JOC Article

Copper(I) *tert*-Butoxide-Promoted 1,4 C^{sp^2}-to-O Silyl Migration: Generation of Vinyl Copper Equivalents and Their Stereospecific Cross-Coupling with Allylic, Aryl, and Vinylic Halides

Haruhiko Taguchi, Kazushi Ghoroku, Makoto Tadaki, Akira Tsubouchi, and Takeshi Takeda*

Department of Applied Chemistry, Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan

takeda-t@cc.tuat.ac.jp

Received May 27, 2002

Successive treatment of the (*Z*)-γ-trimethylsilyl allylic alcohols with copper(I) *tert*-butoxide and allylic halides followed by the tetrabutylammonium fluoride-assisted hydrolysis produced the allylation products, 2,5-alkadien-1-ols, with complete retention of configuration. Similar treatment of the organometallic intermediates with aryl and vinylic halides in the presence of palladium(0) catalyst gave the corresponding cross-coupling products in good yields. The stereoselective preparation of the starting materials is also described.

Introduction

The increased importance of organosilicon compounds in organic synthesis has led to considerable interest in organosilicon-based cross-coupling reactions. Palladium-catalyzed cross-coupling reactions of functionalized alkenylsilanes with organic halides have been extensively studied for the preparation of various olefins.[1] To facilitate these reactions, however, the activation of the Si−C bond by introduction of the electronegative substituents on the silicon atom[2] or a silacyclobutane moiety[3] is essential. The use of a strong accelerating additive such as tris(diethylamino)sulfonium difluorotrimethylsilicate is an alternative way for effecting the reaction through the formation of a hypervalent silicate.[4] Recently the copper(I) salt promoted self- and cross-coupling reactions of alkenyl- and alkynylsilanes have also been reported through the formation of a silicate.[5]

The Brook-type rearrangement is another attractive way to convert organosilicon compounds into reactive organometallic species, which are subsequently utilized for organic synthesis. In this context, efforts have been focused on 1,4 C^{sp^3}-to-O silyl migration for the preparation of various carbanions.[6] In contrast, 1,4 C^{sp^2}-to-O silyl migration, which generates vinylmetal species, has provided so far little synthetic significance due to unfavorable equilibrium to the rearrangement products.[7] Although the 1,4 C^{sp^2}-to-O silyl migration of sodium salt of 3-hydroxy-2-(trimethylsilyl)furan was observed, the resulting carbanion at the 2-position could not react with

* Corresponding author. Tel & Fax: 81-42-388-7034.

(1) (a) Hatanaka, Y.; Hiyama, T. *Synlett* **1991**, 845−853. (b) Hiyama, T.; Hatanaka, Y. *Pure Appl. Chem.* **1994**, *66*, 1471−1478. (c) Horn, K. H. *Chem. Rev.* **1995**, *95*, 1317−1350. (d) Hiyama, T. In *Metal-catalyzed Cross-coupling Reactions*; Diederich, F.; Stang, P. J., Eds. Organosilicon Compounds in Cross-coupling Reactions; Wiley-VCH: Weinheim, 1998; p 421.

(2) (a) Yoshida, J.; Tamao, K.; Yamamoto, H.; Kakui, T.; Uchida, T.; Kumada, M. *Organometallics* **1982**, *1*, 542−549. (b) Tamao, K.; Kobayashi, K.; Ito, Y. *Tetrahedron Lett.* **1989**, *30*, 6051−6054. (c) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1989**, *54*, 268−270. (d) Hatanaka, Y.; Goda, K.; Hiyama, T. *J. Organomet. Chem.* **1994**, *465*, 97−100. (e) Mowery, M. E.; Deshong, P. *J. Org. Chem.* **1999**, *64*, 1684−1688. (f) Denmark, S. E.; Wehrli, D. *Org. Lett.* **2000**, *2*, 565−568. (g) Denmark, S. E.; Neuville, L. *Org. Lett.* **2000**, *2*, 3221−3224. (h) Denmark, S. E.; Pan, W. *Org. Lett.* **2001**, *3*, 61−64. (i) Denmark, S. E.; Wang, Z. *Org. Lett.* **2001**, *3*, 1073−1076. (j) Denmark, S. E.; Wang, Z. *J. Organomet. Chem.* **2001**, *624*, 372−375. (k) Denmark, S. E.; Yang, S.-M. *Org. Lett.* **2001**, *3*, 1749−1752. (l) Itami, K.; Nokami, T.; Yoshida, J. *J. Am. Chem. Soc.* **2001**, *123*, 5600−5601. (m) Itami, K.; Nokami, T.; Ishimura, Y.; Mitsudo, K.; Kamei, T.; Yoshida, J. *J. Am. Chem. Soc.* **2001**, *123*, 11577−11585. (n) Denmark, S. E.; Sweis, R. F. *J. Am. Chem. Soc.* **2001**, *123*, 6439−6440. (o) Denmark, S. E.; Yang, S.-M. *J. Am. Chem. Soc.* **2002**, *124*, 2102−2103. (p) Hosoi, K.; Nozaki, K.; Hiyama, T. *Chem. Lett.* **2002**, 138−139.

(3) (a) Denmark, S. E.; Choi, J. Y. *J. Am. Chem. Soc.* **1999**, *121*, 5821−5822. (b) Denmark, S. E.; Wehrli, D.; Choi, J. Y. *Org. Lett.* **2000**, *2*, 2491−2494. (c) Denmark, S. E.; Wang, Z. *Synthesis* **2000**, 999−1003.

(4) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 918−920.

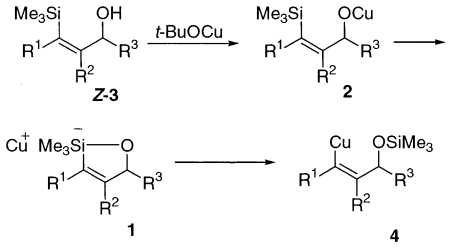
(5) (a) Yoshida, J.; Tamao, K.; Kakui, T.; Kumada, M. *Tetrahedron Lett.* **1979**, 1141−1144. (b) Urata, H.; Fuchikami, T. *Tetrahedron Lett.* **1991**, *32*, 91−94. (c) Lermontov, S. A.; Rakov, I. M.; Zefirov, N. S. *Tetrahedron Lett.* **1996**, *37*, 4051−4054. (d) Kang, S.-K.; Kim, T.-H.; Pyun, S.-J. *J. Chem. Soc., Perkin Trans. 1* **1997**, 797−798. (e) Ikegashira, K.; Nishihara, Y.; Hirabayashi, K.; Mori, A.; Hiyama, T. *Chem. Commun.* **1997**, 1039−1040. (f) Ito, H.; Sensui, H.; Arimoto, K.; Miura, K.; Hosomi, A. *Chem. Lett.* **1997**, 639−640. (g) Ito, H.; Arimoto, K.; Sensui, H.; Hosomi, A. *Tetrahedron Lett.* **1997**, *38*, 3977−3980. (h) Nishihara, Y.; Ikegashira, K.; Mori, A.; Hiyama, T. *Tetrahedron Lett.* **1998**, *39*, 4075−4078.

(6) (a) Woodbury, R. P.; Rathke, M. W. *J. Org. Chem.* **1978**, *43*, 1947−1949. (b) Matsuda, I.; Murata, S.; Ishii, Y. *J. Chem. Soc., Perkin Trans. 1* **1979**, 26−30. (c) Isobe, M.; Kitamura, M.; Goto, T. *Tetrahedron Lett.* **1979**, 3465−3468. (d) Fleming, I.; Floyd, C. D. *J. Chem. Soc., Perkin Trans. 1* **1981**, 969−976. (e) Takeda, T.; Naito, S.; Ando, K.; Fujiwara, T. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 967−968. (f) Takeda, T.; Ando, K.; Fujiwara, T. *Chem. Lett.* **1983**, 1285−1288. (g) Brook, A. G.; Chrusciel, J. J. *Organometallics* **1984**, *3*, 1317−1381. (h) Isobe, M.; Ichikawa, Y.; Funabashi, Y.; Mio, S.; Goto, T. *Tetrahedron* **1986**, *42*, 2863−2872. (i) Tietze, L. F.; Geissler, H.; Gewert, J. A.; Jakobi, U. *Synlett* **1994**, 511−512. (j) Jankowski, P.; Raubo, P.; Wicha, J. *Synlett* **1994**, 985−992. (k) Shinokubo, H.; Miura, K.; Oshima, K.; Utimoto, K. *Tetrahedron* **1996**, *52*, 503−514. (l) Smith, A. B., III; Boldi, A. M. *J. Am. Chem. Soc.* **1997**, *119*, 6925−6926. (m) Smith, A. B., III; Pitram, S. M. *Org. Lett.* **1999**, *1*, 2001−2004. (n) Bräuer, N.; Michel, T.; Schaumann, E. *Tetrahedron* **1998**, *54*, 11481−11488. (o) Moser, W. H. *Tetrahedron* **2001**, *57*, 2065−2084.

(7) (a) Kim, K. D.; Magriotis, P. A. *Tetrahedron Lett.* **1990**, *31*, 6137−6140. (b) Lautens, M.; Delanghe, P. H. M.; Goh, J. B.; Zhang, C. H. *J. Org. Chem.* **1995**, *60*, 4213−4227.

10.1021/jo025973r CCC: $22.00
Published on Web 11/01/2002

SCHEME 1



electrophiles other than proton.[8] Moser and co-workers reported the preparation of the aryllithium derivatives by 1,4 C^{sp^2}-to-O silyl migration of the arene chromium complexes of *o*-(trimethylsilyl)benzyl alkoxides. In this case, the resulting carbanions would be stabilized by the electron-withdrawing capability of $Cr(CO)_3$ coordinated to the benzene ring.[9]

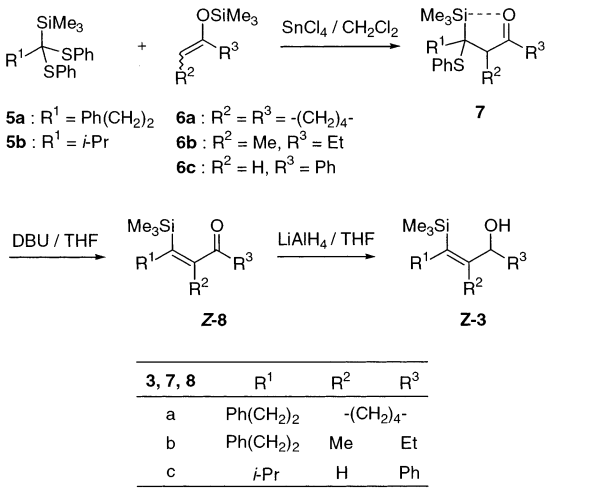
In the course of study on the preparation and synthetic application of group 14 vinylmetal species,[10] we found that vinylsilanes possessing a 2-pyridylthio group at the carbon α to the trimethylsilyl group reacted with allylic halides in the presence of CuI−KF to produce the cross-coupling products.[10e] We tentatively assume that the reaction proceeds through transmetalation of silicon to copper assisted by the intramolecular coordination of nitrogen to silicon. On the basis of this idea, it is expected that the hypercoordinated silicate **1** formed from the copper alkoxide **2** of (*Z*)-*γ*-trimethylsilyl allylic alcohol **3** is converted into a Brook-type rearrangement product, the vinylcopper species **4**, which reacts with various electrophiles (Scheme 1).

Here we describe the generation of a vinyl copper species (or its equivalent) through C^{sp^2}-to-O silyl migration of ***Z*-3** promoted with copper *tert*-butoxide and their cross-coupling reactions with allylic, vinylic, and aryl halides.[11]

Results and Discussion

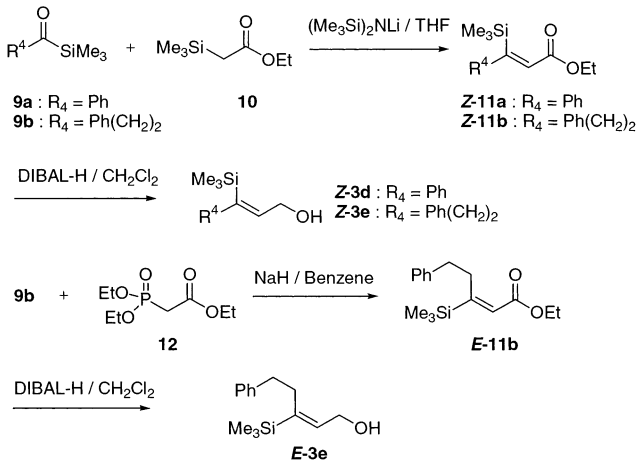
Stereoselective Synthesis of *γ*-Trimethylsilyl Allylic Alcohols 3. To substantiate the above idea, the *Z*-isomers of *γ*-trimethylsilyl allylic alcohols **3** are requisite. Although various methods for the stereoselective preparation of silyl alcohols **3** have been developed, most of them can be employed only for the preparation of *E*-isomers.[12] Although *Z*-isomers of **3** are prepared via 1,4 O-to-C^{sp^2} silyl migration,[7a] the method requires multistep transformation. Therefore, we first established the stereoselective preparation of ***Z*-3** by the reaction sequence similar to that employed for the synthesis of (*Z*)-*β*-(tributylstannyl)-α,*β*-unsaturated ketones.[10a]

SCHEME 2



3, 7, 8	R^1	R^2	R^3
a	$Ph(CH_2)_2$	$-(CH_2)_4-$	
b	$Ph(CH_2)_2$	Me	Et
c	*i*-Pr	H	Ph

SCHEME 3



The tin(IV) chloride-promoted reaction of α-trimethylsilyl thioacetals **5** with enol trimethylsilyl ethers **6** gave the *β*-phenylthio ketones (**7a**, 91%; **7b**, 75%; **7c**, 90%). The elimination of thiophenol from **7** with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) afforded (*Z*)-*β*-(trimethylsilyl)-α,*β*-unsaturated ketones ***Z*-8** (***Z*-8a**, 77%; ***Z*-8b**, 91%; ***Z*-8c**, 49%) with complete stereoselectivity. The stereochemical outcome of the elimination might be due to the intramolecular coordination of the carbonyl oxygen to silicon, which maintains the conformation favorable to the formation of the *Z*-isomers. The reduction of the silyl ketones **8** with lithium aluminum hydride gave the secondary alcohols **3** (***Z*-3a**, 86%; ***Z*-3b**, 73%; ***Z*-3c**, 63%) (Scheme 2).

The primary alcohols ***E*-** and ***Z*-3d** and ***Z*-3e** were prepared from acylsilanes (Scheme 3).[13] The Peterson olefination of acylsilanes **9** with lithium enolate of ethyl trimethylsilyl acetate **10** produced (*Z*)-α,*β*-unsaturated esters predominantly, and the pure *Z*-isomers were easily separated by silica gel chromatography (***Z*-11a**, 50%;

(8) Spinazzé, P. G.; Keay, B. A. *Tetrahedron Lett.* **1989**, *30*, 1765−1768.

(9) Moser, W. H.; Endsley, K. E.; Colyer, J. T. *Org. Lett.* **2000**, *2*, 717−719.

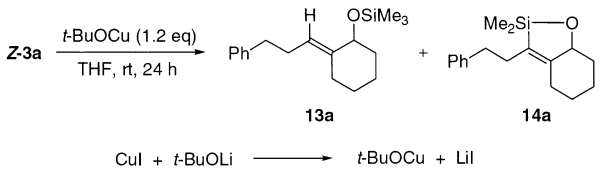
(10) (a) Takeda, T.; Sugi, S.; Nakayama, A.; Suzuki, Y.; Fujiwara, T. *Chem. Lett.* **1992**, 819−822. (b) Takeda, T.; Kabasawa, Y.; Fujiwara, T. *Tetrahedron* **1995**, *51*, 2515−2524. (c) Takeda, T.; Matsunaga, K.; Kabasawa, Y.; Fujiwara, T. *Chem. Lett.* **1995**, 771−772. (d) Takeda, T.; Matsunaga, K.; Uruga, T.; Takakura, M.; Fujiwara, T. *Tetrahedron Lett.* **1997**, *38*, 2879−2882. (e) Takeda, T.; Uruga, T.; Gohroku, K.; Fujiwara, T. *Chem. Lett.* **1999**, 821−822.

(11) Preliminary communication: Taguchi, H.; Ghoroku, K.; Tadaki, M.; Tsubouchi, A.; Takeda, T. *Org. Lett.* **2001**, *3*, 3811−3814.

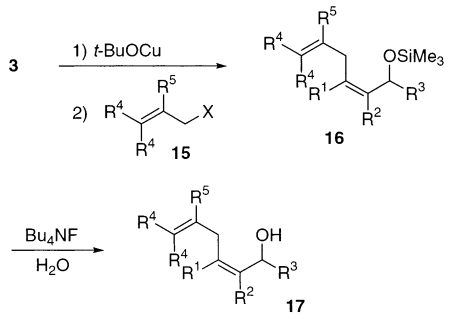
(12) (a) Sato, F.; Watanabe, H.; Tanaka, Y.; Sato, M. *J. Chem. Soc., Chem. Commun.* **1982**, 1126−1127. (b) Denmark, S. E.; Jones, T. K. *J. Org. Chem.* **1982**, *47*, 4595−4597. (c) Murphy, P. J.; Spencer, J. L.; Procter, G. *Tetrahedron Lett.* **1990**, *31*, 1051−1054. (d) Takai, K.; Kataoka, Y.; Utimoto, K. *J. Org. Chem.* **1990**, *55*, 1707−1708. (e) Rane, A. M.; Vaquer, J.; Colberg, J. C.; Soderquist, J. A. *Tetrahedron Lett.* **1995**, *36*, 987−990. (f) Takeuchi, R.; Nitta, S.; Watanabe, D. *J. Org. Chem.* **1995**, *60*, 3045−3051.

(13) Fujiwara, T.; Sawabe, K.; Takeda, T. *Tetrahedron* **1997**, *53*, 8349−8370.

SCHEME 4



SCHEME 5



E*-11a**, not produced; ***Z*-11b**, 71%; ***E*-11b**, 14%). Alternatively the *E*-ester ***E*-11b** was stereoselectively prepared by the Horner−Wadsworth−Emmons reaction of **9b** using diethyl ethoxycarbonylmethylphosphonate **12** (*E*, 54%; *Z*, 13%). The reduction of **11** with diisobutylaluminum hydride (DIBAL-H) produced the primary alcohols **3** (Z*-3d**, 62%; ***Z*-3e**, 88%; ***E*-3e**, 90%).

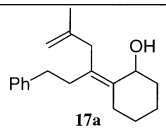
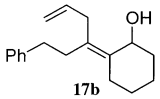
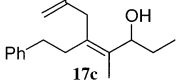
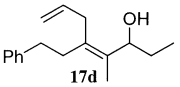
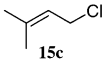
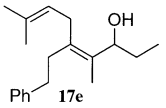
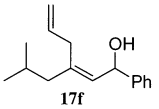
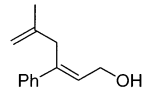
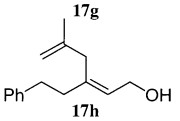
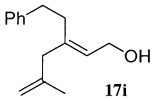
1,4 C^{sp^2}-to-O Silyl Migration of (*Z*)-γ-Trimethylsilyl Allylic Alcohols *Z*-3. As expected, the treatment of the silyl alcohol ***Z*-3a** with copper(I) *tert*-butoxide (1.2 equiv), prepared in situ by the reaction of copper(I) iodide with lithium *tert*-butoxide,[14] in THF at room temperature gave the Brook-type rearrangement product **13a** (59%), together with a small amount of the cyclic silyl ether **14a** (20%) (Scheme 4).

The above result implies the formation of the vinyl copper species **4** as the initial product via C^{sp^2}-to-O silyl migration. The formation of cyclic silyl ether **14a**, indeed, indicates that the reaction proceeds through the formation of intermediary pentavalent silicon anion **1**.

Copper(I) *tert*-Butoxide-Promoted Cross-Coupling of *(Z)*-γ-Trimethysilyl Allylic Alcohols 3 with Allylic Halides. The results of the copper(I) *tert*-butoxide-promoted 1,4 C^{sp^2}-to-O silyl migration of γ-trimethylsilyl allylic alcohols **3** prompted us to investigate the reaction of the intermediate organocopper species **4** with allylic halides **15**. The treatment of ***Z*-3a** with copper(I) *tert*-butoxide (1.5 equiv) and methallyl chloride **15a** (1.2 equiv) for 23 h at room temperature produced the trimethylsilyl ether of dienyl alcohol **16a** in 92% yield. The tetrabutylammonium fluoride-assisted hydrolysis of **16a** afforded the alcohol **17a** in 80% overall yield (Scheme 5).

Under similar reaction conditions, the coupling reactions of several γ-trimethylsilyl allylic alcohols **3** with allylic halides **15** were performed using THF or DMF as a solvent, and the allylation products **17** were obtained with complete retention of configuration (Table 1). The fact that the reaction of (*E*)-allylic alcohol ***E*-3e** with methallyl chroride **15a** was messy and no formation of the corresponding dienyl alcohol **17i** was observed clearly shows the crucial importance of intramolecular coordination in 1,4 C^{sp^2}-to-O silyl migration.

TABLE 1. Stereospecific Allylation of γ-Trimethylsilyl Allylic Alcohols 3 by Copper(I) *tert*-Butoxide

entry	γ-silyl allylic alcohol **3**	allylic halide **15**	solvent / time (h)	product (yield / %)[a]
1	***Z*-3a**	 **15a**	DMF / 2	 **17a** (84)
2	***Z*-3a**	 **15b**	THF / 16	 **17b** (88)
3	***Z*-3b**	**15a**	THF / 21	 **17c** (85)
4	***Z*-3b**	**15b**	THF / 14	 **17d** (80)
5[b]	***Z*-3b**	 **15c**	DMF / 4	 **17e** (75)
6	***Z*-3c**	**15b**	DMF / 10	 **17f** (76)
7	***Z*-3d**	**15a**	DMF / 15	 **17g** (74)
8	***Z*-3e**	**15a**	DMF / 12	 **17h** (73)
9	***E*-3e**	**15a**	DMF / 12	 **17i** (0)

[a] The configurations of the products were confirmed by NOE experiments. [b] A 1.2 equiv portion of copper(I) *tert*-butoxide was used.

Palladium-Catalyzed Cross-Coupling of Alkenylcopper Intermediates Generated by 1,4 C^{sp^2}-to-O Silyl Migration with Aryl and Vinylic Halides. The intermediary organocopper species is so reactive that it is expected to be employed for various carbon−carbon bond formations. We next examined the palladium-catalyzed cross-coupling of γ-trimethylsilyl allylic alcohols ***Z*-3** with aryl halides **18**. The successive treatment of ***Z*-3b** with copper(I) *tert*-butoxide (1.2 equiv) and iodobenzene **18a** (1.2 equiv) in the presence of $Pd(PPh_3)_4$ (3 mol %) at room temperature for 4 h produced the coupling product **19d** in 62% yield after hydrolysis with TBAF (Scheme 6). Increasing the amount of **18a** to 2.0 equiv slightly increased the yield (68%). In both cases, the arylation product **19d** was produced as a mixture of stereoisomers (*Z*:*E* = 92:8). The formation of the *E*-isomer was completely suppressed and **19d** was obtained in higher yield by the use of copper(I) chloride for the

(14) Tsuda, T.; Hashimoto, T.; Saegusa, T. *J. Am. Chem. Soc.* **1972**, *94*, 658−659.

SCHEME 6

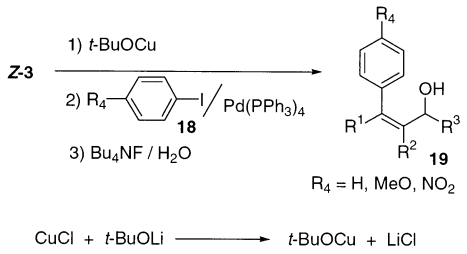
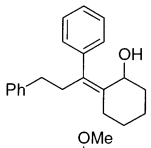
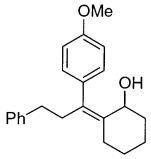
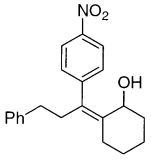
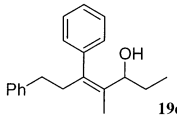
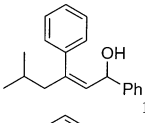
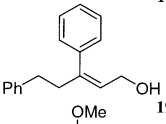
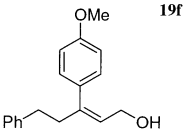
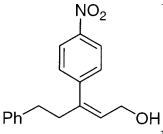


TABLE 2. Palladium(0)-Catalyzed Cross-Coupling of (*Z*)-γ-Trimethylsilyl Allylic Alcohols *Z*-3 with Aryl Halides 18

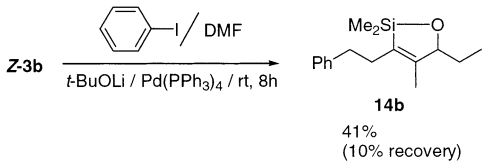
entry	γ-silyl allylic alcohol **3**	aryl halide **18**	product (yield / %)[a]
1	**Z-3a**	**18a**	 **19a** (78)
2	**Z-3a**	**18b**	 **19b** (60)
3	**Z-3a**	**18c**	 **19c** (67)
4	**Z-3b**	**18a**	 **19d** (77)
5	**Z-3d**	**18a**	 **19e** (70)
6	**Z-3e**	**18a**	 **19f** (77)
7	**Z-3e**	**18b**	 **19g** (66)
8	**Z-3e**	**18c**	 **19h** (63)

[a] The configurations of the products were confirmed by NOE experiments.

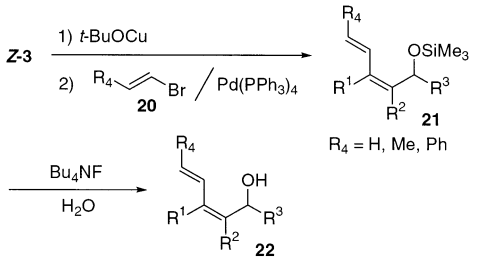
preparation of copper(I) *tert*-butoxide (entry 4, Table 2). Using the optimized conditions, the reactions of several γ-silyl allylic alcohols ***Z*-3** with aryl iodides **18** were performed and the arylation products were obtained in good yields with complete retention of configuration.

It was confirmed that no cross-coupling product was produced in the absence of the palladium catalyst. The reaction of ***Z*-3b** with iodobenzene **18a** in the presence of lithium *tert*-butoxide and $Pd(PPh_3)_4$ ended up with the formation of the cyclic silyl ether **14b**, and no formation of **19b** was observed (Scheme 7).

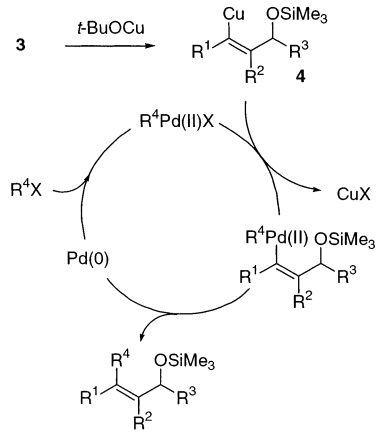
SCHEME 7



SCHEME 8



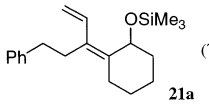
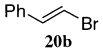
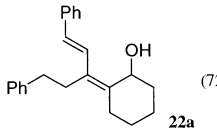
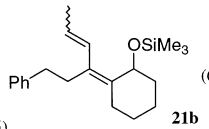
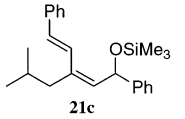
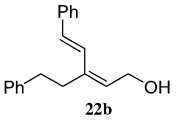
SCHEME 9



The vinylation of ***Z*-3** was also accomplished using vinylic bromides **20** in a manner similar to that employed for the arylation of ***Z*-3**. The treatment of ***Z*-3** with copper(I) *tert*-butoxide prepared from copper(I) chloride and lithium *tert*-butoxide and then **20** in the presence of a catalytic amount of $Pd(PPh_3)_4$ (3 mol %) gave the stereochemically defined conjugated dienyl silyl ether **21**. The subsequent hydrolysis of **21** with TBAF produced the dienyl alcohols **22** (Scheme 8, Table 3).

The palladium-catalyzed cross-coupling reactions of vinylsilanes possessing an electronegative ligand and the reactions accelerated by a fluoride ion are believed to involve transmetalation and reductive elimination of palladium. The coupling reaction of trimethylvinylsilane with aryl halides under ordinary Heck conditions was investigated, and its regiochemistry was found to be opposite to the above reactions of activated vinylsilanes, indicating that it proceeds via 1,2-addition of arylpalladium species to the double bond.[15] A plausible pathway for the palladium(0)-catalyzed cross-coupling reaction of γ-silyl allylic alcohols ***Z*-3** is illustrated in Scheme 9.

TABLE 3. Palladium(0)-Catalyzed Cross-Coupling of (*Z*)-γ-Trimethylsilyl Allylic Alcohols *Z*-3 with Vinylic Bromides 20

entry	γ-silyl allylic alcohol **3**	vinylic bromide **20**	product (yield / %)[a]
1[b]	**Z-3a**	 **20a**	 **21a** (71)
2	**Z-3a**	 **20b**	 **22a** (72)
3[b]	**Z-3a**	 **20c** (*E* : *Z* = 75 : 25)	 **21b** (*E* : *Z* = 70 : 30) (61)
4[b]	**Z-3c**	**20b**	 **21c** (64)
5	**Z-3e**	**20b**	 **22b** (63)

[a] The configurations of the products were confirmed by NOE experiments. [b] The product was isolated without hydrolysis.

Transmetalation of the vinylcopper species **4** with the organopalladium species $R_4Pd(II)X$, followed by reductive elimination, affords the cross-coupling product.

Conclusions

We have developed the copper(I) *tert*-butoxide-promoted 1,4 C^{sp^2}-to-O silyl migration of (*Z*)-γ-trimethylsilyl allylic alcohols. The intermediates, probably vinylcopper species, react with organic halides in the absence or presence of a palladium(0) catalyst to afford the cross-coupling products with complete retention of configuration. These reactions, together with the stereoselective methods for the preparation of the starting materials provide a useful synthesis of geometrically well-defined tri- and tetrasubstituted olefins. It should be noted that the present study first demonstrated the synthetic utility of the Brook-type rearrangement via copper(I) alkoxide.

Experimental Section

General Methods. α-Trimethylsilyl thioacetals were prepared according to the method reported by Reich et al.[16] Acylsilanes were synthesized from dithianes.[16] Tetrahydrofuran (THF) was distilled from sodium and benzophenone. Dimethylformamide (DMF) was distilled from calcium hydride under reduced pressure. Dichloromethane (CH_2Cl_2) was distilled from calcium hydride. Preparative thin-layer chromatography (PTLC) was carried out using Wakogel B-5F. Column chromatography was performed on Merck Si 60 or Merck aluminum oxide 90 deactivated by addition of water (5 wt %). ^1H (500 MHz) and ^{13}C (125 MHz) NMR spectra were recorded in $CDCl_3$ and chemical shifts (δ) are quoted in parts per million from tetramethylsilane for ^1H and $CDCl_3$ for ^{13}C spectroscopy. IR absorptions are reported in cm^{-1}.

Preparation of (*Z*)-2-[3-Phenyl-1-(trimethylsilyl)propan-1-ylidene]cyclohexanone (*Z*-8a). To a CH_2Cl_2 (15 mL) solution of 3-phenyl-1,1-bis(phenylthio)-1-(trimethylsilyl)propane (**5a**) (12.3 g, 30 mmol) was added a CH_2Cl_2 (15 mL) solution of 1-(trimethylsiloxy)cyclohexene **6a** (6.6 g, 30 mmol) at room temperature under argon. After cooling to −78 °C, a CH_2Cl_2 solution of $SnCl_4$ (1.5 M, 20 mL, 30 mmol) was added and the mixture was stirred for 12 h. The reaction was quenched by addition of water. After warming up to room temperature, organic materials were extracted with CH_2Cl_2, washed with 1 M NaOH and then water, and dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was chromatographed on silica gel (hexane/AcOEt = 98/2) to give 2-[3-phenyl-1-(phenylthio)-1-(trimethylsilyl)-propyl]cyclohexanone (**7a**) (10.8 g, 91%). **7a**: IR (neat) 3087, 3064, 3032, 3003, 2968, 2904, 2870, 1716, 1604, 1583, 1496, 1473, 1456, 1439, 1410, 1348, 1311, 1263, 1252, 1207, 1128, 1097, 1080, 1066, 1026, 1003, 885, 854, 793, 752, 702, 658 cm^{-1}; ^1H NMR δ 0.26 (s, 3.6H), 0.27 (s, 5.4H), 1.44−1.55 (m, 1H), 1.60−1.89 (m, 3H), 1.93−2.09 (m, 2.6H), 2.18−2.37 (m, 2H), 2.41−2.51 (m, 1.4H), 2.64 (dd, *J* = 13.1, 4.3 Hz, 0.6 H), 2.68−2.78 (m, 2H), 2.86 (dt, *J* = 13.1, 4.3 Hz, 0.4H), 7.05−7.07 (m, 1H), 7.13−7.18 (m, 2H), 7.22−7.36 (m, 5H), 7.56−7.59 (m, 2H); ^{13}C NMR δ 1.23, 1.41, 25.8, 26.1, 28.3, 28.4, 30.8, 31.3, 32.0, 32.7, 36.7, 38.7, 43.3, 43.4, 45.5, 46.5, 56.9, 58.7, 125.8, 128.2, 128.31, 128.34, 128.5, 128.57, 128.61, 128.7, 132.2, 132.7, 137.0, 137.3, 142.2, 142.5, 211.9, 212.2.

The ketone **7a** (4.52 g, 11.4 mmol) and DBU (3.4 mL, 22.9 mmol) were dissolved in THF (11 mL) at 0 °C, and the mixture was stirred for 5 days. The reaction was quenched by addition of water, and the organic materials were extract with ether. The combined extracts were washed with 1 M NaOH and water, dried over Na_2SO_4, and then concentrated under reduced pressure. The residue was purified by column chromatography (silica gel, hexane/AcOEt = 98/2) to afford ***Z*-8a** (2.52 g, 77%). ***Z*-8a**: IR (neat) 3062, 3026, 2945, 1676, 1603, 1545, 1495, 1454, 1433, 1412, 1335, 1319, 1279, 1244, 1144, 1084, 1068, 914, 843, 768, 748, 698, 671 cm^{-1}; ^1H NMR δ 0.18 (s, 9H), 1.69−1.74 (m, 2H), 1.83−1.89 (m, 2H), 2.44 (t, *J* = 6.7 Hz, 2H), 2.52 (t, *J* = 6.7 Hz, 2H), 2.55 (bs, 4H), 7.18−7.22 (m, 3H), 7.26−7.31 (m, 2H); ^{13}C NMR δ 0.71, 24.1, 24.4, 29.4, 34.6, 35.2, 41.3, 126.0, 128.3, 128.4, 141.7, 146.6, 153.2, 203.5. Anal. Calcd for $C_{18}H_{26}OSi$: C, 75.46; H, 9.15. Found: C, 75.43; H, 9.39.

In a similar manner, the β-(trimethylsilyl)-α,β-unsaturated ketones ***Z*-8b** and ***Z*-8c** were obtained.

Preparation of (*Z*)-2-[3-Phenyl-1-(trimethylsilyl)propan-1-ylidene]cyclohexanol (*Z*-3a). To a THF (8.8 mL) suspension of lithium aluminum hydride (334 mg, 8.8 mmol) was added dropwise a THF (8.8 mL) solution of the ketone ***Z*-8a** (2.52 g, 8.8 mmol) at −78 °C under argon. After stirring for 5 h at −78 °C, the reaction was quenched by dropwise addition of a saturated aqueous solution of Na_2SO_4. Insoluble materials were filtered off through Celite and washed with ether. The filtrate was condensed under reduced pressure and the residue was recrystalized from hexane to give ***Z*-3a** (2.18 g, 86%). ***Z*-3a**: mp 72.0−72.5 °C; IR (KBr) 3357, 3084, 3064, 3026, 3001, 2939, 2852, 1603, 1493, 1468, 1454, 1282, 1252, 1086, 997, 984, 883, 862, 835, 760, 750, 702, 687 cm^{-1}; ^1H NMR δ 0.21 (s, 9H), 1.12−1.21 (m, 1H), 1.29 (bs, 1H), 1.48−1.55 (m, 2H), 1.78−1.86 (m, 2H), 1.94−1.98 (b, 1H), 2.10 (dt, *J* = 4.0,

(15) (a) Daves, G. D., Jr.; Hallberg, A. *Chem. Rev.* **1989**, *89*, 1433−1445. (b) Hallberg, A.; Westerlund, C. *Chem. Lett.* **1982**, 1993−1994. (c) Karabelas, K.; Hallberg, A. *J. Org. Chem.* **1989**, *54*, 1773−1776. (d) Alvisi, D.; Blart, E.; Bonini, B. F.; Mazzanti, G.; Ricci, A.; Zani, P. *J. Org. Chem.* **1996**, *61*, 7139−7146.

(16) Reich, H. J.; Holtan, R. C.; Bolm, C. *J. Am. Chem. Soc.* **1990**, *112*, 5609−5617.

13.7 Hz, 1H), 2.34−2.57 (m, 5H), 4.62 (br, 1H), 7.17−7.20 (m, 3H), 7.26−7.29 (m, 2H); ^{13}C NMR δ 1.25, 20.3, 25.4, 27.8, 33.2, 33.9, 37.1, 71.4, 125.8, 128.3, 128.4, 133.6, 142.1, 152.3. Anal. Calcd for $C_{18}H_{28}OSi$: C, 74.94; H, 9.78. Found: C, 75.17; H, 9.60.

In a similar manner, the γ-trimethylsilyl allylic alcohols ***Z*-3b** and ***Z*-3c** were obtained.

Preparation of Ethyl (*Z*)-3-Phenyl-3-(trimethylsilyl)-prop-2-enoate (*Z*-11a). To a THF (10 mL) solution of tetramethyldisilazane (1.3 mL, 6.0 mmol) was added butyllithium (1.6 M in hexane, 3.8 mL, 6.0 mmol) at 0 °C under argon. After stirring for 20 min at 0 °C, a THF (7.5 mL) solution of ethyl (trimethylsilyl)acetate (**10**) (962 mg, 6.0 mmol) and a THF (7.5 mL) solution of **9a** (892 mg, 5.0 mmol) were successively added at −78 °C over an interval of 15 min. The reaction mixture was warmed to 0 °C and stirred for 4 h. The reaction was quenched by addition of a saturated aqueous solution of $NaHCO_3$, and organic materials were extracted with ether. The organic layer was washed with water, dried over Na_2SO_4, and concentrated. The residue was chromatographed on silica gel (hexane/AcOEt = 99/1) to give the *Z* isomer ***Z*-11a** (552 mg, 50%). ***Z*-11a:** IR (neat) 3080, 3060, 3028, 2987, 2958, 2904, 1726, 1593, 1491, 1442, 1367, 1325, 1250, 1232, 1190, 1097, 1036, 893, 850, 773, 752, 702 cm^{-1}; ^{1}H NMR δ 0.19 (s, 9H), 1.32 (t, J = 7.0 Hz, 3H), 4.23 (q, J = 7.0 Hz, 2H), 6.34 (s, 1H), 7.03−7.05 (m, 2H), 7.22−7.26 (m, 1H), 7.28−7.32 (m, 2H); ^{13}C NMR δ −0.02, 14.3, 60.4, 126.2, 126.6, 127.9, 132.9, 145.3, 165.7, 166.8. Anal. Calcd for $C_{14}H_{20}O_2Si$: C, 67.70; H, 8.11. Found: C, 67.38; H, 8.24.

Similarly, the α,β-unsaturated ester ***Z*-11b** was obtained by the reaction of **9b** with **10**.

Preparation of Ethyl (*E*)-5-Phenyl-3-(trimethylsilyl)-pent-2-enoate (*E*-11b). To a benzene (1 mL) suspension of NaH (55 wt % in mineral oil, 44 mg, 1.0 mmol) was added a benzene (1 mL) solution of diethyl ethoxycarbonylmethylphosphonate (224 mg, 1.0 mmol) under argon. The mixture was stirred for 1 h at room temperature. The acylsilane **9b** (206 mg, 1.0 mmol) in benzene (1 mL) was added to the reaction mixture. After stirring for 2 h at 60 °C, hexane (20 mL) was added to the mixture, and insoluble materials were separated by decantation with hexane. The solvent was removed under reduced pressure. The residue was purified by PTLC (hexane/AcOEt = 98/2) to give ***E*-11b** (150 mg, 54%) and ***Z*-11b** (35 mg, 13%). ***E*-11b**: IR (neat) 3087, 3066, 3032, 2962, 2933, 2906, 2870, 1716, 1604, 1496, 1456, 1367, 1342, 1252, 1196, 1167, 1090, 1059, 1036, 843, 752, 700 cm^{-1}; ^{1}H NMR δ 0.17 (s, 9H), 1.32 (t, J = 7.2 Hz, 3H), 2.67−2.72 (m, 2H), 2.91−2.96 (m, 2H), 4.23 (q, J = 7.2 Hz, 2H), 6.10 (s, 1H), 7.17−7.21 (m, 1H), 7.27−7.31 (m, 4H); ^{13}C NMR δ −1.9, 14.3, 33.7, 35.9, 59.8, 125.8, 127.1, 128.3, 128.4, 142.2, 165.2, 165.4. Anal. Calcd for $C_{16}H_{24}O_2Si$: C, 69.52; H, 8.75. Found: C, 69.41; H, 8.96.

Preparation of (*Z*)-5-Phenyl-3-(trimethylsilyl)pent-2-en-1-ol (*Z*-3e). To a mixture of DIBAL-H (1 M in hexane, 12.3 mL, 12.3 mmol) and CH_2Cl_2 (11.2 mL) was added a CH_2Cl_2 (7 mL) solution of ***Z*-11a** (1.55 g, 5.6 mmol) under argon. After stirring for 2 h at room temperature, the reaction was quenched by dropwise addition of a saturated aqueous solution of $NaHCO_3$. Insoluble materials were filtered off and washed with ether. The filtrate was concentrated and the residue was purified by column chromatography (silica gel, hexane/AcOEt = 4/1) to afford ***Z*-3e** (1.16 g, 88%). ***Z*-3e**: IR (neat) 3462, 3087, 3066, 3032, 2972, 1604, 1496, 1456, 1410, 1252, 1074, 1003, 839, 748, 698, 660 cm^{-1}; ^{1}H NMR δ 0.20 (s, 9H), 1.19 (bs, 1H), 2.37−2.41 (m, 2H), 2.64−2.67 (m, 2H), 4.20 (d, J = 7.0 Hz, 2H), 6.13 (tt, J = 6.9, 1.1 Hz, 1H), 7.16−7.20 (m, 3H), 7.26−7.30 (m, 2H); ^{13}C NMR δ 0.35, 36.9, 39.9, 62.2, 125.8, 128.3, 128.5, 140.7, 142.1, 143.7. Anal. Calcd for $C_{14}H_{22}OSi$: C, 71.73; H, 9.46. Found: C, 71.38; H, 9.59.

The γ-trimethylsilyl allylic alcohols ***Z*-3d** and ***E*-3e** were prepared in a similar manner.

The Brook-type Rearrangement of *Z*-3a with Copper *tert*-Butoxide. CuI (63 mg, 0.33 mmol) and THF (1.5 mL) were placed in a flask and cooled to 0 °C. Lithium *tert*-butoxide (1 M in THF, 0.36 mL, 0.36 mmol) was added under argon and the mixture was stirred for 20 min at room temperature. A THF (1.5 mL) solution of ***Z*-3a** (86 mg, 0.30 mmol) was added to the mixture. After stirring for 24 h at room temperature, the reaction was quenched by addition of 3.5% NH_3 aqueous solution. The organic materials were extracted with ether, dried over Na_2SO_4, and concentrated. The residue was purified by column chromatography (aluminum oxide, hexane/EtOAc = 95/5) to give (*E*)-1-(3-phenylpropan-1-ylidene)-2-(trimethylsiloxy)cyclohexane (**13a**) (51 mg, 59%) and 8,8-dimethyl-9-phenethyl-7-oxa-8-silabicyclo[4.3.0]non-9-ene **14a** (16 mg, 20%). **13a**: IR (neat) 3087, 3066, 3032, 2933, 2862, 1496, 1456, 1252, 1149, 1132, 1105, 1082, 1039, 1018, 926, 908, 839, 748, 698 cm^{-1}; ^{1}H NMR δ 0.09 (s, 9H), 1.19−1.28 (m, 1H), 1.35−1.49 (m, 3H), 1.70−1.82 (m, 3H), 2.30−2.43 (m, 3H), 2.65 (t, J = 7.8 Hz, 2H), 3.98 (dd, J = 7.9, 3.1 Hz, 1H), 5.40 (t, J = 7.0 Hz, 1H), 7.15−7.19 (m, 3H), 7.25−7.28 (m, 2H); ^{13}C NMR δ 0.08, 23.5, 26.5, 27.2, 28.8, 36.3, 37.5, 73.9, 119.2, 125.6, 128.2, 128.5, 141.5, 142.3. Anal. Calcd for $C_{18}H_{28}OSi$: C, 74.93; H, 9.78. Found: C, 74.85; H, 9.80. **14a**: IR (neat) 3086, 3062, 3028, 2933, 2856, 1616, 1604, 1496, 1454, 1335, 1252, 1078, 953, 881, 854, 827, 783, 748, 698 cm^{-1}; ^{1}H NMR δ 0.23 (s, 3H), 0.26 (s, 3H), 0.87−0.98 (m, 1H), 1.06−1.16 (m, 1H), 1.39 (m, 1H), 1.60−1.75 (m, 3H), 2.20−2.25 (m, 1H), 2.46−2.50 (m, 2H), 2.58−2.69 (m, 3H), 4.34 (dd, J = 11.3, 5.2 Hz, 1H), 7.16−7.20 (m, 3H), 7.23−7.30 (m, 2H); ^{13}C NMR δ 0.76, 1.74, 24.3, 26.7, 27.1, 28.8, 36.7, 38.2, 82.7, 125.8, 128.2, 128.4, 128.7, 142.0, 156.3. Anal. Calcd for $C_{17}H_{24}OSi$: C, 74.94; H, 8.88. Found: C, 74.62; H, 9.12.

Allylation of *Z*-3a with Methallyl Chloride (15a). CuI (63 mg, 0.33 mmol) and DMF (1 mL) were placed in a flask and cooled to 0 °C. Lithium *tert*-butoxide (1 M in THF, 0.36 mL, 0.36 mmol) was added under argon and the mixture was stirred for 20 min at room temperature. A DMF (1 mL) solution of **3a** (86 mg, 0.30 mmol) and a DMF (1 mL) solution of **15a** (33 mg, 0.36 mmol) were successively added to the mixture. After stirring for 2 h at room temperature, the reaction was quenched by addition of 3.5% NH_3 aqueous solution. The organic materials were extracted with ether, dried over Na_2SO_4, and concentrated. The residue was dissolved in THF (3 mL), and TBAF (1 M in THF, 0.3 mL, 0.3 mmol) was added to the solution. The mixture was stirred for 2 h at room temperature and diluted with water (15 mL). The organic materials were extracted with AcOEt, washed with 1 M HCl and water, and dried over Na_2SO_4. The solvent was removed under reduced pressure. The residue was purified by PTLC (hexane/AcOEt = 4/1) to afford (*Z*)-2-(2-methyl-6-phenylhex-1-en-4-ylidene)cyclohexanol (**17a**) (65 mg, 80%). **17a**: IR (neat) 3369, 3064, 3026, 2931, 2854, 1645, 1603, 1496, 1452, 1373, 1350, 1335, 1255, 1227, 1176, 1142, 1093, 1074, 1045, 1030, 987, 964, 889, 748, 698 cm^{-1}; ^{1}H NMR δ 1.09−1.20 (m, 1H), 1.32 (bs, 1H), 1.40−1.53 (m, 2H), 1.71 (s, 3H), 1.70−1.82 (m, 2H), 1.89−1.95 (m, 1H), 2.11 (dt, J = 13.7, 3.4 Hz, 1H), 2.25−2.37 (m, 2H), 2.45 (d, J = 13.7 Hz, 1H), 2.63 (t, J = 8.2 Hz, 2H), 2.75 (d, J = 15.9 Hz, 1H), 2.87 (d, J = 15.9 Hz, 1H), 4.68 (s, 2H), 4.77 (s, 1H), 7.16−7.20 (m, 3H), 7.24−7.28 (m, 2H); ^{13}C NMR δ 20.1, 22.9, 25.1, 27.4, 33.7, 34.4, 35.2, 39.8, 66.7, 110.8, 125.8, 128.2, 128.3, 130.0, 136.8, 142.1, 144.4. Anal. Calcd for $C_{19}H_{26}O$: C, 84.39; H, 9.69. Found: C, 84.16; H, 10.15.

The silyl ether (*Z*)-1-[(2-methyl-6-phenylhex-1-en-4-ylidene)]-2-(trimethylsiloxy)cyclohexane (**16a**) (95 mg, 92%) was obtained when the product was purified, before hydrolysis, by column chromatography (aluminum oxide, hexane/AcOEt = 95/5). **16a**: IR (neat) 3064, 3028, 2933, 2852, 1651, 1604, 1496, 1454, 1373, 1360, 1340, 1248, 1176, 1147, 1093, 1074, 1047, 1018, 901, 870, 839, 748, 698 cm^{-1}; ^{1}H NMR δ 0.09 (s, 9H), 1.13−1.23 (m, 1H), 1.34−1.44 (m, 2H), 1.70 (s, 3H), 1.76−1.89 (m, 3H), 2.14−2.26 (m, 2H), 2.34−2.41 (m, 2H), 2.55−2.65 (m, 3H), 2.99 (d, J = 15.6 Hz, 1H), 4.67 (s, 1H), 4.69 (s, 1H), 4.77 (s, 1H), 7.15−7.18 (m, 3H), 7.25−7.28 (m, 2H); ^{13}C NMR δ 0.49,

20.3, 22.8, 25.4, 28.2, 34.3, 35.2, 35.8, 40.1, 67.2, 111.2, 125.7, 127.0, 128.25, 128.30, 138.3, 142.5, 144.1. Anal. Calcd for $C_{22}H_{34}OSi$: C, 77.13; H, 10.00. Found: C, 77.20; H, 10.27.

In a similar manner, the dienyl alcohols **17b**−**h** were obtained.

Palladium-Catalyzed Cross-Coupling of *Z*-3a with Iodobenzene (18a). To a DMF (1 mL) suspension of CuCl (33 mg, 0.33 mmol) and $Pd(PPh_3)_4$ (10 mg, 9 μmol) was added lithium *tert*-butoxide (1 M in THF, 0.36 mL, 0.36 mmol) under argon at 0 °C. After stirring for 20 min at room temperature, a DMF (1 mL) solution of ***Z*-3a** (86 mg, 0.30 mmol) and a DMF (1 mL) solution of **18a** (122 mg, 0.60 mmol) were successively added to the mixture. After stirring for 2 h at room temperature, the reaction was quenched by addition of 3.5% NH_3 aqueous solution (15 mL). The organic materials were extracted with ether, dried over Na_2SO_4, and concentrated. The residue was dissolved in THF (3 mL), and TBAF (1 M in THF, 0.3 mL, 0.3 mmol) was added to the solution. The mixture was stirred for 2 h at room temperature and then diluted with water (15 mL). The organic materials were extracted with AcOEt, washed with 1 M HCl and water, and dried over Na_2SO_4. The solvent was removed under reduced pressure. The residue was purified by PTLC (hexane/AcOEt = 4/1) to afford (*Z*)-2-(1,3-diphenylpropan-1-ylidene)cyclohexanol **19a** (68 mg, 78%). **19a**: IR (neat) 3394, 3059, 3024, 2929, 2854, 1601, 1491, 1452, 1335, 1255, 1142, 1101, 1070, 1030, 1014, 980, 914, 768, 748, 698 cm^{-1}; ^1H NMR δ 1.11−1.25 (m, 2H), 1.38−1.52 (m, 2H), 1.72−1.82 (m, 3H), 2.21(dt, J = 3.9, 13.6 Hz, 1H), 2.46−2.71 (m, 5H), 4.29 (s, 1H), 7.12−7.18 (m, 5H), 7.23−7.28 (m, 3H), 7.32−7.35 (m, 2H); ^{13}C NMR δ; 20.1, 25.1, 27.5, 34.1, 34.4, 36.0, 68.0, 125.8, 126.4, 128.1, 128.2, 128.4, 128.7, 135.0, 137.1, 141.9, 142.4. Anal. Calcd for $C_{21}H_{24}O$: C, 86.26; H, 8.27. Found: C, 86.02; H, 8.48.

The arylation and vinylation products **19b**−**h**, **21a**−**c**, and **22a**,**b** were also obtained by similar reactions of ***Z*-3** with the corresponding aryl and vinylic halides **18** and **20**. The silyl ethers **21a**−**c** were isolated before hydrolysis.

Acknowledgment. This work was partially supported by a Grant-in-Aid for Scientific Research on Priority Area (A) "Exploitation of Multi-Element Cyclic Molecules" (No. 14044022) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Supporting Information Available: Characterization data for compounds ***Z*-3b**−**d**, ***E*-3e**, **7b,c**, ***Z*-8b**, ***Z*-8c**, ***Z*-11b**, **14b**, **17b**−**h**, **19b**−**h**, **21a**−**c**, and **22a,b**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO025973R