# Synthesis of 1,2-Diheteroatom-Substituted Alkenes via Rhodium-Catalyzed Intramolecular Hydrogen Transfer

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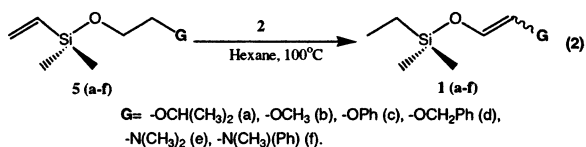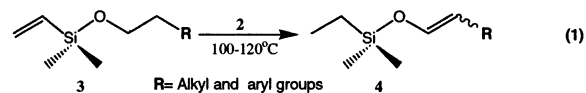
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While 1,2-diheteroatom-substituted alkenes represent useful synthetic building blocks, there are no simple, general procedures available for preparation of such compounds. Most of the examples reported[1-11] suffer from either low yields or poor stereoselectivity and frequently require extreme reaction conditions or multistep syntheses. We report here a convenient catalytic method which incorporates a rhodium-mediated C–H bond activation process for the synthesis of alkenes of type **1**.

G= -OCH(CH₃)₂ (**1a**), -OCH₃ (**1b**), -OPh (**1c**), -OCH₂Ph (**1d**), -N(CH₃)₂ (**1e**), -N(CH₃)(Ph) (**1f**).
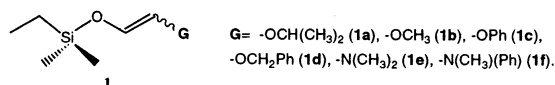
Earlier we reported[12] that treatment of silyl ether substrates, **3**, with catalytic amounts of Cp*Rh[CH₂=CHSi(CH₃)]₂, **2**,[13] results in intramolecular hydrogen transfer to generated silyl enol ethers, **4** (eq 1). We show here that this catalytic hydrogen transfer reaction also succeeds for β-alkoxy- and amino-substituted silyl ethers, **5** (eq 2), which are easily prepared from chlorodimethylvinylsilane and β-substituted alcohols, HOCH₂CH₂G.

$$\text{**3**} \xrightarrow[100-120^\circ C]{\text{**2**}} \text{**4**} \quad (1)$$

R= Alkyl and aryl groups

$$\text{**5 (a-f)**} \xrightarrow[\text{Hexane, }100^\circ C]{\text{**2**}} \text{**1 (a-f)**} \quad (2)$$

G= -OCH(CH₃)₂ (**a**), -OCH₃ (**b**), -OPh (**c**), -OCH₂Ph (**d**), -N(CH₃)₂ (**e**), -N(CH₃)(Ph) (**f**).

The presumed catalytic cycle is shown in Scheme 1. The labile trimethylvinylsilane ligands are displaced by substrate **5** to yield **A**. Alkene loss generates a 16-electron monoalkene complex, **B**, capable of intramolecular C–H oxidative addition (**B** to **C**). A sequence of standard migratory insertion, β-elimination, and reductive elimination reactions (**C** to **D** to **E**) generates complex **F**. Displacement of product by substrate (**F** to **B**) closes the catalytic cycle.

Table 1 summarizes results of these hydrogen transfer reactions for substrates **5a**–**f**. Generally, complete conversion can be obtained with 4 mol % catalyst loading at 100 °C in hexane over 4–15 h time periods depending on the substrate. No side reactions occur even at high conversions. As shown for a series of runs with **5a** (G = –OiPr) (Table 1, entries 1–4), the initial (kinetic) E:Z selectivity is high (99:1 at 2 h, 25% conversion, entry 1), but it degrades as the reaction proceeds (94:6 at 12 h, 94% conversion, entry 2; 68:32 at 33 h, >99% conversion, entry 4).[14] We have postulated that isomerization likely occurs by recoordination of product and reversal of the steps shown in Scheme 1, which would ultimately result in E:Z equilibration. As the substrate concentration decreases, the product competes more effectively for binding to rhodium, and the

**Scheme 1.** Intramolecular Mechanism for Transfer Hydrogenation
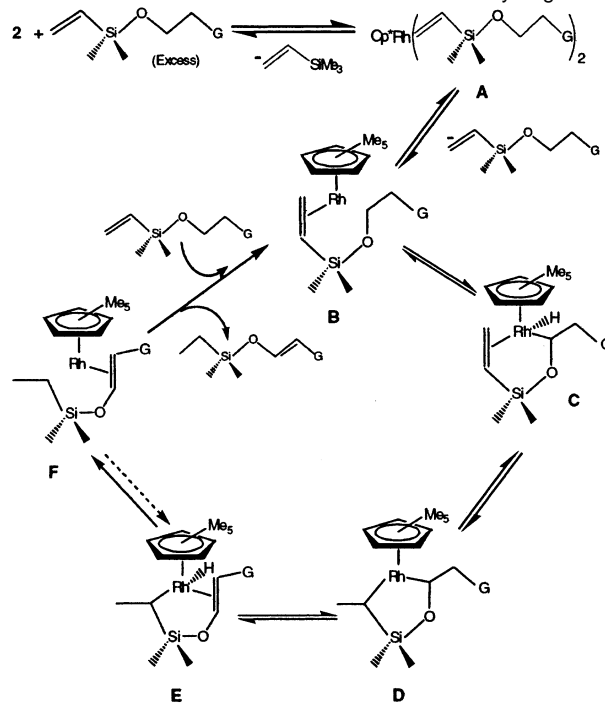


isomerization rate increases. We have found that addition of excess (inert) trimethylvinylsilane (5–20 equiv) significantly retards the E:Z equilibration by competing with the product for binding to rhodium. Trimethylvinylsilane also competes with the substrate for binding to rhodium, so the rate of hydrogen transfer is somewhat retarded, but high E:Z selectivity can be maintained to high conversion, as is illustrated in entries 5 and 6 for **5a** (G = –OiPr).

Reactions employing **5b** (G = –OCH₃), **5c** (–OPh), and **5d** (–OCH₂Ph) exhibit behavior similar to that of **5a**. For **5b** (G = –OCH₃), conversion occurs at a rate similar to that of **5a**, but the diastereoselectivity is lower (E:Z = 66:34, 12 h, >99% conversion, entry 8). Again, addition of excess trimethylvinylsilane restores a high E:Z ratio (entry 9). For **5c** (G = –OPh), conversion is somewhat slower, but a high E:Z ratio (>99:1) is maintained throughout the reaction to complete conversion (see entries 10 and 11). In the case of **5d** (G = –OCH₂Ph), the conversion is considerably faster (99% after 5 h), but the E:Z selectivity degrades rapidly. Moreover, in entry 14 (72 h reaction time), thermodynamic equilibrium has been reached, and, as is expected, the Z isomer is favored (E:Z = 15:85).[16] Addition of 20 equiv of trimethylvinylsilane allows retention of a reasonably high E:Z ratio (90:10) at complete conversion (entry 15).

Entries 16–20 illustrate results for β-amino-substituted silyl ethers. Similar rates of reaction are observed for G = –N(CH₃)₂ (**5e**) and G = –N(CH₃)(Ph) (**5f**), as compared to G = –OMe (**5b**)

***Table 1.*** Catalytic Conversion of **5a**−**f** to **1a**−**f**

| entry[a] | substrate G= | time (h) | added trimethylvinylsilane (equiv) | conversion | product | E:Z ratio |
|---|---|---|---|---|---|---|
| 1 | **5a**, −OiPr | 2 | 0 | 25% | **1a**, EtMe$_2$SiOCH=CH(OiPr) | >99:1 |
| 2 | **5a**, −OiPr | 12 | 0 | 94% | **1a**, EtMe$_2$SiOCH=CH(OiPr) | 94:6 |
| 3 | **5a**, −OiPr | 13.5 | 0 | >99% | **1a**, EtMe$_2$SiOCH=CH(OiPr) | 92:8 |
| 4 | **5a**, −OiPr | 33 | 0 | >99% | **1a**, EtMe$_2$SiOCH=CH(OiPr) | 68:32 |
| 5 | **5a**, −OiPr | 18 | 5 | 99% | **1a**, EtMe$_2$SiOCH=CH(OiPr) | 96:4 |
| 6 | **5a**, −OiPr | 18 | 10 | 82% | **1a**, EtMe$_2$SiOCH=CH(OiPr) | 98:2 |
| 7 | **5b**, −OMe | 7 | 0 | 62% | **1b**, EtMe$_2$SiOCH=CH(OMe) | 84:16 |
| 8 | **5b**, −OMe | 13 | 0 | >99% | **1b**, EtMe$_2$SiOCH=CH(OMe) | 66:34 |
| 9 | **5b**, −OMe | 18 | 15 | >99% | **1b**, EtMe$_2$SiOCH=CH(OMe) | 90:10 |
| 10 | **5c**, −OPh | 6 | 0 | 40% | **1c**, EtMe$_2$SiOCH=CH(OPh) | >99:1 |
| 11 | **5c**, −OPh | 18 | 0 | 96% | **1c**, EtMe$_2$SiOCH=CH(OPh) | >99:1 |
| 12 | **5d**, −OCH$_2$Ph | 5 | 0 | >99% | **1d**, EtMe$_2$SiOCH=CH(OCH$_2$Ph) | 74:26 |
| 13 | **5d**, −OCH$_2$Ph | 18 | 0 | >99% | **1d**, EtMe$_2$SiOCH=CH(OCH$_2$Ph) | 19:81 |
| 14 | **5d**, −OCH$_2$Ph | 72 | 0 | >99% | **1d**, EtMe$_2$SiOCH=CH(OCH$_2$Ph) | 15:85 |
| 15 | **5d**, −OCH$_2$Ph | 6 | 20 | 99% | **1d**, EtMe$_2$SiOCH=CH(OCH$_2$Ph) | 90:10 |
| 16 | **5e**, −N(CH$_3$)$_2$ | 10 | 0 | >99% | **1e**, EtMe$_2$SiOCH=CH[N(CH$_3$)$_2$] | 70:30 |
| 17 | **5e**, −N(CH$_3$)$_2$ | 14 | 10 | >99% | **1e**, EtMe$_2$SiOCH=CH[N(CH$_3$)$_2$] | 86:14 |
| 18 | **5f**, −N(CH$_3$)(Ph) | 14 | 0 | >99% | **1f**, EtMe$_2$SiOCH=CH[N(CH$_3$)(Ph)] | 72:28 |
| 19 | **5f**, −N(CH$_3$)(Ph) | 20 | 10 | >99% | **1f**, EtMe$_2$SiOCH=CH[N(CH$_3$)(Ph)] | 94:6 |
| 20 | **5f**, −N(CH$_3$)(Ph) | 72 | 0 | >99% | **1f**, EtMe$_2$SiOCH=CH[N(CH$_3$)(Ph)] | 40:60 |

$^a$ All reactions[15] were conducted at 100 °C in hexanes with 4 mol % catalyst **2**.

and G = −OiPr (**5a**), but *E:Z* selectivities are somewhat lower, ca. 70:30 (entries 16 and 18). Significant increases in the *E:Z* ratios are obtained upon addition of trimethylvinylsilane (entries 17 and 19). Finally, entry 20 (72 h) establishes the *E:Z* equilibrium ratio of 40:60 for G = −N(CH$_3$)(Ph) (**5f**).

A key to successful catalysis is the purity of the substrate, **5**. A common trace impurity in commercial (CH$_2$=CH)SiCl(CH$_3$)$_2$ is the divinyl siloxane, **6**, formed from the reaction of the chlorodimethylvinylsilane with water. The divinyl compound **6** reacts rapidly and quantitative with catalyst **2** to form the chelate complex **7** (eq 3), which is completely unreactive under catalytic conditions. Thus, any traces of **6** in the substrate can reduce the concentration of active catalyst via formation of **7**.
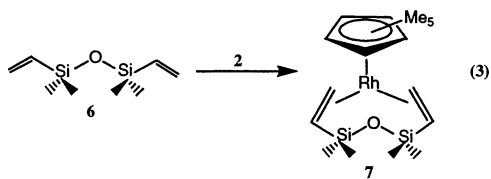
The procedure for isolation of product is remarkably simple. Addition of a small amount of CHCl$_3$ to the reaction mixture[15] results in precipitation of an insoluble rhodium species. Filtration followed by removal of solvent and trimethylvinylsilane results in isolation of the analytically pure product.

In summary, we have described here a simple catalytic procedure based on rhodium C−H bond activation for the synthesis of 1,2-diheteroatom-substituted alkenes of the type R$_3$SiOCH=CHG (G = −OR, −NRR′). These compounds are attractive substrates for the use in inverse electron demand Diels−Alder, Paterno−Büchi, and enamine reactions, among others. We are currently examining the chemistry of these compounds and extending this catalytic procedure to more complex substrates.

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(13) The precatalyst **2** was prepared using published procedures by reducing the dimer [Cp*RhCl$_2$]$_2$ with Zn powder in the presence of excess trimethylvinylsilane.[12]
(14) The *E* and *Z* isomers are easily distinguished by the large difference between olefinic vicinal $J_{HH}$ coupling constants. For example, for **1a**, *E* isomer: $\delta$ 6.35 (d, 14 Hz), $\delta$ 6.15 (d, 14 Hz). Z isomer: $\delta$ 5.42 (d, 4.5 Hz), $\delta$ 5.34 (d, 4.5 Hz).
(15) Typical experimental procedure: Complex **2** (0.05 mmol) was dissolved in hexanes (10 mL), and 1.25 mmol of substrate (**5a**−**f**) was added. This solution was heated in a sealed Kontes flask at 100 °C. After the desired reaction time, 0.25 mL of CHCl$_3$ was added, and the mixture was stirred 4−6 h. The solution was filtered, and the solvent was removed to yield pure product.
(16) For relative stability of *cis*- and *trans*-1,2-dialkoxy ethylenes, see: (a) Waldron, J. T.; Snyder, W. H. *J. Am. Chem. Soc.* **1973**, *95*, 5491. (b) Taskinen, E.; Bjorkqvist, H. *Struct. Chem.* **1994**, *5*, 321.

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