives bearing terminal alkynes, the radical hydrosilylation and hydrogermylation of propargylic alcohols having internal alkynes has not been reported,[36] so we decided to assess experimentally the potential of these transformations (Table 2).

Table 2. Radical hydrosilylation and hydrogermylation of internal propargylic alcohols at 100 °C.



$R_3YH = (Me_3Si)_3SiH$ **7a** **7b**

$R_3YH = Ph_3GeH$ **8a–10a** **8b–10b**

Entry	Substrate	R_3YH [equiv]	Products [α (*Z*/*E*)/β (*Z*/*E*)][a]	Yield (%)[b]
1	**4** (R^1=Hept, n=1)	$(Me_3Si)_3SiH$	**7**α/**7**β	14
		1.5	[>98(>98:2):2]	
2	**4** (R^1=Hept, n=1)	Ph_3GeH	**8**α/**8**β	92
		2.0	[76 (39:61):24(39:61)]	
3	**4** (R^1=Hept, n=1)	Ph_3GeH	**8**α/**8**β	74[c]
		0.8	[78(>95:5):22(>95:5)]	
4	**5** (R^1=Ph, n=1)	Ph_3GeH	**9**α/**9**β	84
		2.0	[>98(14:86):2(-)]	
5	**5** (R^1=Ph, n=1)	Ph_3GeH	**9**α/**9**β	67[c]
		0.8	[>98(>95:5):2(-)]	
6	**6** (R^1=*n*Hex, n=2)	Ph_3GeH	**10**α/**10**β	84
		2.0	[57(34:66):43(33:67)]	
7	**6** (R^1=*n*Hex, n=2)	Ph_3GeH	**10**α/**10**β	80[c]
		0.8	[48(>95:5):52(>95:5)]	

[a] Determined by ^1H NMR analysis of the crude reaction mixture. [b] Determined by ^1H NMR spectroscopy using butadiene sulfone as internal standard. [c] Based on $(Me_3Si)_3SiH$ or Ph_3GeH (limiting reagent).

Very modest reactivity was observed when alcohol **4**, having an alkyl-substituted internal alkyne, was opposed to $(Me_3Si)_3SiH$ under similar conditions (heptane, 100 °C) to those applied with propargyl alcohol (entry 1). On the contrary, the reaction with Ph_3GeH proceeded readily with **4**, as well as with phenyl-substituted propargylic alcohol **5**, delivering respectively vinylgermanes **8**α/**8**β and **9**α/**9**β in high

yields (entries 2–5). Opposite regioselectivity with respect to terminal propargylic alcohols was observed, as the α regioisomers (**8**α and **9**α) were formed predominantly. In the absence of a strong steric bias to orient the radical addition step, this general behavior can be ascribed to an O-directing effect similar to the one observed for the better-established hydrostannylation reactions with Ph_3SnH, wherein interaction between the oxygen and the tin atoms directs the addition at the carbon of the alkyne proximal to the oxygen atom.[37] Note that in the case of **5**, the vinyl radical arising from the addition of the triphenylgermyl radical at the α carbon beneficiates from stabilization by the adjacent phenyl group, and this explains the higher levels of regioselectivity (compare entries 2 and 3 with 4 and 5). Additional support for the importance of the O-directing effect came from the result of the hydrogermylation of homopropargylic alcohol **6** under similar conditions (entries 6 and 7), since an almost equimolar mixture of α and β isomers of **10** was obtained.

Regarding stereoselectivity, the obtained ratios followed a similar trend as for the hydrogermylation of propargyl alcohol, and we could again identify two different regimes depending on the amount of triphenylgermane. In default-Ph_3GeH (0.8 equiv), close-to-perfect *Z*-stereoselectivity was obtained (entries 3, 5 and 7): This corresponds to the kinetic selectivity of the H-atom transfer reaction to the vinyl radical intermediate. By contrast, with excess Ph_3GeH (2.0 equiv), moderate *E*-stereoselectivity was obtained (entries 2, 4 and 6), as Ph_3Ge-radical-promoted *Z*-to-*E* isomerization of the initially formed *Z*-isomer takes place.[33]

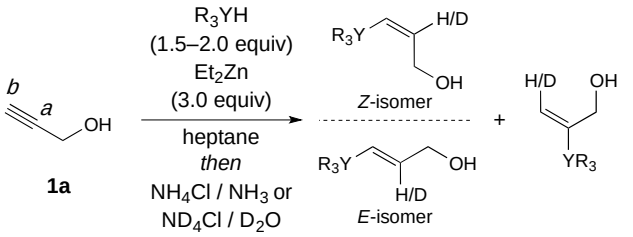
Radical Silyl- and Germylzincation of Propargylic Alcohols

Terminal Propargylic Alcohols

With this context in mind, we went on to consider silyl- and germylzincation reactions, focusing first on propargyl alcohol (**1a**) by reaction with respectively $(Me_3Si)_3SiH$ or Ph_3GeH in the presence of Et_2Zn (Table 3).

Only very low amounts of product were detected for both reactions under the operating conditions previously developed for terminal ynamides (i.e., 0 °C, 3 h) (entries 1 and 2), presumably because no reaction occurred. Conversely, at a higher temperature (100 °C), and in the presence of radical initiator AIBN, the formation of vinylsilane **2a** and vinylgermane **3a** was observed in respectively 58% and 78% yield (entries 3 and 5). In line with the hydrosilylation and hydrogermylation reactions, the regioselectivity was in favor of the β regioisomers, but here the selectivity levels were lower, especially in the case of germylzincation, for which 18% of the α isomer (**3a**α) was formed. Vinylsilane **2a**β was delivered exclusively as a *Z* isomer (whereas direct hydrosilylation gives *Z*/*E* = 79:21 (Table 1, entry 2)), and vinylgermane **3a**β was obtained as a *Z*/*E* = 67:33 mixture, unlike for direct hydrogermylation for which the *E* isomer is the major one (*Z*/*E* = 15:85). For both reactions, on quenching with ND_4Cl/D_2O, more than 90% of deuterium incorporation were detected for the β isomers (entries 4 and 6), evidencing that silyl- or germylzincation are the major reaction pathways and that direct hydrosilylation or hydrogermylation are not competitive processes in these conditions. This result is relevant because it contrasts sharply with the case of terminal aryl-substituted acetylenes for which hydrosilylation and hydrogermylation were found to predominate under similar conditions. Note that deuterium incorporation for the very minor α isomers could not be quantified.

Table 3. Silyl- and Germylzincation of propargyl alcohol **1a**.

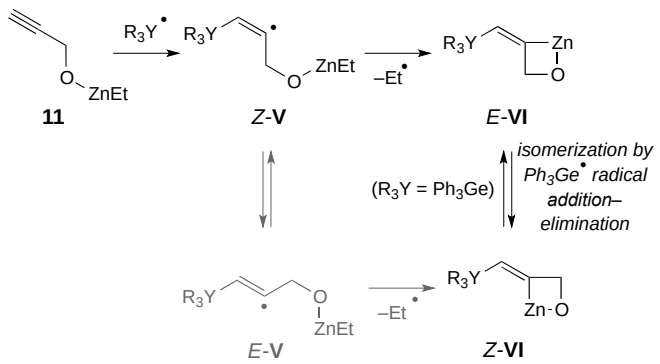


Entry	R_3YH	Conditions	Products [β (*Z*/*E*)/α][a]	Yield (%)[b]
1	$(Me_3Si)_3SiH$ (1.5 equiv)	0 °C, 3 h	**2a**β/**2a**α [90(>98:2):10(-)]	9%
2	Ph_3GeH (2.0 equiv)	0 °C, 3 h	**3a**β/**3a**α –	< 5%
3	$(Me_3Si)_3SiH$ (1.5 equiv)	100 °C, 3 h AIBN (10 mol%)	**2a**β/**2a**α [90(>98:2):10(-)]	58%
4	$(Me_3Si)_3SiH$ (1.5 equiv)	100 °C, 3 h AIBN (10 mol%)	**2a**β-d_1/**2a**α-d_1[c] [96(>98:2):4]	59%
5	Ph_3GeH (2.0 equiv)	100 °C, 3 h AIBN (10 mol%)	**3a**β/**3a**α [82(67:33):18]	78%
6	Ph_3GeH (2.0 equiv)	100 °C, 3 h AIBN (10 mol%)	**3a**β-d_1/**3a**α-d_1[c] [84(68:32):16]	65%
7	Ph_3GeH (2.0 equiv)	100 °C, 5 min AIBN (10 mol%)	**3a**β/**3a**α [82(68:32):18]	77%

[a] Determined by ^1H NMR analysis of the crude reaction mixture. [b] Determined by ^1H NMR spectroscopy using butadiene sulfone as internal standard. [c] The reaction was quenched with ND_4Cl/D_2O; the percentage of deuterium incorporation for the β isomers was estimated >90% by ^1H NMR spectroscopy.

In the present case, zinc alkoxide **11** should be the radical acceptor and vinylzinc formation can occur through intramolecular homolytic substitution at the tethered zinc atom of radical **V** (Scheme 3).

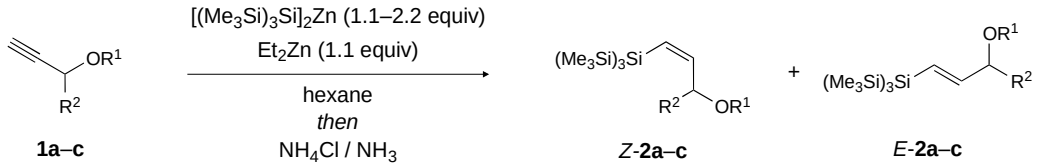
Scheme 3. Stereoselectivity model for the silyl- and germylzincation of propargyl alcohol by reaction with R_3YH/Et_2Zn (R_3Y = $(Me_3Si)_3Si$, Ph_3Ge).



Our hypothesis is that the zinc transfer event is thus accelerated in such a way that it prevents competitive H-atom transfer from the hydrosilane or the hydrogermane. Such acceleration may also be at the origin of the exclusive *trans* stereoselectivity for the silylzincation reaction, as the homolytic substitution event could become faster than *Z*-to-*E* isomerization of the primarily formed *Z*-**V**, and thus only *E*-**VI** (ultimately leading to *Z*-**2a**β) would be produced, in a situation that is reminiscent of the one encountered in the radical silylzincation of terminal ynamides.[9,13] For the same reasons, one would also expect *trans* germylzincation to be kinetically favored. Yet, under the operating conditions (excess Ph_3GeH, 100 °C), Ph_3Ge-radical induced isomerization of the vinylzinc intermediates should intervene[14] and the stereoselectivity should be rather related to the relative stability of *E*-**VI** versus *Z*-**VI**. Alas, this last speculation could not be demonstrated experimentally since the reaction was found to be very fast and the same outcome in terms of yield, regio- and stereoselectivity was already obtained after only 5 minutes of reaction time (Table 3, entry 7)!

We then turned our attention to our silylzincation method relying on $[(Me_3Si)_3Si]_2Zn$ as source of silyl radicals (Table 4). The reaction of **1a** with $[(Me_3Si)_3Si]_2Zn$ (1.1 equiv) in the presence of Et_2Zn (1.1 equiv) according to our protocol developed for α-heteroatom-substituted alkynes (i.e. hexane, –30 °C, 3 h) delivered, following work-up, vinylsilane **2a**, which was isolated in 42% yield with excellent β regio- and *Z* diastereoselectivity (entry 1). The yield in **2a** could be further improved with similar levels of selectivity to a reasonable 50%, but to the expense of using a larger amount (2.2 equiv) of $[(Me_3Si)_3Si]_2Zn$ (entry 2).

Table 4. Silylzincation of propargylic alcohols with terminal alkynes by reaction with $[(Me_3Si)_3Si]_2Zn/Et_2Zn$.



1a–c — *Z*-**2a–c** — *E*-**2a–c**

Entry	Substrate	R^1	R^2	$[(Me_3Si)_3Si]_2Zn$ (equiv)	Conditions	Conversion (**2a–c**/**1a–c**)[a]	Product[b]	Yield (%)[c] [*Z*/*E*][d]
1	**1a**	H	H	1.1	–30 °C, 3 h	nd[e]	**2a**	42 [97:3]
2	**1a**	H	H	2.2	–30 °C, 16 h	nd[e]	**2a**	50 [98:2]
3	**1b**	4-MeO-Ph	H	1.1	–30 °C, 3 h	48:52	**2b**	39 [83:17]
4	**1b**	4-MeO-Ph	H	1.1	0 °C, 16 h	63:37	**2b**	57[f] [85:15]
5	**1b**	4-MeO-Ph	H	2.2	–15 °C, 16 h	90:10	**2b**	69 [86:14]
6	**1c**	H	Ph	1.1	–30 °C, 3 h	30:70	**2c**	29 [19:81]
7	**1c**	H	Ph	2.2	–30 °C, 3 h	45:55	**2c**	45 [15:85]
8	**1c**	H	Ph	1.1	–30 °C, 16 h	40:60	**2c**	40[f] [45:55]
9	**1c**	H	Ph	2.2	0 °C, 16 h	55:45	**2c**	55[f] [33:67]

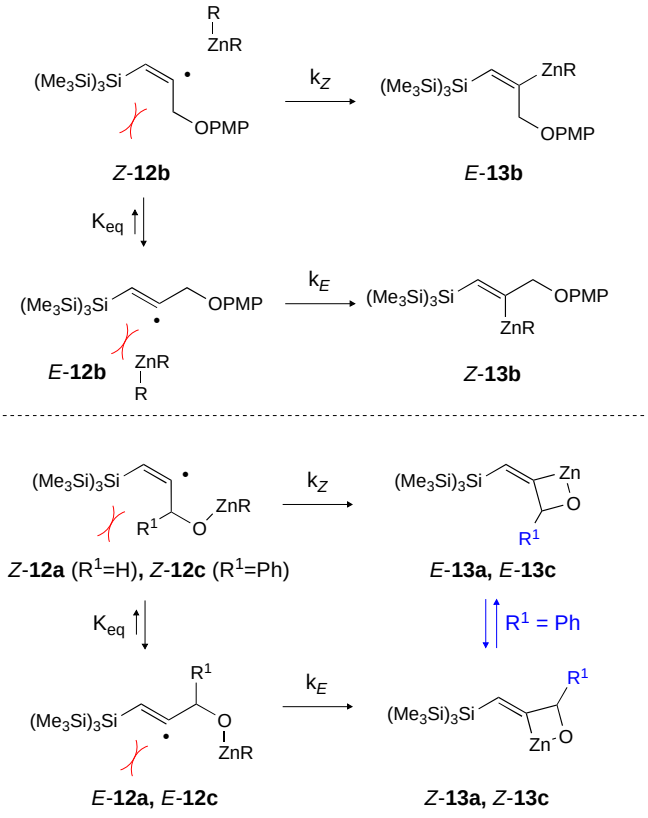
[a] Ratio between **2a–c**/**1a–c** determined by ^1H NMR analysis of the crude reaction mixture. [b] Only β-silylated regioisomers were detected (β:α > 98:2). [c] Combined yield of isolated diastereomers unless otherwise noted. [d] Determined by ^1H NMR analysis of the crude reaction mixture. [e] Not determined. [f] Determined by ^1H NMR spectroscopy using butadiene sulfone as internal standard.

To investigate the effect of the presence of the free hydroxy unit on the silylzincation reaction, *O*-PMP-protected propargyl alcohol **1b** was then considered. Here, complete β regioselectivity was also noted but with lower levels of *Z* stereoselectivity (entry 3). Following reaction at –30 °C, vinylsilane **2b** was obtained with *Z*/*E* = 83:17 in 39% yield. Performing the reaction at higher temperatures allowed for better conversion rates and thus better yields, but had no impact on the stereoselectivity (entries 4-5). Hence, alcohol protection has little impact in terms of reactivity but is deleterious for (*trans)*stereoselectivity.

Secondary propargylic alcohol **1c** proved less reactive, but was also amenable to silylzincation, though with a preference for *cis* addition delivering the *E* vinylsilane. At –30 °C, product **2c** was obtained after 3 h in *Z*/*E* = 19:81 ratio and a low 29% yield associated to poor conversion (entry 6). As for the two other substrates, slightly improved yields were obtained by either increasing the amount of $[(Me_3Si)_3Si]_2Zn$ to 2.2 equiv (entry 7), the reaction time to 16 h (entry 8) or the reaction temperature to 0 °C (entry 9). Interestingly, a significant loss of the stereoselectivity was noted with prolonged (16 h) reaction times.

The results with the $[(Me_3Si)_3Si]_2Zn/Et_2Zn$ system can also be nicely accommodated with the scenarios depicted in Scheme 4 involving zinc transfer to bent radicals **12a-c**.

Scheme 4. Stereoselectivity models for the silylzincation of **1a–c** by reaction with $[(Me_3Si)_3Si]_2Zn/Et_2Zn$ (R = $(Me_3Si)_3Si$ or Et).



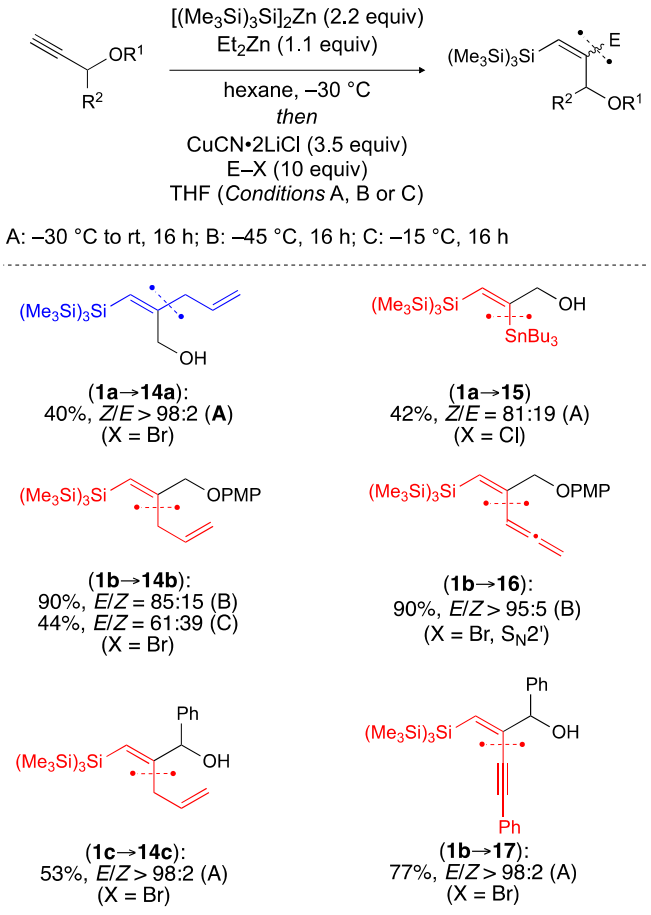
In the case of **12b** arising from the addition of the $(Me_3Si)_3Si$ radical to *O*-PMP-protected propargyl ether **1b** (Scheme 4, top), zinc transfer occurs preferentially on the *Z* isomer (*Z*-**12b** → *E*-**13b**) for which the interaction between the diorganozinc reagent and the bulky $(Me_3Si)_3Si$ unit is avoided. Notwithstanding (as in the case of direct hydrosilylation of propargyl alcohol – Table 1), the *E* isomer of **12b** also reacts to some extent (*E*-**12b** → *Z*-**13b**), thereby indicating that the minimization of this $(Me_3Si)_3Si/ZnR_2$ interaction does not override fully the allylic strain that destabilizes *Z*-**12b** with respect to *E*-**12b**. Vinylzinc intermediate **13b** is thus obtained as a *E*/*Z* ~85:15 mixture and no subsequent *E*-to-*Z* isomerization was noted.

The situation differs in the case of non-protected propargylic alcohols, as radical addition occurs on the corresponding zinc alkoxides and afford radicals **12a** and **12c** (initially as *Z*-isomers). We have no evidence to exclude a bimolecular zinc transfer as the one discussed for **12b**, but it seems reasonable to rather invoke formation of vinylzincs **13a** and **13c** upon intramolecular homolytic substitution at the tethered zinc atom (Scheme 4, bottom). Starting from propargyl alcohol (**1a**), as discussed previously for the $(Me_3Si)_3SiH/Et_2Zn$ protocol (see Scheme 3), primarily formed *Z*-**12a** should undergo intramolecular zinc transfer faster than *Z*-to-*E* isomerization to produce exclusively *E*-**13a**. Conversely, in the case of secondary propargylic alcohol **1c**, destabilization of *Z*-**12c** reduces the efficiency of the vinylzinc formation step (*Z*-**12c** → *E*-**13c**) and isomerization (*Z*-**12c** → *E*-**12c**) becomes relevant. In this situation, zinc transfer occurs preferentially on the *E* isomer (*E*-**12c** → *Z*-**13c**) wherein allylic strain is avoided. Importantly, by contrast with **13a**, vinylzinc reagent **13c** showed configurational lability (certainly not radical-induced) and it is interesting to note that there is no thermodynamic preference for either diastereomeric form. Configurational lability of vinylzinc species is rather uncommon, but it has been noted that the presence of a tethered zinc alkoxide can promote isomerization[15] and this is likely the case here.

We then contemplated the use of the $C(sp^2)$–Zn bond produced as handle for subsequent in-situ functionalization in order to access trisubstituted vinylsilanes, which represents a key asset of the radical alkyne silylzincation chemistry with respect to radical hydrosilylation. For this purpose, Cu(I)-mediated electrophilic substitution has proved particularly useful in other systems, allowing for functionalization with exquisite retention of the double bond geometry. Such was the case for the Cu(I)-mediated allylation of vinylzinc *E*-**13a** arising from the silylzincation of propargyl alcohol (**1a**): Upon treatment with allyl bromide in the presence of THF-soluble salt CuCN•2LiCl, vinylsilane **14a** was obtained in 40% yield and *Z*/*E* > 98:2 (Scheme 5). However, we quickly learned that this was not a general trend. For instance,

trapping of **13a** with tributyltin chloride under similar conditions delivered β-stannylated vinylsilane **15** as a *Z*/*E* = 81:19 mixture resulting from predominant *cis*-difunctionalization! Likewise, the Cu(I)-mediated allylation of **13b** arising from *trans*-selective silylzincation of *O*-PMP protected derivative **1b**, yielded vinylsilane **14b** in *E*/*Z* = 61:39 ratio (i.e., overall major *cis*-difunctionalization). For this system, performing the electrophilic substitution step at –45 °C upon silylzincation at –30 °C led to even higher ratios of the *E* isomer (*E*/*Z* = 85:15). Such was also the case for the trapping of **13b** with propargyl bromide, as allene **16** was produced as a single *E* isomer. Similarly, complete *E*-selectivity was observed for the succeeding silylzincation/allylation (**14c**) and silylzincation/alkynylation (**17**) reactions of α-substituted propargylic alcohol **1c**, even though in this case, the preference for *cis* selectivity was already noted at the silylzincation step.

Scheme 5. Access to trisubstituted vinylsilanes from **1a–c** by sequential silylzincation / Cu-mediated electrophilic substitution.



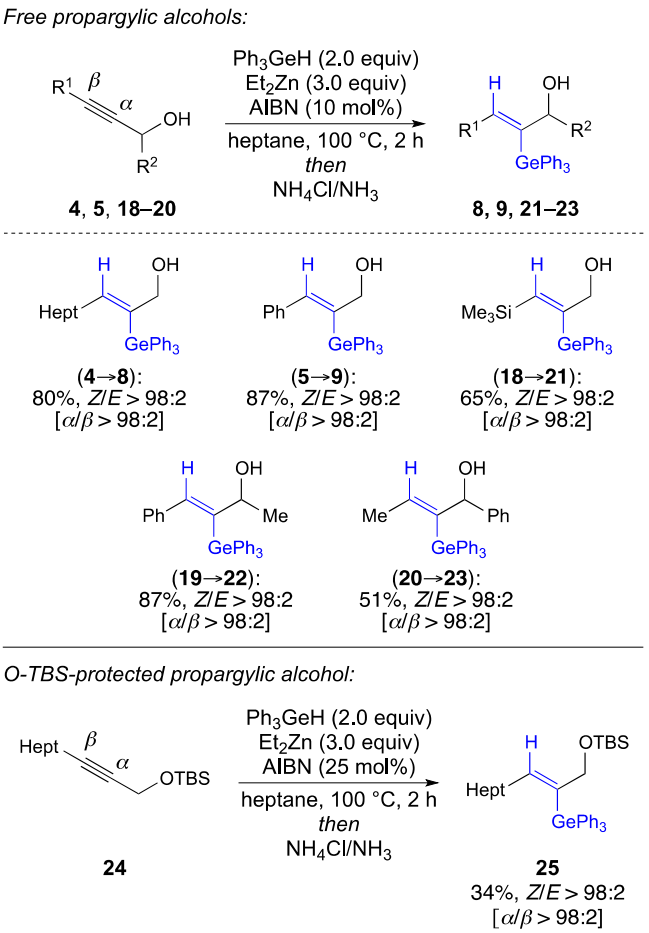
It is generally admitted that electrophilic substitution of vinylcopper intermediates proceeds with retention of configuration. We thus ascribe the observed behavior to the isomerization prior to electrophilic substitution of the vinylcopper reagents generated by transmetallation of the vinylzinc adducts **13a–c** with CuCN. Such isomerization could be the result of a certain configurational lability, but could also occur through an elimination/*syn*-silylcupration process associated to a reversible silylcupration reaction.[38] At this point, we do not have enough evidence to provide a definite conclusion, but the yields obtained for compounds **14b**, **14c**, **16** and **17**, which are significantly higher than the yields of the silylzincation/protonolysis reactions (Table 4, entries 5 and 7) support this last hypothesis. Regardless of its origin, this preference for *cis* renders our approach weakly competitive against direct silylcupration chemistry in this context and we did not push it further.

Germylzincation of Internal Propargylic Alcohols

We next steered our study towards internal propargylic alcohols and focused on germylzincation given that our preliminary studies on hydrosilylation and hydrogermylation had shown that radical addition of Ph_3Ge was more general for these substrates than that of $(Me_3Si)_3Si$. Application of our procedure previously developed for internal dialkyl- or aryl, alkyl-substituted alkynes proved successful.[14] Upon reaction with Ph_3GeH and Et_2Zn in heptane at 100 °C, in the presence of AIBN, compounds **4** and **5** underwent germylzincation in 80–87% yield with excellent α regioselectivity and complete *trans* stereoselectivity, affording *Z* vinylgermanes **8** and **9** after protonolysis (Scheme 6, top). The protocol was similarly applied with trimethylsilyl-substituted propargylic alcohol **18** which afforded β-trimethylsilyl vinylgermane **21** as a single regio- and stereoisomer. Derivatives of secondary propargylic alcohols were also amenable to germylzincation with this procedure, as shown with the formation of **22** and **23** from **19** and **20**.

The same regio- and stereochemical behavior was observed for the germylzincation of *O*-(*tert*-butyldimethylsilyl)-protected propargylic alcohol **24** which delivered **25** as a single β-regio- and *Z*-stereoisomer (Scheme 6, bottom). Here however, the yield was low (34%) and the product could not be separated from the considerable amount of unreacted starting material (36%, see *Supporting Information*).

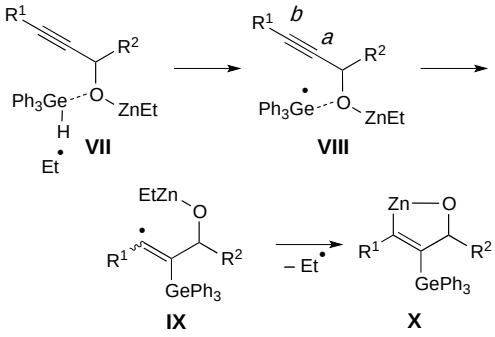
Scheme 6. Germylzincation of internal propargylic alcohols.



The excellent regio- and stereoselectivities observed for these reactions can be readily rationalized through the combined influence of an *O*-directing effect for the radical addition step and the formation of a 5-member-chelated vinylzinc species (Scheme 7). By analogy with Hale's proposal for the hydrostannylation reactions with Ph_3SnH,[37] we conjecture that formation of adduct **VII** by interaction between the oxygen and the germanium atoms facilitates H-atom transfer from Ph_3GeH and provides radical **VIII** poised for addition across the C–C triple bond at the proximal (α) carbon. The lower reactivity observed with *O*-silylated substrate **24** is consistent with this hypothesis, as in that case, the less favorable O–Ge interaction should prevent facilitation of the H-atom transfer step and therefore the radical chain should be less efficient. In this context, the improved regioselectivity observed for the germylzincation of **4** (Scheme 6, top) compared to hydrogermylation (Table 2, entries 2 and 3) is noteworthy, as it is coherent with a stronger *O*-directing effect for alkoxides than for alcohols, associated to a more favorable O–Ge interaction. Note that the same effect can account for the lower regioselectivity of germylzincation versus hydrogermylation of **1a**.

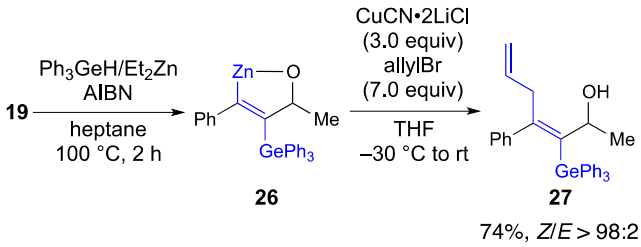
Upon addition of the germanium-centered radical, intermediate **IX** is formed and undergoes Zn transfer to deliver ultimately vinylzinc **X**. For simple alkynes, Ph_3Ge-radical-induced isomerization of the vinylzinc intermediates arising from germylzincation was observed in heptane at 100 °C. For **X**, the formation of a 5-member chelate stabilizes the *E*-isomer and makes it thermodynamically more stable, so that it's not possible to conclude whether the Zn transfer step is under kinetic or thermodynamic control (and this might also be substrate-dependent). It should also be mentioned that, as previously discussed, the possibility to have a bimolecular zinc transfer followed by ligand exchange leading to chelate formation cannot be fully excluded.

Scheme 7. Stereoselectivity model for the germylzincation of internal propargylic alcohols.



Similarly to the terminal propargylic alcohol silylzincation protocol, in-situ functionalization of the produced C(sp^2)–Zn bond was also possible with the germylzincation protocol for internal propargylic alcohols. Illustratively, our established procedure for Cu(I)-mediated allylation was advantageously applied with **26** to obtain in 74% yield tetrasubstituted vinylgermane **27** as a single regio- and stereoisomer by tandem germylzincation/electrophilic substitution of secondary propargylic alcohol **19** (Scheme 8). Perfect retention of the double-bond geometry of intermediate **24** was observed. Here, by contrast with the afore-discussed copper-mediated electrophilic substitution reactions of **13a** and **13b**, owing to chelation control, retention of double-bond geometry should be general for an array of electrophiles, even though this point is still to be ascertained.

Scheme 8. Access to tetrasubstituted vinylgermane **25** by sequential germylzincation / Cu-mediated electrophilic substitution.



Conclusions

In conclusion, we have demonstrated that our procedures developed for radical alkyne silyl- and germylzincation can be advantageously applied with propargylic alcohols as substrates. In both reactions, the C(sp^2)–Zn bond remains available for subsequent in-situ functionalization. The presence of the hydroxy unit has a definite impact on the reactivity and allows in most cases to obtain excellent regio- and stereocontrol. The protocols developed to achieve the β-regioselective silylzincation of propargyl alcohol and the α-regioselective germylzincation of internal propargylic alcohols are particularly relevant, as they occur with *trans* stereoselectivity, which remains a challenge in the field of alkyne elementometalation reactions.[39] The exquisite α regioselectivity of the germylzincation reactions of internal propargylic alcohols also merits to be emphasized as it is quite uncommon if one makes the analogy with the established silylmetalation chemistry relying on silicon nucleophiles and thus illustrates well the synthetic input of our radical elementozincation chemistry.

Experimental Section

*General Procedure (**GP I**) for Radical Hydrosilylation with $(Me_3Si)_3SiH$ or Hydrogermylation with Ph_3GeH of Propargylic Alcohols (Tables 1 and 2)*

A dry tube under argon was charged with AIBN (6 mg, 0.03 mmol), $(Me_3Si)_3SiH$ (0.8–1.5 equiv) or Ph_3GeH (0.8–2.0 equiv), heptane (1.4 mL) and the appropriate propargylic alcohol (0.25 mmol). The tube was sealed with a cap and placed immediately in an oil bath preheated at 100 °C. After the given reaction time, the tube was cooled rapidly, the cap was removed and the mixture was transferred to a round-bottom flask, diluted in CH_2Cl_2 and concentrated under reduced pressure. The residue was dissolved in $CDCl_3$, and butadiene sulfone (5.0 – 6.5 mg) was added as internal standard for ^{1}H NMR analysis.

*General Procedure (**GP II**) for Silylzincation with $(Me_3Si)_3SiH/Et_2Zn$ or Germylzincation with Ph_3GeH/Et_2Zn of Propargylic Alcohols (Table 3 and Scheme 6, top)*

A dry tube under argon was charged with AIBN (10 mg, 0.06 mmol), $(Me_3Si)_3SiH$ (0.12 mL, 0.39 mmol) or Ph_3GeH (153 mg, 0.50 mmol), heptane (0.7 mL) and the appropriate propargylic alcohol (0.25 mmol). Et_2Zn (1.0 M in hexane, 0.75 mL, 0.75 mmol) was added and the tube was sealed with a cap and placed immediately in an oil bath preheated at 100 °C. After the given reaction time, the tube was cooled down to rt, the cap was removed and the mixture was poured onto a mixture of aqueous NH_4Cl/NH_3 (2:1) (10 mL) and CH_2Cl_2 (10 mL). The layers were separated and the aqueous one was extracted with CH_2Cl_2 (2 x 10 mL). The combined organics were washed with brine (10 mL), dried (Na_2SO_4), filtered and concentrated under reduced pressure. The residue was either purified by flash column chromatography on silica gel (Scheme 6, top) or dissolved in $CDCl_3$, and butadiene sulfone (5.0 – 6.5 mg) was added as internal standard for ^{1}H NMR analysis (Table 3).

*General Procedure (**GP III**) for Silylzincation of Terminal Propargylic alcohols and Ethers with $[(Me_3Si)_3Si]_2Zn/Et_2Zn$ (Table 4)*

A Schlenk tube was charged with the appropriate terminal propargylic alcohol (0.25 mmol) and a suspension of $[(Me_3Si)_3Si]_2Zn$[40] (308 mg, 0.55 mmol) in *n*-hexane (2.0 mL) was added at –30 °C, followed by Et_2Zn (1.0 M in hexane, 0.28 mL, 0.28 mmol). The turbid mixture was stirred at this temperature for the given time. The mixture was then diluted with CH_2Cl_2 (10 mL) and quenched with aqueous NH_4Cl/NH_3 (2:1) (10 mL). The layers were separated and the aqueous one was extracted with CH_2Cl_2 (2 x 10 mL). The combined organics were washed with brine (10 mL), dried (Na_2SO_4), filtered and concentrated under reduced pressure. The crude product was purified by flash column chromatography on silica gel.

*General Procedure (**GP IV**) for Tandem Silylzincation / Cu(I)-mediated Electrophilic Substitution of Terminal Propargylic Alcohols (Scheme 5)*

A Schlenk tube was charged with the appropriate terminal propargylic alcohol (0.25 mmol) and a suspension of $[(Me_3Si)_3Si]_2Zn$ (308 mg, 0.55 mmol) in *n*-hexane (2.0 mL) was added at –30 °C, followed by Et_2Zn (1.0 M in hexane, 0.28 mL, 0.28 mmol). The turbid mixture was stirred at this temperature for the given time and then CuCN•2LiCl (1.0 M in THF, 0.88 mL, 0.88 mmol) was added, followed by the appropriate electrophile (2.50 mmol). The mixture was stirred for the given temperature and time and then diluted with CH_2Cl_2 (15 mL) and quenched with aqueous NH_4Cl/NH_3 (2:1) (10 mL). The layers were separated and the aqueous one was extracted with CH_2Cl_2 (2 x 15 mL). The combined organics were washed with brine (10 mL), dried (Na_2SO_4), filtered and concentrated under reduced pressure. The crude product was purified by flash column chromatography on silica gel.

(*Z*)-3-(1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)prop-2-en-1-ol (2a): Prepared according to **GP III**. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1 to 97/3) afforded **2a** (38 mg, 50%, *Z*/*E* > 98:2) as a colorless oil.

^{1}H-NMR (300 MHz, C_6D_6): 6.57 – 6.48 (m, 1H), 5.76 (dt, ^3J(H,H) = 13.2, ^4J(H,H)= 1.2, 1H), 4.04 (dd, ^3J(H,H) = 6.5, ^4J(H,H) = 1.2, 2H), 0.23 (s, 27H). ^{13}C-NMR (75 MHz, C_6D_6): 147.9, 123.5, 65.0, 1.1. HR-MS (ESI): 343.1161 ([M + K]$^+$, $C_{12}H_{32}KOSi_4^+$; calc. 343.1162). The spectral data was in good agreement with that previously reported.[35]

(*Z*)-2-(3-(4-methoxyphenoxy)prop-1-en-1-yl)-1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilane (2b): Prepared according to **GP III**. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1) afforded **2b** (71 mg, 69% yield, *Z*/*E* = 86:14) as a colorless oil.

IR (neat): 2949, 2895, 2361, 2341, 1508, 1462, 1441, 1245, 1227, 1042, 1021, 835, 758, 689, 622. ^{1}H-NMR (300 MHz, C_6D_6): (*Z* isomer) 6.95 – 6.92 (m, 2H), 6.83 – 6.74 (m, 3H), 5.94 (d, ^3J(H,H) = 13.4, 1H), 4.52 (dd, ^3J(H,H) = 6.5, ^4J(H,H) = 1.1, 2H), 3.33 (s, 3H), 0.24 (s, 27H). ^{13}C-NMR (100 MHz, C_6D_6): (*Z* isomer) 154.6, 153.5, 144.1, 125.8, 115.8, 115.1, 70.7, 55.2, 1.2. HR-MS (ESI): 433.1827 ([M + Na]$^+$, $C_{19}H_{38}NaO_2Si_4^+$; calc. 433.1841).

The Z configuration was established on the basis of the ^3J(H,H) (13.4 Hz) coupling constant between the vinylic protons.

(*E*)-1-Phenyl-3-(1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)prop-2-en-1-ol (2c): Prepared according to **GP III**. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1) afforded **2c** (43 mg, 45% yield, *E*/*Z* = 85:15) as a colorless oil. The spectral data of the *Z* isomer was in good agreement with that previously reported.[31] An analytically pure sample of the *E* isomer was obtained upon further purification by flash chromatography on silica gel.

^{1}H-NMR (300 MHz, C_6D_6) 7.35 – 7.32 (m, 2H), 7.19 – 7.14 (m, 2H), 7.08 – 7.02 (m, 1H), 6.34 (dd, ^3J(H,H) = 18.3, ^3J(H,H) = 5.4, 1H), 6.05 (dd, ^3J(H,H) = 18.3, ^4J(H,H) = 1.3, 1H), 4.95 (d, ^3J(H,H) = 5.4, 1H), 0.22 (s, 27H). ^{13}C-NMR (100 MHz, C_6D_6): 150.8, 143.8, 128.6, 127.6, 126.6, 121.4, 77.4, 1.0. HR-MS (ESI): 381.1919 ([M + H]$^+$, $C_{18}H_{37}OSi_4^+$; calc. 381.1916).

The E configuration was established on the basis of the ^3J(H,H) (18.3 Hz) coupling constant between the vinylic protons.

(*Z*)-2-((1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)methylene)pent-4-en-1-ol (14a): Prepared according to **GP IV** using allyl bromide (0.22 mL, 2.50 mmol) as electrophile. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 100/0 to 99/1) afforded **14a** (35 mg, 40% yield, *E*/*Z* > 98:2) as a colorless oil.

IR (neat): 2951, 2895, 2360, 2341, 1398, 1260, 1028, 830, 754, 686, 622, 564. ^{1}H-NMR (400 MHz, C_6D_6) 5.82 (ddt, ^3J(H,H) = 16.9, ^3J(H,H) = 10.0, ^3J(H,H) = 6.8, 1H), 5.60 (s(br), 1H), 5.06 – 4.98 (m, 2H), 4.06 (s, 2H), 2.99 – 2.97 (m, 2H), 0.26 (s, 27H). ^{13}C-NMR (100 MHz, C_6D_6): 156.3, 137.0, 119.2, 116.3, 66.2, 41.7, 1.2. HR-MS (ESI): 367.1731 ([M + Na]$^+$, $C_{15}H_{36}NaOSi_4^+$; calc. 367.1735).

The Z configuration was established on the basis of NOESY correlations.

2-(2-((4-methoxyphenoxy)methyl)penta-1,4-dien-1-yl)-1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilane (14b): Prepared according to **GP IV** using allyl bromide (0.22 mL, 2.50 mmol) as electrophile. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1) afforded **14b** (101 mg, 90% yield, *E*/*Z* = 85:15) as a colorless oil.

IR (neat): 2947, 2893, 2833, 2360, 1612, 1506, 1466, 1244, 1226, 1043, 917, 822, 748, 686, 623. ^{1}H-NMR (300 MHz, C_6D_6): (*E* isomer) 6.85 – 6.79 (m, 4H), 5.78 (ddt, ^3J(H,H) = 17.0, ^3J(H,H) = 10.1, ^3J(H,H) = 6.8, 1H), 5.70 (s, 1H), 5.15 (d, ^3J(H,H) = 17.0, 1H), 5.11 (d, ^3J(H,H) = 10.1, 1H), 4.49 (s, 2H), 3.76 (s, 3H), 3.00 (d, ^3J(H,H) = 6.6, 2H), 0.18 (s, 27H). ^{13}C-NMR (75 MHz, C_6D_6): (*E* isomer) 154.5, 153.3, 151.3, 153.9, 119.4, 117.5, 116.3, 114.9, 72.7, 55.3, 40.0, 1.4. HR-MS (ESI): 473.2146 ([M + Na]$^+$, $C_{22}H_{42}NaO_2Si_4^+$; calc. 473.2154).

The E configuration was established on the basis of NOESY correlations.

(*E*)-1-phenyl-2-((1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)methylene)pent-4-en-1-ol (14c): Prepared according to **GP IV** using allyl bromide (0.22 mL, 2.50 mmol) as electrophile. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1) afforded **14c** (56 mg, 53% yield, *E*/*Z* > 98:2) as a colorless oil.

IR (neat): 2947, 2892, 2360, 1637, 1601, 1492, 1453, 1395, 1243, 827, 762, 685, 621. ^{1}H-NMR (400 MHz, C_6D_6): 7.33 – 7.30 (m, 2H), 7.19 – 7.14 (m, 2H), 7.09 – 7.05 (m, 1H), 6.10 (d, ^4J(H,H) = 1.3, 1H), 5.78 (dddd, ^3J(H,H) = 17.8, ^3J(H,H) = 9.4, ^3J(H,H) = 7.7, ^3J(H,H) = 5.4, 1H), 5.10 (s(br), 1H), 5.04 – 4.99 (m, 2H), 3.15 (ddt, ^3J(H,H) = 14.9, ^3J(H,H) = 5.4, ^4J(H,H) = 1.9, 1H), 2.80 – 2.68 (m, 1H), 0.26 (s, 27H). ^{13}C-NMR (100 MHz, C_6D_6): 157.4, 143.6, 137.1, 128.5, 127.8, 127.4, 117.1, 116.5, 77.1, 40.1, 1.5. HR-MS (ESI): 443.2048 ([M + Na]$^+$, $C_{21}H_{40}NaOSi_4^+$; calc. 443.2058).

3-(1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)-2-(tributylstannyl)prop-2-en-1-ol (15): Prepared according to **GP IV** using Bu_3SnCl (0.67 mL, 2.50 mmol) as electrophile. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1 to 98/2) afforded **15** (62 mg, 42% yield, *Z/E* = 81:19) as a colorless oil.

IR (neat): 3418, 2953, 2921, 2872, 1679, 1457, 1376, 1243, 1048, 1019, 828, 745, 685, 623. ^{1}H-NMR (400 MHz, C_6D_6): (*Z* isomer) 6.84 (t, ^4J(H,H) = 1.6, 1H), 4.14 (d, ^4J(H,H) = 1.6, 2H), 1.69–1.63 (m, 6H), 1.49–1.40 (m, 6H), 1.18 – 1.06 (m, 6H), 0.99 – 0.95 (m, 9H), 0.33 (s, 27H). ^{13}C-NMR (100 MHz, C_6D_6): (*Z* isomer) 165.9, 133.6, 76.1, 29.8, 28.0, 14.0, 11.3, 2.0. HR-MS (ESI): 617.2500 ([M + Na]$^+$, $C_{24}H_{58}NaOSi_4Sn^+$; calc. 617.2480).

The Z configuration of the major isomer was established on the basis of the $^3J(^{119}Sn,H)$ coupling constant values of the vinylic protons[41] (171 Hz for the Z isomer and 94 Hz for the E isomer).

(*E*)-2-(2-((4-methoxyphenoxy)methyl)penta-1,3,4-trien-1-yl)-1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilane (16): Prepared according to **GP IV** using propargyl bromide (80% wt. % in toluene, 0.28 mL, 2.50 mmol) as electrophile. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1) afforded **16** (109 mg, 97% yield, *E/Z* > 98:2) as a colorless oil.

IR (neat): 2947, 2893, 2832, 1933, 1506, 1243, 1211, 1181, 1041, 821, 686, 623. ^{1}H-NMR (300 MHz, C_6D_6): 6.85 – 6.84 (m, 2H), 6.74 – 6.71 (m, 2H), 6.38 (t, ^3J(H,H) = 6.8, 1H), 6.13 – 6.12 (m, 1H), 4.77 (dd, ^3J(H,H) = 6.8, ^4J(H,H) = 1.6, 2H), 4.65 (m, 2H), 3.33 (s, 3H), 0.25 (s, 27H). ^{13}C-NMR (100 MHz, C_6D_6): 209.9, 154.5, 153.2, 144.7, 121.8, 116.3, 114.9, 94.9, 78.7, 70.6, 55.3, 1.3. HR-MS (ESI): 471.1981 ([M + Na]$^+$, $C_{22}H_{40}NaO_2Si_4^+$; calc. 471.1998).

The E configuration was established on the basis of NOESY correlations.

(*E*)-1,4-diphenyl-2-((1,1,1,3,3,3-hexamethyl-2-(trimethylsilyl)trisilan-2-yl)methylene)but-3-yn-1-ol (17): Prepared according to **GP IV** using phenylethynyl bromide (453 mg, 2.50 mmol) as electrophile. Purification of the crude product by flash chromatography on silica gel (eluent cyclohexane/ethyl acetate = 99/1) afforded **17** (84 mg, 65% yield, *E/Z* > 98:2) as a colorless oil.

IR (neat): 3062, 2947, 2891, 2197, 1598, 1571, 1489, 1442, 1396, 1242, 1068, 1027, 827, 753, 687, 605. ^{1}H-NMR (400 MHz, C_6D_6): 7.47 – 7.43 (m, 2H), 7.37 – 7.31 (m, 2H), 7.18 – 7.15 (m, 2H), 7.09 – 7.05 (m, 1H), 7.00 – 6.92 (m, 3H), 6.62 (d, ^4J(H,H) = 1.3, 1H), 5.18 (s, 1H), 0.33 (s, 27H). ^{13}C-NMR (75 MHz, C_6D_6): 143.2, 142.8, 131.9, 129.74, 129.72, 128.5, 127.8, 127.0, 123.8, 95.8, 91.2, 79.7, 1.6. HR-MS (ESI): 503.2048 ([M + Na]$^+$, $C_{26}H_{40}NaOSi_4^+$; calc. 503.2065).

For the sake of completeness, experimental procedures leading to compounds **8**, **9**, **21**–**23** and **25** as well as their NMR characterization data that have been published in a previous study[14] are reproduced hereafter.

***(Z)*-2-(triphenylgermyl)dec-2-en-1-ol (8):**[14] Prepared according to **GP II**. Purification of the crude product (α/β = 90(*Z/E* > 98:2):10) by flash chromatography on silica gel (eluent pentane/toluene/Et_2O = 80:10:10) afforded analytically pure **8** (92 mg, 80%, *Z/E* > 98:2) as a colorless liquid.

^{1}H-NMR (400 MHz, $CDCl_3$): 7.63 – 7.61 (m, 6H), 7.41 – 7.37 (m, 9H), 6.55 (t, ^3J(H,H) = 7.4, 1H), 4.19 (s, 2H), 1.94 (q, ^3J(H,H) = 7.4, 2H), 1.34 (br s, 1H), 1.26 – 0.93 (m, 10H), 0.87 (t, ^3J(H,H) = 7.2, 3H). ^{13}C-NMR ($CDCl_3$, 100 MHz): 145.5, 136.9, 135.8, 135.2, 129.1, 128.4, 69.2, 33.4, 31.8, 29.3, 29.2, 29.1, 22.7, 14.2.

***(Z)*-3-phenyl-2-(triphenylgermyl)prop-2-en-1-ol (9):**[14] Prepared according to **GP II**. Purification of the crude product (*Z/E* > 98:2) by flash chromatography on silica gel (eluent toluene/Et_2O = 90:10) afforded analytically pure **9** (96 mg, 87%, *Z/E* > 98:2) as a colorless liquid.

^{1}H-NMR (400 MHz, $CDCl_3$): 7.74 (s, 1H), 7.58 – 7.55 (m, 6H), 7.40 – 7.31 (m, 9H), 7.20 – 7.17 (m, 2H), 7.00 – 6.95 (m, 1H), 6.93 – 6.89 (m, 2H), 4.39 (s, 2H), 1.60 (br s, 1H). ^{13}C-NMR ($CDCl_3$, 100 MHz): 143.2, 138.2, 137.3, 136.6, 135.2, 129.0, 128.8, 128.3, 127.5, 127.4, 69.9.

***(Z)*-3-(trimethylsilyl)-2-(triphenylgermyl)prop-2-en-1-ol (21):**[14] Prepared according to **GP II**. Purification of the crude product (*Z/E* > 98:2) by flash chromatography on silica gel (eluent pentane/toluene/Et_2O = 50:45:5) afforded analytically pure **21** (70 mg, 65%, *Z/E* > 98:2) as a colorless liquid.

^{1}H-NMR (400 MHz, $CDCl_3$): 7.62 – 7.59 (m, 6H), 7.43 – 7.36 (m, 9H), 6.93 (s, 1H), 4.16 (s, 2H), 1.49 (br s, 1H), –0.22 (s, 9H). ^{13}C-NMR (100 MHz, $CDCl_3$): 152.9, 144.1, 137.3, 135.4, 129.2, 128.3, 72.3, –0.2.

***(Z)*-3-phenyl-2-(triphenylgermyl)prop-2-en-1-ol (22):**[14] Prepared according to **GP II**. Purification of the crude product (*Z/E* > 98:2) by flash chromatography on silica gel (eluent pentane/Et_2O/toluene = 75:15:10) afforded analytically pure **22** (94 mg, 83%, *Z/E* > 98:2) as a colorless liquid.

^{1}H-NMR (400 MHz, $CDCl_3$): 7.84 (s, 1H), 7.57 – 7.54 (m, 6H), 7.36 – 7.30 (m, 9H), 7.17 – 7.15 (m, 2H), 6.94 – 6.90 (m, 1H), 6.87 – 6.83 (m, 2H), 4.60 (q, ^3J(H,H) = 6.4, 1H), 1.70 (br s, 1H), 1.36 (d, ^3J(H,H) = 6.4, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): 143.2, 140.6, 137.3, 137.1, 135.3, 128.9, 128.85, 128.2, 127.4, 127.2, 72.4, 24.4.

***(Z)*-1-phenyl-2-(triphenylgermyl)but-2-en-1-ol (23):**[14] Prepared according to **GP II**. Purification of the crude product (*Z/E* > 98:2) by flash chromatography on silica gel (eluent pentane/Et_2O/toluene = 75:15:10) afforded analytically pure **23** (58 mg, 51%, *Z/E* > 98:2) as a white paste.

^{1}H-NMR (400 MHz, $CDCl_3$): 7.48 – 7.45 (m, 6H), 7.39 – 7.30 (m, 9H), 7.20 – 7.17 (m, 3H), 7.10 – 7.07 (m, 2H), 6.66 (qd, ^3J(H,H) = 6.9, ^4J(H,H) 1.2, 1H), 5.33 (s, 1H), 1.87 (br s, 1H), 1.65 (dd, ^3J(H,H) = 6.9, ^4J(H,H) = 0.9, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): 142.6, 140.2, 139.0, 137.0, 135.2, 128.9, 128.2, 128.1, 127.1, 126.9, 78.6, 19.5.

***(Z)*-4-phenyl-3-(triphenylgermyl)hepta-3,6-dien-2-ol (27):**[14] A dry tube under argon was charged with AIBN (10 mg, 0.06 mmol), Ph_3GeH (153 mg, 0.50 mmol), heptane (0.7 mL) and 4-phenylbut-3-yn-2-ol **19** (37 mg, 0.25 mmol). Et_2Zn (1.0 M in hexane, 0.75 mL, 0.75 mmol) was added and the tube was sealed with a cap and placed immediately in an oil bath preheated at 100 °C. The reaction mixture was stirred for 2 h and then progressively cooled to –30 °C. Next, CuCN·2LiCl (1.0 M in THF, 0.75 mL, 0.75 mmol) followed by allyl bromide (0.15 mL, 1.75 mmol) were added at this temperature and the reaction mixture was allowed to warm slowly to rt overnight under stirring. Then, aq NH_4Cl/NH_3 (2:1) (10 mL) and CH_2Cl_2 (10 mL) were added and after 1 h stirring the layers were separated. The aqueous layer was extracted with CH_2Cl_2 (3 x 10 mL), and the combined organic layers were washed with brine (2 x 10 mL), dried over Na_2SO_4, filtered, and concentrated under reduce pressure to afford the crude product. Purification of the crude product by flash chromatography on silica gel (eluent pentane/Et_2O/toluene = 80:10:10) afforded analytically pure **27** (91 mg, 74%, *Z/E* > 98:2) as a white solid; mp.

M.p. 109 – 112 °C. ^{1}H-NMR (400 MHz, $CDCl_3$): 7.55 – 7.52 (m, 6H), 7.33 – 7.27 (m, 9H), 6.84 (d, ^3J(H,H) = 7.6, 2H), 6.79 – 6.75 (m, 1H), 6.67 (t, ^3J(H,H) = 7.6, 2H), 5.80 (ddt, ^3J(H,H) = 16.6, ^3J(H,H) = 10.6, ^3J(H,H) = 6.4, 1H), 5.15 – 5.05 (m, 3H), 3.41 – 3.38 (m, 2H), 1.65 (br s, 1H), 1.40 (d, ^3J(H,H) = 6.4, 3H). ^{13}C-NMR (100 MHz, $CDCl_3$): 150.9, 142.6, 141.5, 139.3, 135.4, 135.1, 128.8, 128.3, 127.9, 127.2, 126.7, 116.1, 70.6, 41.1, 24.6.

Supplementary Material

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/MS-number.

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Author Contribution Statement

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References

[1] A. B. Flynn, W. W. Ogilvie, 'Stereocontrolled Synthesis of Tetrasubstituted Olefins', *Chem. Rev.* **2007**, *107*, 4698–4745.

[2] F. Buttard, J. Sharma, P. A. Champagne, 'Recent advances in the stereoselective synthesis of acyclic all-carbon tetrasubstituted alkenes', *Chem. Commun.* **2021**, *57*, 4071–4088.

[3] E. Negishi, G. Wang, H. Rao, Z. Xu, 'Alkyne Elementometalation-Pd-Catalyzed Cross-Coupling. Toward Synthesis of All Conceivable Types of Acyclic Alkenes in High Yields, Efficiently, Selectively, Economically, and Safely: "Green" Way', *J. Org. Chem.* **2010**, *75*, 3151–3182.

[4] L.-B. Han, M. Tanaka, 'Transition metal-catalysed addition reactions of H–heteroatom and inter-heteroatom bonds to carbon–carbon unsaturated linkages via oxidative additions', *Chem. Commun.* **1999**, 395–402.

[5] I. Beletskaya, C. Moberg, 'Element−Element Additions to Unsaturated Carbon−Carbon Bonds Catalyzed by Transition Metal Complexes', *Chem. Rev.* **2006**, *106*, 2320–2354.

[6] M. B. Ansell, O. Navarro, J. Spencer, 'Transition metal catalyzed element–element additions to alkynes', *Coord. Chem. Rev.* **2017**, *336*, 54–77.

[7] H. Yoshida, 'Copper Catalysis for Synthesizing Main-Group Organometallics Containing B, Sn or Si', *Chem. Rec.* **2016**, *16*, 419–434.

[8] F. Chemla, F. Dulong, F. Ferreira, M. P. Nüllen, A. Pérez-Luna, 'Radical Zinc Atom-Transfer Based Multicomponent Approaches to 3-Alkylidene Tetrahydrofurans', *Synthesis* **2011**, 1347–1360.

[9] E. Romain, C. Fopp, F. Chemla, F. Ferreira, O. Jackowski, M. Oestreich, A. Perez-Luna,' Trans-Selective Radical Silylzincation of Ynamides', *Angew. Chem. Int. Ed.* **2014**, *53*, 11333–11337.

[10] C. Fopp, E. Romain, K. Isaac, F. Chemla, F. Ferreira, O. Jackowski, M. Oestreich, A. Perez-Luna, 'Stereodivergent Silylzincation of α-Heteroatom-Substituted Alkynes', *Org. Lett.* **2016**, *18*, 2054–2057.

[11] C. Fopp, K. Isaac, E. Romain, F. Chemla, F. Ferreira, O. Jackowski, M. Oestreich, A. Perez-Luna, 'Stereodivergent Synthesis of β-Heteroatom-Substituted Vinylsilanes by Sequential Silylzincation–Copper(I)-Mediated Electrophilic Substitution', *Synthesis* **2017**, *49*, 724–735.

[12] E. Romain, K. de la Vega-Hernández, F. Guégan, J. Sanz García, C. Fopp, F. Chemla, F. Ferreira, H. Gerard, O. Jackowski, S. Halbert, M. Oestreich, A.

Perez-Luna, 'Development of a Radical Silylzincation of (Het)Aryl-Substituted Alkynes and Computational Insights into the Origin of the Trans-Stereoselectivity', *Adv. Synth. Catal.* **2021**, *363*, 2634–2647.

[13] K. de la Vega-Hernández, E. Romain, A. Coffinet, K. Bijouard, G. Gontard, F. Chemla, F. Ferreira, O. Jackowski, A. Perez-Luna, 'Radical Germylzincation of α-Heteroatom-Substituted Alkynes', *J. Am. Chem. Soc.* **2018**, *140*, 17632–17642.

[14] K. de la Vega-Hernández, F. Chemla, F. Ferreira, O. Jackowski, A. Perez-Luna, 'Radical Germylzincation of Aryl- and Alkyl-Substituted Internal Alkynes', *Org. Lett.* **2021**, *23*, 4426–4430.

[15] K. Wakamatsu, T. Nonaka, Y. Okuda, W. Tückmantel, K. Oshima, K. Utimoto, H. Nozaki, 'Transition-metal Catalyzed Silylzincation and Silylalumination of Acetylenic Compounds', *Tetrahedron* **1986**, *42*, 4427–4436.

[16] G. Auer, M. Oestreich, 'Silylzincation of carbon–carbon multiple bonds revisited', *Chem. Commun.* **2006**, 311–313.

[17] A. Garcia-Rubia, J. A. Romero-Revilla, P. Mauleon, R. Gomez Arrayas, J. C. Carretero, 'Cu-Catalyzed Silylation of Alkynes: A Traceless 2-Pyridylsulfonyl controller Allows Access to Either Regioisomer on Demand', *J. Am. Chem. Soc.* **2015**, *137*, 6857–6865.

[18] H. Yoshida, Y. Hayashi, Y. Ito, K. Takaki, 'Inverse Regioselectivity in the Silylstannylation of Alkynes and Allenes: Copper-Catalyzed Three-Component Coupling with a Silylborane and a Tin Alkoxide', *Chem. Commun.* **2015**, *51*, 9440–9442.

[19] B. H. Lipshutz, D. C. Reuter, E. L. Ellsworth, 'Fine Tuning the Si–Sn Bond: Transmetalations Forming Either Trialkylstannyl or Trialkylsilyl Higher Order Cyanocuprates', *J. Am. Chem. Soc.* **1989**, *54*, 4975–4977.

[20] I. Fleming, R. Henning, D. C. Parker, H. E. Plaut, P. E. J. Sanderson, 'The Phenyldimethylsilyl Group as a Masked Hydroxy Group', *J. Chem. Soc. Perkin Trans. 1* **1995**, 317–337.

[21] B. Shi, N. A. Hawryluk, B. B. Snider, 'Formal Synthesis of (±)-Guanacastepene', *J. Org. Chem.* **2003**, *68*, 1030–1042.

[22] G. Altnau, L. Rösch, F. Bohlmann, M. Lonitz, 'Syn-Addition von Tris(trimethylsilyl)aluminium an alkine: eine Neue Synthese fur Vinylsilane, *Tetrahedron Lett.* **1980**, *21*, 4069–4072.

[23] S. Nakamura, M. Uchiyama, T. Ohwada, 'Chemoselective Silylzincation of Functionalized Terminal Alkynes Using Dianion-Type Zincate (SiBNOL-Zn-ate): Regiocontrolled Synthesis of Vinylsilanes', *J. Am. Chem. Soc.* **2004**, *126*, 11146–11147.

[24] V. N. Bochatay, Z. Neouchy, F. Chemla, F. Ferreira, O. Jackowski, A. Pérez-Luna, '4-Amino-1-allenylsilanes from 4-Aminopropargylic Acetates through a Silylzincation/Elimination Sequence', *Synthesis* **2016**, *48*, 3287–3300.

[25] Y. Nagashima, D. Yukimori, C. Wang, M. Uchiyama, 'In Situ Generation of Silylzinc by Si–B Bond Activation Enabling Silylzincation and Silaboration of Terminal Alkynes', *Angew. Chem. Int. Ed.* **2018**, *57*, 8053–8057.

[26] T. N. Mitchell, R. Wickenkamp, A. Amamria, R. Dicke, U. Schneider, 'Formation and Reactions of Olefins with Vicinal Silyl and Stannyl Substituents', *J. Org. Chem.* **1987**, *52*, 4868–4874.

[27] T. Ohmura, K. Oshima, H. Taniguchi, M. Suginome, 'Switch of Regioselectivity in Palladium-Catalyzed Silaboration of Terminal Alkynes by Ligand-Dependent Control of Reductive Elimination', *J. Am. Chem. Soc.* **2010**, *132*, 12194–12196.

[28] B. Kopping, C. Chatgililaloglu, M. Zehnder, B. Giese, 'Tris(trimethylsilyl)silane: an efficient hydrosilylating agent of alkenes and alkynes', *J. Org. Chem.* **1992**, *57*, 3994–4000.

[29] K. Miura, K. Oshima, K. Utimoto, 'Triethylborane induced stereoselective radical addition of R_3SiH to acetylenes and stereoselective reduction of alkenyl iodides with tris(trimethylsilyl)silane, *Bull. Chem. Soc. Jpn.* **1993**, *66*, 2356–2364.

[30] F. David-Quillot, V. Thiery, M. Abarbri, J. Thibonnet, T. Besson, A. Duchene, 'Regio- and Stereoselective Synthesis of (Z)-Vinylgermanes by Hydrogermylation of Alkynes, *Main Group Met. Chem.* **2007**, *30*, 235–244.

[31] J. Wang, Z. Zhu, W. Huang, M. Deng, X. Zhou, 'Air-initiated hydrosilylation of unactivated alkynes and alkenes and dehalogenation of halohydrocarbons by tris(trimethylsilyl)silane under solvent-free conditions', *J. Organomet. Chem.* **2008**, *693,* 2188–2192.

[32] K. Schmohl, D. Wandschneider, H. Reinke, A. Heintz, H. Oehme, ' The Cationic Rearrangement of (3 Hydroxy-1-propenyl)tris(trimethylsilyl)-silanes into (1-Trimethylsilyl-2-propenyl)bis(trimethylsilyl)silanols – Experimental and Theoretical Studies, *Eur. J. Inorg. Chem.* **2002**, 597–601.

[33] K. Nozaki, Y. Ichinose, K. Wakamatsu, K. Oshima, K. Utimoto, 'Et_3B Induced Stereoselective Radical Addition of Ph_3GeH to Carbon–Carbon Multiple Bonds and Ist Application to Isomerization of Olefins', *Bull. Chem. Soc. Jpn.* **1990**, *63,* 2268–2272.

[34] A. Odedra, K. Geyer, T. Gustafsson, R. Gilmour, P. H. Seeberger, 'Safe, facile radical-based reduction and hydrosilylation reactions in a microreactor using tris(trimethylsilyl)silane', *Chem. Commun.* **2008**, 3025–3027.

[35] J. Zhu, W.-C. Cui, S. Wang, Z.-J. Yao, ' Radical Hydrosilylation of Alkynes Catalyzed by Eosin Y and Thiol under Visible Light Irradiation', *Org. Lett.* **2018**, *20*, 3174–3178.

[36] For a single example involving hydrosilylation of a propagylic ester, see: Y. Cai, W. Zhao, S. Wang, Y. Liang, Z.-J. Yao, 'Access to Functionalized E-Allylsilanes and E-Alkenylsilanes through Visible-Light-Driven Radical Hydrosilylation of Mono- and Disubstituted Allenes', *Org. Lett.* **2019**, *21*, 9836–9840.

[37] K. J. Hale, S. Manaviazar, H. A. Watson, 'The O-Directed Free Radical Hydrostannation of Propargyloxy Dialkyl Acetylenes with Ph_3SnH/cat. Et_3B. A Refutal of the Stannylvinyl Cation Mechanism', *Chem. Rec.* **2019**, *19*, 238–319.

[38] M. A. Cubillo de Dios, I. Fleming, W. Friedhoff, P. D. W. Woode, 'Silyl-cupration of a propargylsilane as a test for the reversibility of a metallo-metallation', *J. Organomet. Chem.* **2001**, *624*, 69–72.

[39] Y. Nagashima, K. Hirano, R. Takita, M. Uchiyama,' Trans-Diborylation of Alkynes: Pseudo-Intramolecular Strategy Utilizing a Propargylic Alcohol Unit', *J. Am. Chem. Soc.* **2014**, *136*, 8532–8535.

[40] Dobrovetsky, R.; Kratish, Y.; Tumanskii, B.; Botoshansky, M.; Bravo-Zhivotovskii, D.; Y. Apeloig, 'Radical Activation of Si–H Bonds by Organozinc and Silylzinc Reagents: Synthesis of Geminal Dizinciosilanes and Zinciolithiosilanes', *Angew. Chem. Int. Ed.* **2012**, *51*, 4671–4675.

[41] M. S. Oderinde, R. D. J. Froese, M. G. Organ, 'On the Hydrostannylation of Aryl Propargylic Alcohols and Their Derivatives: Remarkable Differences

in Both Regio- and Stereoselectivity in Radical- and Nonradical-Mediated Transformations', *Chem. Eur. J.* **2014**, *20*, 8579–8583.