Efficient Syntheses of Secondary and Tertiary 2-Aryl- and 2-Heteroaryl-allyl Alcohols

Alan R. Katritzky,* Dorin Toader, and Xiaojing Wang

Center for Heterocyclic Compounds, Department of Chemistry, University of Florida, Gainesville, Florida 32611-7200

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Reactions of α-aryl-, α-heteroaryl-, and α-heteroatom-substituted masked alkenyllithiums with aldehydes and ketones provide a general method for the synthesis of allylic alcohols substituted with an aryl or heteroaryl in the β position and aryl, heteroaryl or alkyl substituents in the α position via a [1,4]-C→O silicon rearrangement. In the case of reactions with enolizable aldehydes and ketones, anhydrous $CeCl_3$ was used as an additive. High diastereoselectivities are observed for allyl alcohols produced from α-substituted aldehydes.

Introduction

Allyl alcohols are substrates in many important synthetic transformations including sigmatropic processes,[1a] palladium-catalyzed π-allyl reactions,[1b] and asymmetric epoxidations.[1c] Consequently, a large amount of work has been aimed at building these versatile molecules and it resulted in methods with considerable generality.

A major group of syntheses utilizes epoxides as a ready source and includes the following: (i) rearrangements of 2,3-epoxy alcohols and their derivatives;[2,3] (ii) reactions of α,β-epoxyalkylsilanes with arylsulfonyl-stabilized anions;[4] (iii) heteroatom-assisted isomerizations of epoxides promoted by bases;[5] (iv) organopalladium addition to unsaturated epoxides;[6] (v) ring openings with organoselenium reagents followed by elimination,[7] with iodotrimethylsilane,[8] or electrochemically.[9]

A second large group of methods is based on the (vi) selective 1,2-reduction of α,β-unsaturated enals and enones.[10] Other important general methods involve rearrangements: (vii) [2,3]-sigmatropic rearrangement of allylic sulfoxides[11] and of allylic hypoiodites prepared in situ from the corresponding iodides;[12] (viii) [1,4]-C→O silicon rearrangements.[13]

Useful reagents that have been developed for the synthesis of allyl alcohols include the following: (ix) 1-chloroalkyl phenyl sulfoxide via α,β-epoxyalkyl sulfoxides;[14] (x) dimethylsulfonium methylide;[15] (xi) α-lithio selenoxides,[16] (xii) α-(diphenylphosphinoyl)acetaldehydes by the intermolecular pinacol cross-coupling with saturated aldehydes;[17] (xiii) β-acyloxy sulfones.[18]

A group of transition metal methods includes the following: (xiv) metal−alkyne complexes of tantalum;[19] (xv) alkene transfer from zirconium[20] or boron[21] to zinc followed by addition to aldehydes or ketones; (xvi) alkenylzirconocene chlorides catalyzed by zinc bromide.[22]

Miscellaneous methods worthy of mention are (xvii) transformations of allylsilanes into allyl alcohols via allyl selenides[23] and (xviii) reductive eliminations of γ-(phenylthio)-β-nitro alcohols with tributyltin hydride.[24]

Most of the methods listed above provide allylic alcohols unsubstituted in the 2-position. The few available methods which can provide 2-substituted allylic alcohols are as follows: (vi) selective reduction of enones and enals[10] which are limited by the availability of the starting materials; (xiv−xvi) transition metal methods which suffer from occasional poor regiochemistry[19] and

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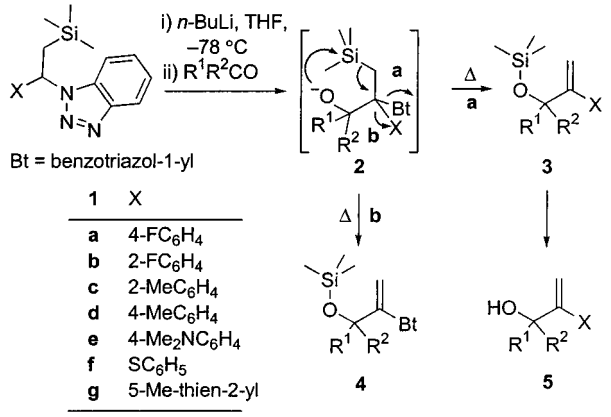
Scheme 1[a]



[a]For the significance of R^1 and R^2 in **3**, **4**, and **5** see Table 1 and Table 2

are limited by the availability of the precursors alkynes,[20] boranes,[21] or zirconocenes;[22] (viii) the [1,4]-C→O silicon rearrangement for 2-alkyl-substituted allylic alcohols,[13b] which has not been applied yet to the 2-aryl analogues.

We have previously presented our preliminary results of new masked (α-arylalkenyl)lithium reagents which can be used for the synthesis of secondary allylic alcohols possessing an aryl substituent in the 2-position.[25] A detailed account of that work together with the further scope and limitations of this methodology is presented herein.

Results and Discussion

Reagents **1a**−**d** were prepared as previously described.[25] Three novel reagents **1e**−**g** were prepared by the lithiation of the corresponding methylenebenzotriazolyl substrates and nucleophilic displacement of chlorine from (chloromethyl)trimethylsilane in good yields. Thus, the electron-rich **1e**, phenylthio **1f**, and heteroaromatic **1g**, precursors for masked α-substituted-alkenyllithiums, are made available.

When 0.1 M THF solutions of **1a**−**g** were treated with *n*-BuLi at −78 °C, the corresponding α-benzotriazolyl carbanions were formed. These anions underwent quantitative addition to nonenolizable aldehydes and afforded intermediate lithium alkoxides **2** (Scheme 1). The existence of these intermediates was proven by quenching the reaction mixture with water at −78 °C. In most cases, upon simple warming from −78 °C to room temperature, lithium alkoxides **2** undergo a [1,4]-C→O Brook rearrangement[13,26] where benzotriazole acts as a leaving group (Scheme 1) and the trimethylsilyl ethers **3** are obtained (Table 1). This process is most likely intramolecular since the stereochemistry of the intermediate alkoxides **2** dramatically influences the reaction conditions required. When either the phenyl group of the incoming nucleophile (as is the case with **1c**) or of the aromatic aldehyde (as is the case with 2-anisaldehyde) possesses a bulky substituent in the 2- or 6-position, the rearrangement of the alkoxide **2** needs to be accomplished under harsher reaction conditions, i.e. heating at 90 °C for 5 h in the case of **3b** or reflux in THF for 5 h in the case of **5f** (Experimental Section and Table 2). Even harsher conditions are required when both the substrate (*o*-anisaldehyde) and the reagent (**1c**) possess a substituent in the 2-position. Thus, heating at 115 °C for 8 h was necessary to accomplish the rearrangement to afford **3j**. However, significant retro-addition was observed in this case and starting materials were recovered. A bulky substituent in the α position of the alkoxide has a similar effect, probably by preventing **2** from reaching the appropriate conformation for the rearrangement. Thus **3f** and **7** are obtained by heating at 115 °C for 24 h and 120 °C for 1 h, respectively. A fluorine atom in the 2-position shows no steric effect due to the short C−F bond, and for **3a**,**c**−**f** the rearrangement takes place upon warming to room temperature.

The fact that the preparation of **3i** necessitated quite harsh reaction conditions is puzzling since steric factors cannot be invoked to explain this finding. The electron-donating 4-(*N*,*N*-dimethylamino)phenyl is known to facilitate the ionization of the benzotriazole;[27] therefore, this reaction is controlled by conformational rather than electronic factors. In the case of **1f** (X = SPh), the phenylthio group is a better leaving group than benzotriazole; consequently the benzotriazolyl moiety is retained in the allyl ether product **4**.

Table 1. Synthesis of Trimethylsilyl Allyl Ethers 3a−j, 4, and 7

				reacn conditions[a]		
product	X	R^1	R^2	temp (°C)/ time (h)	additive/ equiv	yield (%)
3a	2-FC_6H_4	H	3-$MeOC_6H_4$	rt/16		52
3b	2-FC_6H_4	H	2-$MeOC_6H_4$	90/5		22[b]
3c	2-FC_6H_4	H	$CH_2CH_2C_6H_5$	rt		77
3d	2-FC_6H_4		$-(CH_2)_5-$	rt	$CeCl_3$/1	75
3e	2-FC_6H_4	H	*i*-Pr	rt	$CeCl_3$/1	67
3f	2-FC_6H_4	H	*c*-C_6H_{11}	115/24		67
3g	4-MeC_6H_4	H	*t*-Bu	rt		87
3h	C_6H_5	H	3-$MeOC_6H_4$	rt		72
3i	4-$Me_2NC_6H_4$	H	Ph	105/7		52
3j	2-MeC_6H_4	H	2-$MeOC_6H_4$	115/8		53[b,c]
4	Bt	H	Ph	rt		70
7	2-FC_6H_4	H	CH(Me)Ph	120/1		56

[a] All addition reactions were performed at −78 °C. These reaction conditions refer to the rearrangement step. [b] Significant *O*-desilylation was observed, and the free allyl alcohol was isolated. [c] Yield calculated on recovered material.

Table 2. Synthesis of Allyl Alcohols 5a−j

				reacn conditions solvent/additive/ time (h)	yield (%)
product	X	R^1	R^2		
5a	2-FC_6H_4	H	2-$MeOC_6H_4$	*a*	40
5b	2-FC_6H_4	H	$CH_2CH_2C_6H_5$	MeOH/H^+/1	97
5c	2-FC_6H_4	H	*c*-C_6H_{11}	THF/TBAF/4	93
5d	2-FC_6H_4	H	*i*-Pr	THF/TBAF/3.5	79
5e	2-FC_6H_4		$-(CH_2)_5-$	MeOH/H^+/1	100
5f	2-MeC_6H_4	H	3-$MeOC_6H_4$	THF/TBAF/2	70[b]
5g	4-$Me_2NC_6H_4$	H	Ph	MeOH/H^+/2	48[c]
5h	5-Me-thien-2-yl	H	2-$MeOC_6H_4$	silica gel	56[d]
5i	2-MeC_6H_4	H	2-$MeOC_6H_4$	*a*	46[e]
5j	2-FC_6H_4	H	CH(Me)Ph	MeOH/H^+/1	97

[a] Isolated after workup along with the silyl ether. [b] Overall yield without isolation of **3**. [c] Significant addition of methanol to the double bond was observed. [d] Hydrolysis occurred during column chromatography. [e] Yield calculated on recovered starting material.

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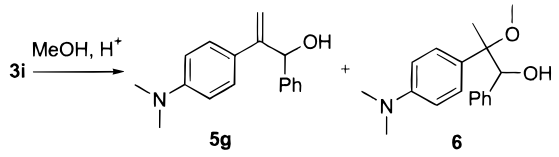
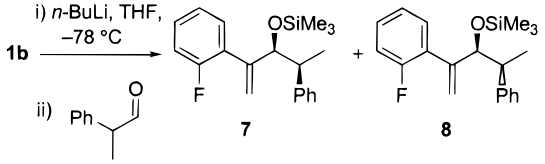
Scheme 2



Scheme 3



The reactions involving enolizable aldehydes posed some additional challenges due to the possibility of proton abstraction by the hard alkanyl anion. While reactions of hydrocinnamic aldehyde and cyclohexyl carboxaldehyde did not need any additives and the additions were the predominant process, isobutyric aldehyde and cyclohexanone underwent enolization. Formation of Ce(III) reagent[28] by transmetalation with 1 equiv of anhydrous $CeCl_3$[29] prevents the enolization, and addition to the carbonyl is successfully accomplished to give allyl ethers **3d**,**e** in 75 and 67% yield, respectively (Table 1).

Allyl trimethylsilyl ethers **3a**−**i** and **4** survive the workup in most cases and can be isolated by chromatography on silica gel. In the case of 2-thiophenyl-substituted allylic alcohol **5h**, the intermediate silyl ether could not be purified on silica gel due to complete hydrolysis to afford the free alcohol (Table 2). Significant hydrolysis was observed during workup of the reaction mixture in the case of alcohol **5a**. The 2 M NaOH aqueous solution used for the extraction of benzotriazole caused partial hydrolysis of the silyl ether. In other cases where the silyl ether was isolated, the cleavage of Si−O bond was accomplished with 1 M tetrabutylammonium fluoride (TBAF) in THF at room temperature for 2−4 h in high yields (Table 2). A procedure which did not isolate the intermediate silyl ether afforded the allyl alcohol **5f** in 70% overall yield (Table 2). The main drawback of the TBAF procedure is the necessity of removing the tetrabutylammonium salt. A more convenient procedure for the hydrolysis of silyl ethers is stirring the substrate with a catalytic amount of *p*-toluenesulfonic acid in methanol at room temperature. In this way **5b**,**e** are obtained in quantitative yield. When electron-rich substrate **3i** was subjected to hydrolysis in methanol under acidic catalysis, the desired **5g** was obtained in 48% yield (Table 2) while adduct **6** was formed as a byproduct in 37% isolated yield (Scheme 2). The formation of compound **6** can be explained by a process which comprises the protonation of the styrene followed by trapping of the carbocation by the solvent. When **6** is treated with catalytic amounts of acid in chloroform, it slowly reverts back to **5g**. Therefore, the TBAF procedure is recommended in case of allyl trimethylsilyl ethers with an electron-rich aryl group in the 2-position.

To study the diastereoselectivity of the addition to the carbonyl, the reaction of **1b** was attempted with racemic α-phenylpropionaldehyde (Scheme 3). The crude mixture obtained after reaction was subjected to GC and GC-MS analysis. A 13.3:1 ratio of two diastereomers with molecular weight 328 and very similar fragmentation patterns were found. According to the Felkin−Anh model of nucleophilic attack on aldehyde, compound **7** is most likely the major diastereomer and was isolated in 56% yield. Compound **8**, formed in only a minute amount, was not isolated but was detected in the ^{1}H NMR spectrum of the crude mixture. This high degree of diastereoselectivity is probably due to the bulkiness of the carbanion derived from **1b**.

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Conclusion

Reactions of α-aryl-, α-heteroaryl-, and α-heteroatom-substituted masked alkenyllithiums with aldehydes and ketones provide a general method for the synthesis of allylic alcohols substituted with an aryl or heteroaryl in the β position and aryl, heteroaryl, or alkyl substituent in the α position via a [1,4]-C→O silicon rearrangement. The trimethylsilyl ethers of these allylic alcohols are stable compounds and undergo cleavage of the O−Si bond under basic or acidic conditions.

Experimental Section

General Procedures. Melting points were determined with a MEL-TEMP capillary melting point apparatus equipped with a Fluke 51 digital thermometer. NMR spectra were recorded in $CDCl_3$ with tetramethylsilane as the internal standard for ^{1}H (300 MHz) or solvent as the internal standard for ^{13}C (75 MHz). THF was distilled from sodium/benzophenone under nitrogen immediately prior to use. All reactions with air-sensitive compounds were carried out under an argon atmosphere. Column chromatography was conducted with silica gel 230−400. 1-(5-Methyl-2-thienyl)-1*H*-benzotriazole, 1-(4-dimethyaminobenzyl)-1*H*-benzotriazole,[29] and **1a**−**d**[25] were prepared according to previously reported procedures. Cerium(III) chloride was dried under high vacuum as described in the literature.[28a]

General Procedure for the Synthesis of Compounds 1e−**g.** *n*-BuLi (1.6 M, 2.5 mL, 4 mmol) was added to a solution of the corresponding benzotriazolylarylmethane (4 mmol) in THF (50 mL) at −78 °C under argon. After 15 min of stirring, (chloromethyl)trimethylsilane (0.49 g, 4 mmol) was added. The reaction mixture was allowed to warm to room temperature overnight, before being washed with brine (2 × 20 mL) and dried ($MgSO_4$), and the solvent was removed under reduced pressure. The crude oil was subjected to flash chromatography with 3:1 hexanes/ethyl ether to give the pure product.

4-[1-(1*H*-1,2,3-Benzotriazol-1-yl)-2-(trimethylsilyl)ethyl]-*N*,*N*-dimethylaniline (1e): white microcrystals (89% yield), mp 134.9−136.2 °C; ^{1}H NMR δ 0.13 (s, 9H), 1.94−2.13 (m, 2H), 2.91 (s, 6H), 5.96 (t, J = 8.0 Hz, 1H), 6.65 (d, J = 8.0 Hz, 2H), 7.26(7.38 (m, 4H), 7.45 (d, J = 7.8 Hz, 1H), 8.02 (d, J = 7.7 Hz, 1H); ^{13}C NMR δ −1.6 (3C), 23.3, 40.3 (2C), 61.1, 110.3, 112.2 (2C), 119.8, 123.5, 126.6, 127.8 (2C), 128.0, 132.1, 146.4, 150.2. Anal. Calcd for $C_{19}H_{26}N_4Si$: C, 67.41; H, 7.74; N, 16.55. Found: C, 67.45; H, 7.44; N, 16.61.

1-[1-(Phenylthio)-2-(trimethylsilyl)ethyl]-1*H*-1,2,3-benzotriazole (1f): yellow prisms (74% yield), mp 64.5−65.5 °C; ^{1}H NMR δ −0.01 (s, 9H), 1.70−1.79 (m, 1H), 1.92−2.00 (m, 1H), 6.32−6.37 (m, 1H), 7.00−7.16 (m, 5H), 7.34 (t, J = 7.9 Hz, 1H), 7.45 (t, J = 7.4 Hz, 1H), 7.75 (d, J = 8.3 Hz, 1H), 8.00 (d, J = 8.3 Hz, 1H); ^{13}C NMR δ −1.8 (3C), 23.7, 65.6, 111.3, 120.0, 123.8, 126.8, 128.6, 128.8 (2C), 131.2, 131.7, 133.3 (2C), 146.6. Anal. Calcd for $C_{17}H_{21}N_3SSi$: C, 62.34; H, 6.46; N, 12.83. Found: C, 62.44; H, 6.66; N, 12.79.

1-[1-(5-methylthiophen-2-yl)-2-(trimethylsilyl)ethyl]-1*H*-1,2,3-benzotriazole (1g): light yellow prisms (90% yield),

mp 78.4−80.3 °C (hexanes); ^{1}H NMR δ (0.15 (s, 9H), 1.93 (dd, J = 14.6 and 7.4 Hz, 1H), 2.05 (dd, J = 14.6 and 8.8 Hz, 1H), 2.38 (s, 3H), 6.28 (t, J = 8.0 Hz, 1H), 6.56 (d, J = 2.3 Hz, 1H), 6.88 (d, J = 3.3 Hz, 1H), 7.32 (t, J = 7.5 Hz, 1H), 7.40 (t, J = 7.0 Hz, 1H), 7.42 (d, J = 8.2 Hz, 1H), 8.03 (d, J = 8.3 Hz, 1H); ^{13}C NMR δ (1.8, 15.2, 24.1, 57.0, 110.3, 120.0, 123.7, 124.6, 125.4, 126.9, 131.6, 140.3, 141.9, 146.5. Anal. Calcd for $C_{16}H_{21}N_3SSi$: C, 60.91; H, 6.71; N, 13.32. Found: C, 61.29; H, 6.86; N, 12.97.

General Procedure for the Synthesis of Compounds 3a−j, 4, 5a−i, and 7. The corresponding benzotriazole derivative **1** (2 mmol) was dissolved in THF (20 mL) and cooled to −78 °C, and *n*-BuLi in hexanes (1.6 M, 1.25 mL, 2 mmol) was added. For the preparation of compounds **3d**,**e**, anhydrous cerium(III) chloride (0.493 g, 2 mmol) was added. After 30 min of stirring, the corresponding aldehyde (2 mmol) was added and the mixture was allowed to warm to room temperature over 16 h. In the case of compounds **3b**,**f**,**i**, and **j** the solvent was distilled out under a stream of argon and the remaining oil was heated at the temperature and for the time indicated in Table 1 followed by the addition of methylene chloride (40 mL). The reaction mixture was washed with brine (2 × 20 mL) and dried in case of compounds **3a**,**g**,**h** and **4**. In case of **3b**−**f**,**i** the reaction mixture was washed with sodium hydroxide aqueous solution (2 M, 40 mL) and dried. After solvent removal the remaining oil was subjected to flash column chromatography with 5:1 hexanes/diethyl ether in the case of **3a,g,h** and **4** to give the pure product. For all other cases the chromatographic system is indicated individually. Compound **5a** was obtained alongside with **3b**, and compound **5i** was obtained alongside with **3j**. Compound **5h** was obtained after the column chromatography due to desilylation.

{**[2-(4-Fluorophenyl)-1-(3-methoxyphenyl)allyl]oxy**}**trimethylsilane (3a):** colorless oil (52% yield); ^{1}H NMR δ 0.11 (s, 9H), 3.71 (s, 3H), 5.35 (s, 1H), 5.44 (s, 1H), 5.54 (s, 1H), 6.71−6.73 (m, 1H), 6.84−6.90 (m, 4H), 7.14 (t, J = 8.3 Hz, 1H), 7.21−7.26 (m, 2H); ^{13}C NMR δ 0.0 (3C), 55.0, 77.0, 112.4 (d, J = 5.9 Hz), 114.3, 114.5, 114.8, 119.1 (2C), 129.0 (d, J = 7.1 Hz, 2C), 135.5, 144.1, 149.8, 159.5, 162.1 (d, J = 244.6 Hz). Anal. Calcd for $C_{19}H_{23}FO_2Si$: C, 69.06; H, 7.01. Found: C, 69.17; H, 7.34.

(2-(2-Fluorophenyl)-1-[2-(methyloxy)phenyl]prop-2-enyloxy)trimethylsilane (3b): purified by column chromatography with 50:1 hexanes/ethyl acetate, colorless oil (22% yield); ^{1}H NMR δ 0.22 (s, 9H), 3.81 (s, 3H), 5.39 (s, 1H), 5.70 (s, 1H), 6.25 (s, 1H), 6.89 (d, J = 8.0 Hz, 1H), 7.04−7.16 (m, 3H), 7.21 (t, J = 7.4 Hz, 1H), 7.30−7.35 (m, 2H), 7.59 (d, J = 7.6 Hz, 1H); ^{13}C NMR δ −0.1 (3C), 55.2, 69.0, 110.2, 115.1 (d, J = 22.7 Hz), 115.3, 120.5, 123.4 (d, J = 3.4 Hz), 128.2 (d, J = 13.4 Hz), 128.5 (d, J = 8.1 Hz), 130.9 (d, J = 4.4 Hz), 147.0, 156.3, 160.0 (d, J = 245.1 Hz). Anal. Calcd for $C_{19}H_{23}FO_2Si$: C, 69.05; H, 7.02. Found: C, 69.08; H, 7.31.

{**[2-(2-Fluorophenyl)-1-(2-phenylethyl)prop-2-enyl]oxy**}**trimethylsilane (3c):** purified by column chromatography with 100:1 hexanes/ethyl acetate, colorless oil (75% yield); ^{1}H NMR δ 0.19 (s, 9H), 1.60−1.83 (m, 2H), 2.50−2.60 (m, 1H), 2.70−2.80 (m, 1H), 4.62−4.64 (m, 1H), 5.20 (s, 1H), 5.57 (s, 1H), 6.99−7.14 (m, 4H), 7.19−7.26 (m, 5H); ^{13}C NMR δ 0.1 (3C), 31.8, 38.4, 73.7, 115.4, 115.7, 124.0 (d, J = 3.3 Hz), 125.6, 128.2, 128.4, 129.0 (d, J = 8.1 Hz), 130.8 (d, J = 4.4 Hz), 142.3, 147.5, 159.7 (d, J = 245.1 Hz). Anal. Calcd for $C_{20}H_{25}FOSi$: C, 73.13; H, 7.67. Found: C, 72.85; H, 7.87.

(1-[1-(2-Fluorophenyl)ethenyl]cyclohexyloxy)trimethylsilane (3d): purified by column chromatography with hexanes, colorless oil (75% yield); ^{1}H NMR δ −0.19 (s, 9H), 0.84−0.90 (m, 1H), 1.09 (br s, 3H), 1.16−1.36 (m, 7H), 4.74 (s, 1H), 5.24 (s, 1H), 6.61−6.69 (m, 2H), 6.80−6.87 (m, 1H), 6.90−6.96 (m, 1H); ^{13}C NMR δ 2.8 (3C), 22.6, 25.6, 37.8, 77.7, 115.3 (d, J = 23.3 Hz), 116.8, 123.0 (d, J = 3.2 Hz), 128.4 (d, J = 8.0 Hz), 129.5 (d, J = 16.2 Hz), 131.7 (d, J = 3.5 Hz), 149.8, 159.8 (d, J = 243.5 Hz). Anal. Calcd for $C_{17}H_{25}FOSi$: C, 69.81; H, 8.63. Found: C, 69.72; H, 8.89.

{**[2-(2-Fluorophenyl)-1-(1-methylethyl)prop-2-enyl]oxy**}**trimethylsilane (3e):** purified by column chromatography with hexanes, colorless oil (67% yield); ^{1}H NMR δ −0.22 (s, 9H), 0.38 (d, J = 6.8 Hz, 3H), 0.48 (d, J = 6.6 Hz, 3H), 1.04−1.18 (m, 1H), 4.01 (s, 1H), 4.82 (s, 1H), 5.09 (d, J = 1.7 Hz, 1H), 6.59−6.71 (m, 2H), 6.80−6.90 (m, 2H); ^{13}C NMR δ 0.2 (3C), 15.4, 20.2, 31.4, 78.6, 115.6 (d, J = 22.8 Hz), 116.3, 123.9 (d, J = 3.5 Hz), 128.8 (d, J = 8.1 Hz), 128.9, 130.6 (d, J = 4.5 Hz), 146.6, 159.8 (d, J = 244.8 Hz). Anal. Calcd for $C_{15}H_{23}FOSi$: C, 67.62; H, 8.70. Found: C, 67.75; H, 9.03.

{**[1-Cyclohexyl-2-(2-fluorophenyl)prop-2-enyl]oxy**}**trimethylsilane (3f):** purified by column chromatography with 100:1 hexanes/ethyl acetate, colorless oil (67% yield); ^{1}H NMR δ 0.17 (s, 9H), 1.07−1.16 (m, 6H), 1.50−1.71 (m, 5H), 4.37 (s, 1H), 5.23 (s, 1H), 5.47 (s, 1H), 7.00−7.12 (m, 2H), 7.21−7.31 (m, 2H); ^{13}C NMR δ 0.2 (3C), 26.2, 26.2, 26.5, 26.5, 30.7, 41.4, 78.7, 115.6 (d, J = 23.0 Hz), 116.5, 123.9 (d, J = 3.3 Hz), 128.7 (d, J = 8.3 Hz), 128.9, 130.6 (d, J = 4.4 Hz), 146.0, 159.8 (d, J = 249.0 Hz). Anal. Calcd for $C_{18}H_{27}FOSi$: C, 70.54; H, 8.88. Found: C, 70.41; H, 9.04.

{**[1-*tert*-Butyl-2-(4-methylphenyl)-allyl]oxy**}**trimethylsilane (3g):** colorless oil (87% yield); ^{1}H NMR δ 0.15 (s, 9H), 0.73 (s, 9H), 2.33 (s, 3H), 4.34 (s, 1H), 5.28 (s, 2H), 7.10 (d, J = 8.0 Hz, 2H), 7.28 (d, J = 8.0 Hz, 2H); ^{13}C NMR δ 0.3 (3C), 21.1, 26.7 (3C), 36.5, 81.3, 115.9, 126.7 (2C), 128.9 (2C), 136.7, 140.3, 150.5. Anal. Calcd for $C_{17}H_{28}OSi$: C, 73.85; H, 10.21. Found: C, 74.08; H, 10.42.

{**[1-(3-Methoxyphenyl)-2-(4-methylphenyl)allyl]oxy**}**trimethylsilane (3h):** colorless oil (72% yield); ^{1}H NMR δ 0.11 (s, 9H), 2.27 (s, 3H), 3.74 (s, 3H), 5.40 (s, 1H), 5.44 (s, 1H), 5.57 (s, 1H), 6.72 (dd, J = 8.4 and 1.8 Hz, 1H), 6.89−6.91 (m, 2H), 7.02 (d, J = 8.0 Hz, 2H), 7.13−7.20 (m, 3H); ^{13}C NMR δ 0.1 (3C), 21.0, 55.0, 76.7, 112.5 (2C), 113.5, 119.3, 127.1 (2C), 128.6 (2C), 128.9, 136.7, 136.9, 144.5, 150.5, 159.5. Anal. Calcd for $C_{20}H_{26}O_2Si$: C, 73.57; H, 8.03. Found: C, 73.97; H, 8.31.

***N*,*N*-Dimethyl-4-((1-phenyl[(trimethylsilyl)oxy]methyl)ethenyl)aniline (3i):** purified by column chromatography with 50:1hexanes/ethyl acetate, yellow oil (52% yield); ^{1}H NMR δ 0.60 (s, 9H), 3.28 (s, 6H), 5.86 (s, 1H), 5.87 (s, 1H), 6.10 (s, 1H), 7.10 (d, J = 8.7 Hz, 2H), 7.62 (d, J = 7.1 Hz, 2H), 7.67−7.71 (m, 3H), 7.84 (d, J = 7.4 Hz, 2H); ^{13}C NMR δ 0.1 (3C), 40.2, 76.8, 111.1, 111.8, 126.7, 126.8, 127.3, 120.5, 127.8, 128.0, 143.1, 149.7, 150.0. Anal. Calcd for $C_{20}H_{27}NOSi$: C, 73.79; H, 8.36; N, 4.30. Found: C, 73.51; H, 8.53; N, 4.40.

Trimethyl{**[1-[2-(methyloxy)phenyl]-2-(2-methylphenyl)prop-2-enyl]oxy**}**silane (3j):** yellow oil (53% yield); ^{1}H NMR δ 0.39 (s, 9H), 2.60 (s, 3H), 3.97 (s, 3H), 5.32 (s, 1H), 5.75 (s, 1H), 6.25 (s, 1H), 7.12 (d, J = 8.3 Hz, 1H), 7.31(7.63 (m, 6H), 7.86 (d, J = 7.5 Hz, 1H); ^{13}C NMR δ (0.21, 19.5, 55.2, 70.2, 110.1, 113.3, 120.4, 124.6, 126.6, 127.9, 128.0, 129.4, 129.6, 131.1, 135.9, 140.8, 151.4, 159.0. Anal. Calcd for $C_{20}H_{26}O_2Si$: C, 73.57; H, 8.03. Found: C, 73.51; H, 8.44.

{**[2-[1-(1,2,3-Benzotriazol-1-yl)]-1-(3-methoxyphenyl)-allyl]oxy**}**trimethylsilane (4):** colorless oil (70% yield); ^{1}H NMR δ 0.08 (s, 9H), 5.53 (s, 1H), 5.60 (s, 1H), 6.16 (s, 1H), 7.13−7.20 (m, 3H), 7.29−7.34 (m, 3H), 7.38−7.48 (m, 2H), 8.00 (d, J = 8.3 Hz, 1H); ^{13}C NMR δ −0.1 (3C), 74.2, 107.8, 110.5, 119.8, 124.0, 126.7 (2C), 127.8, 127.9, 128.1 (2C), 132.9, 140.4, 145.7, 146.4. Anal. Calcd for $C_{18}H_{21}N_3OSi$: C, 66.84; H, 6.89; N, 12.99. Found: C, 66.51; H, 6.89; N, 13.06.

2-(2-Fluorophenyl)-1-[2-(methyloxy)phenyl]prop-2-en-1-ol (5a): yellow oil (40% yield); ^{1}H NMR δ 3.12 (d, J = 5.3 Hz, 1H), 3.90 (s, 3H), 5.49 (s, 1H), 5.69 (s, 1H), 6.04 (br s, 1H), 6.95−7.05 (m, 2H), 7.10−7.17 (m, 2H), 7.27−7.44 (m, 4H); ^{13}C NMR δ 55.3, 71.9 (d, J = 3.0 Hz), 110.7, 115.3 (d, J = 22.7 Hz), 116.0, 123.6 (d, J = 3.4 Hz), 128.1, 128.4, 128.8 (d, J = 6.2 Hz), 129.8, 130.4 (d, J = 4.4 Hz), 146.2, 157.0, 159.7 (d, J = 245.4 Hz). Anal. Calcd for $C_{16}H_{15}FO_2$: C, 74.40; H, 5.85. Found: C, 74.50; H, 5.98.

1-[2-(Methyloxy)phenyl]-2-(2-methylphenyl)prop-2-en-1-ol (5i): colorless oil (46%); ^{1}H NMR δ 2.41 (s, 3H), 3.23 (d, J = 6.7 Hz, 1H), 3.94 (s, 3H), 5.27 (s, 1H), 5.68 (s, 1H), 5.90 (d, J = 6.7 Hz, 1H), 7.05 (d, J = 8.0 Hz, 1H), 7.13 (t, J = 7.4 Hz, 1H), 7.22 (d, J = 7.4 Hz, 1H), 7.28−7.35 (m, 3H), 7.43−7.49 (m, 2H); ^{13}C NMR δ 19.4, 55.2, 73.5, 110.7, 113.8, 120.6, 124.9,

126.9, 128.2, 128.6, 129.2, 129.8, 135.7, 140.3, 150.8, 156.9. Anal. Calcd for $C_{17}H_{18}O_2$: C, 80.28; H, 7.13. Found: C, 80.12; H, 7.29.

1-[2-(Methyloxy)phenyl]-2-(5-methylthiophen-2-yl)prop-2-en-1-ol (5h): purified by column chromatography with 3:1 hexanes/ethyl acetate, dark-red oil (56%); ^{1}H NMR δ 2.41 (s, 3H), 2.68 (d, J = 4.9 Hz, 1H), 3.89 (s, 3H), 5.29 (s, 1H), 5.57 (s, 1H), 5.98 (d, J = 4.7 Hz, 1H), 6.54 (d, J = 2.8 Hz, 1H), 6.77 (d, J = 3.4 Hz, 1H), 6.90−6.94 (m, 2H), 7.24−7.34 (m, 2H); ^{13}C NMR δ 15.3, 55.5, 69.8, 110.6, 111.1, 120.8, 124.2, 125.4, 128.0, 129.1, 129.9, 138.8, 140.6, 142.8, 157.1. HRMS calcd for $C_{15}H_{16}O_2S$, 260.0810; found, *m/e* 260.0863.

2-(2-Fluorophenyl)-1-(1-phenylethyl)prop-2-enyl trimethylsilyl ether (7): separated by column chromatography with 50:1 hexanes/ethyl acetate, colorless oil (56%); ^{1}H NMR δ 0.14 (s, 9H), 1.45 (d, J = 6.9 Hz, 3H), 2.93−3.00 (m, 1H), 5.04 (s, 1H), 5.55 (s, 1H), 5.85 (s, 1H), 7.32−7.45 (m, 4H), 7.49−7.59 (m, 4H); ^{13}C NMR δ −0.4, 11.8, 42.6, 78.0 (d, J = 3.9 Hz), 115.7 (d, J = 22.9 Hz), 116.4, 124.2 (d, J = 3.4 Hz), 126.0, 127.9, 128.2, 129.0 (d, J = 8.2 Hz), 130.5 (d, J = 18.3 Hz), 145.1, 146.7, 159.7 (d, J = 244.7 Hz). Anal. Calcd for $C_{20}H_{25}$FOSi: C, 73.13; H, 7.67. Found: C, 73.44; H, 7.96.

Preparation of 1-(3-Methoxyphenyl)-2-(2-methylphenyl)-2-propen-1-ol (5f). 1-[1-(2-Methylphenyl)-2-(trimethylsilyl)ethyl]-1*H*-1,2,3-benzotriazole (**1c**) (0.619 g, 2 mmol) was dissolved in THF (50 mL) and cooled to −78 °C, and *n*-BuLi in hexanes (1.6 M, 1.25 mL, 2 mmol) was added. After 15 min of stirring, 3-methoxybenzaldehyde (0.24 mL, 2 mmol) was added, and the mixture was allowed to warm to room temperature over 16 h and stirred under reflux for 5 h. The reaction mixture was washed with brine (2 × 20 mL) and dried. After solvent removal the remaining oil was dissolved in TBAF in THF (1 M, 2.4 mL, 2.4 mmol) and stirred at room temperature for 2 h. After solvent removal, the remaining oil was subjected to flash column chromatography with 1:1 hexanes/diethyl ether to give the pure product (colorless oil, 0.36 g, 70%): ^{1}H NMR δ 2.07 (s, 3H), 2.58 (br s, 1H), 3.65 (s, 3H), 5.01 (s, 1H), 5.30 (s, 1H), 5.56 (s, 1H), 6.73−6.79 (m, 3H), 6.86 (d, J = 7.2 Hz, 1H), 6.99−7.15 (m, 4H); ^{13}C NMR δ 19.5, 55.0, 77.2, 112.0, 113.4, 113.9, 119.1, 125.0, 127.1, 129.0, 129.1, 129.9, 135.8, 139.5, 143.2, 150.9, 159.3. Anal. Calcd for $C_{17}H_{18}O_2$: C, 80.28; H, 7.13. Found: C, 80.09; H, 7.48.

General Procedure for the Preparation of Compounds 5b,e,g,j and 6. Silyl ether **3c**, **3e**, or **3i** (1 mmol) was dissolved in methanol (24 mL), and *p*-toluenesulfonic acid monohydrate (0.08 g, 0.4 mmol) was added. The reaction mixture was stirred at room temperature for 1 h, and the excess methanol was removed under reduced pressure. The residue was dissolved in methylene chloride (20 mL), washed with saturated aqueous sodium bicarbonate solution (20 mL) and water (20 mL), and dried (Na_2SO_4), and the solvent was removed under reduced pressure to give the pure product.

2-(2-Fluorophenyl)-5-phenylpent-1-en-3-ol (5b): colorless oil (97% yield); ^{1}H NMR 1.57−1.81 (m, 2H), 2.19 (br s, 1H), 2.50−2.75 (m, 2H), 4.48 (t, J = 6.6 Hz, 1H), 5.14 (s, 1H), 5.47 (s, 1H), 6.88−7.11 (m, 9H); ^{13}C NMR δ 31.6, 37.4, 73.2, 115.4, 115.7, 124.0 (d, J = 3.3 Hz), 125.7, 127.8 (d, J = 15.1 Hz), 128.3 (d, J = 7.6 Hz), 129.1 (d, J = 8.1 Hz), 130.5 (d, J = 3.8 Hz), 141.8, 147.5, 159.6 (d, J = 244.5 Hz). Anal. Calcd for $C_{17}H_{17}$FO: C, 79.66; H, 6.69. Found: C, 79.38; H, 6.91.

1-[1-(2-Fluorophenyl)ethenyl]cyclohexanol (5e): colorless oil (100% yield); ^{1}H NMR δ 1.08−1.20 (m, 1H), 1.52−1.73 (m, 10H), 5.03 (s, 1H), 5.58 (s, 1H), 7.01−7.11 (m, 2H), 7.16−7.29 (m, 2H); ^{13}C NMR δ 21.8, 25.4, 36.3, 73.6, 114.9, 115.2 (d, J = 23.3 Hz), 123.2 (d, J = 3.3 Hz), 128.7 (d, J = 8.0 Hz), 128.9, 131.7 (d, J = 4.0 Hz), 151.6, 159.6 (d, J = 242.2 Hz). Anal. Calcd for $C_{14}H_{17}$FO: C, 76.33; H, 7.78. Found: C, 76.19; H, 8.03.

2-[4-(Dimethylamino)phenyl]-1-phenylprop-2-en-1-ol (5g): microcrystals, mp 88.6−90.0 °C, (48% yield); ^{1}H NMR δ 2.26 (br s, 1H), 2.88 (s, 6H), 5.28 (s, 1H), 5.43 (s, 1H), 5.66 (s, 1H), 6.59 (d, J = 8.3 Hz, 2H), 7.21−7.32 (m, 5H), 7.41 (d, J = 6.8 Hz, 2H); ^{13}C NMR δ 40.3, 75.7, 110.9, 112.1, 126.8, 126.9, 127.4, 127.5, 128.3, 142.2, 149.6, 150.0. Anal. Calcd for $C_{17}H_{19}NO$: C, 80.60; H, 7.56; N, 5.53. Found: C, 80.48; H, 7.87; N, 5.57.

2-(2-Fluorophenyl)-4-phenylpent-1-en-3-ol (5j): colorless oil (97% yield); ^{1}H NMR δ 1.21 (d, J = 6.9 Hz, 3H), 1.87 (br s, 1H), 2.78−2.81 (m, 1H), 4.81 (br s, 1H), 5.30 (s, 1H), 5.61 (s, 1H), 7.01(7.28 (m, 9H); ^{13}C NMR δ 12.9, 42.8, 77.0, 115.7 (d, J = 22.7 Hz), 116.5, 124.2 (d, J = 3.3 Hz), 126.4, 127.9, 128.3, 129.2 (d, J = 8.2 Hz), 130.4 (d, J = 4.4 Hz), 144.3, 146.2, 159.7 (d, J = 245.0 Hz). Anal. Calcd for $C_{17}H_{17}$FO: C, 79.66; H, 6.69. Found: C, 79.79; H, 6.91.

2-[4-(Dimethylamino)phenyl]-2-(methyloxy)-1-phenylpropan-1-ol (6): white powder (37% yield); ^{1}H NMR δ 3.12 (s, 6H), 3.27 (s, 3H), 3.62 (s, 1H), 4.95 (s, 1H), 6.81 (d, J = 8.5 Hz, 2H), 7.00 (d, J = 7.4 Hz, 2H), 7.15 (d, J = 8.4 Hz, 2H), 7.26−7.28 (m, 3H); ^{13}C NMR δ 14.0, 40.5, 50.2, 81.8, 82.8, 111.8, 127.0, 127.0, 127.5, 128.5, 138.9, 149.9. Anal. Calcd for $C_{18}H_{23}NO_2$: C, 75.76; H, 8.12; N, 4.91. Found: C, 75.34; H, 8.21; N, 4.96.

General Procedure for the Preparation of Compounds 5c,d. Trimethylsilyl ether **3e** or **3f** (0.5 mmol) was dissolved in THF (30 mL) followed by addition of TBAF solution in THF (1 M, 0.7 mL, 0.7 mmol). The reaction mixture was stirred at room temperature for the time shown in Table 2. The solvent was removed under reduced pressure, and the remaining oil was dissolved in methylene chloride. The organic layer was washed with dilute aqueous hydrochloric acid solution (8%, 3 × 10 mL) and water (10 mL) and dried (Na_2SO_4). After the solvent was removed under reduced pressure, the residue was distilled with a Kugelröhr apparatus at 0.4 Torr and 110 °C.

1-Cyclohexyl-2-(2-fluorophenyl)prop-2-en-1-ol (5c): colorless oil (93%); ^{1}H NMR δ 0.96−1.24 (m, 4H), 1.31−1.40 (m, 1H), 1.63−1.82 (m, 6H), 4.37 (d, J = 4.0 Hz, 1H), 5.30 (s, 1H), 5.54 (s, 1H), 7.03−7.15 (m, 2H), 7.25−7.31 (m, 2H); ^{13}C NMR δ 26.0, 26.3, 26.4, 26.6, 30.1, 41.4, 78.3 (d, J = 2.5 Hz), 115.6 (d, J = 22.9 Hz), 116.5, 124.0 (d, J = 3.4 Hz), 128.5 (d, J = 15.3 Hz), 129.0 (d, J = 8.5 Hz), 130.5 (d, J = 4.1 Hz), 146.5, 159.7 (d, J = 244.4 Hz). Anal. Calcd for $C_{17}H_{18}$FO: C, 76.89; H, 8.17. Found: C, 76.52; H, 8.49.

2-(2-Fluorophenyl)-4-methylpent-1-en-3-ol (5d): colorless oil (79%); ^{1}H NMR δ 0.86 (d, J = 6.8 Hz, 3H), 0.96 (d, J = 6.8 Hz, 3H), 1.62−1.70 (m, 1H), 2.00 (br s, 1H), 4.41 (d, J = 4.4 Hz, 1H), 5.29 (s, 1H), 5.56 (s, 1H), 7.02−7.13 (m, 2H), 7.23−7.31 (m, 2H); ^{13}C NMR δ 15.7, 19.7, 31.4, 78.4, 115.6 (d, J = 23.0 Hz), 116.2, 124.0, 128.5 (d, J = 14.9 Hz), 129.0 (d, J = 8.4 Hz), 130.5 (d, J = 4.0 Hz), 146.8, 159.7 (d, J = 244.7 Hz). Anal. Calcd for $C_{12}H_{15}$FO: C, 74.20; H, 7.78. Found: C, 74.10; H, 8.11.

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