

## A Practical Synthesis of Difunctional Organosilane Reagents and Their Application to the Diels–Alder Reaction

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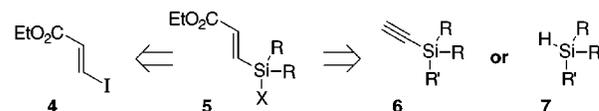
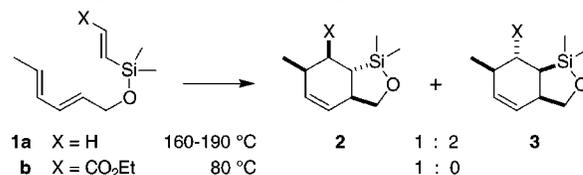
Received January 15, 1999

Difunctional organosilanes, with a leaving group and a reactive organic functionality, have become basic tools for synthetic chemistry.<sup>1</sup> Prominent examples include (bromomethyl)chlorosilanes<sup>2</sup> and chloro(vinyl)silanes.<sup>3,4</sup> Unfortunately, only a small number of these reagents are commercially available, and synthesis of even simple examples can be experimentally demanding.<sup>5</sup> A case in point are the versatile  $\beta$ -(chlorodialkylsilyl) acrylates **5** ( $X = \text{Cl}$ ). The unsaturated ester provides enhanced reactivity and a high level of stereoselectivity in cycloadditions,<sup>6–8</sup> while the silyl ether (e.g., **1**) provides the regioselectivity and entropic advantages of intramolecularity (Scheme 1). For example, ester **1b** cyclizes at a moderate temperature and yields a single product,<sup>3</sup> whereas **1a** requires rather high temperatures and is low in stereoselectivity.<sup>3,4</sup>

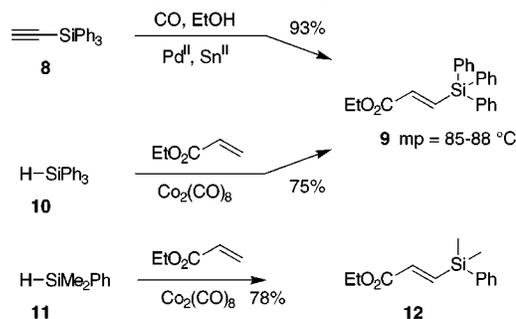
The two published procedures for the synthesis of **5** ( $X = \text{Cl}$ ,  $R = \text{Me}$ ,  $i\text{-Pr}$ ) each require four steps, the use of  $-100^\circ\text{C}$  reaction temperatures, and the isolation of moisture-sensitive intermediates.<sup>3,9</sup> We report here synthetic sequences that make compounds such as **5** and **1** readily available and do not require the isolation of moisture sensitive intermediates. While both earlier procedures employed  $\beta$ -iodo acrylate **4**,<sup>10</sup> the protocols described here utilize commercially available silanes **6** or **7**.

Compound **5** as a triflate ( $X = \text{OTf}$ ) was anticipated to be significantly more reactive than the corresponding chlorosilane<sup>11,12</sup> and, therefore, quite useful *if it could be generated*

### Scheme 1. Electron-Withdrawing Group on the Dienophile Lowers the Reaction Temperature and Improves the Selectivity of the Reaction



### Scheme 2. Preparation of Silyl Acrylates **9** and **12**



*in the presence of the ester.* Silyl triflates *O*-silylate carbonyls<sup>13</sup> and therefore both functional groups in the same molecule might be expected to yield, at best, a polymeric complex. Nevertheless, generation of silyl triflates by protolytic cleavage of phenylsilanes with triflic acid is a reliable reaction,<sup>14</sup> and we therefore targeted triphenylsilane **9** for study (Scheme 2).

Ethyl ester **9** has not been previously prepared; however, two methods provide useful quantities of this acrylate. Takeuchi's ethoxycarbonylation, originally described for trimethylsilylacetylene,<sup>15</sup> also works well with triphenylsilylacetylene **8** to give exclusively **9** as a crystalline solid in 93% isolated yield. The utility of this process, however, is somewhat attenuated by the requirement for high-pressure reaction vessels. The alternative procedure of Seki and Murai,<sup>16</sup> cobalt-catalyzed oxidative hydrosilylation of ethyl acrylate, gave the same crystalline product with complete regio- and stereoselectivity and an acceptable yield (75%). Importantly, this latter procedure can be used to prepare tens of grams of **9**. Under the same conditions, dimethylphenylsilane **11** yields acrylate **12**.

Protodesilylation of organic groups by triflic acid has been extensively studied by Bassindale<sup>17</sup> and Uhlig,<sup>14</sup> and on the basis of this work, a phenyl group is expected to be cleaved from silicon before a simple vinyl group. The ester reinforces this tendency, as triflic acid would initially protonate the carbonyl (**13**), protecting the acrylate from further electrophilic attack (**14**) and leading to triflate **16** via **15** (Scheme 3).

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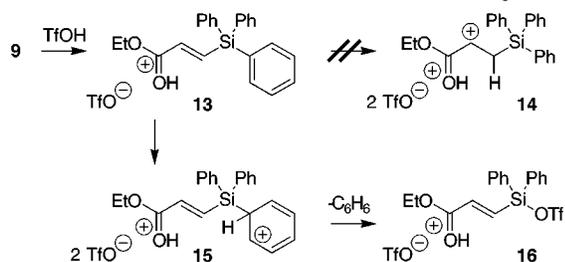
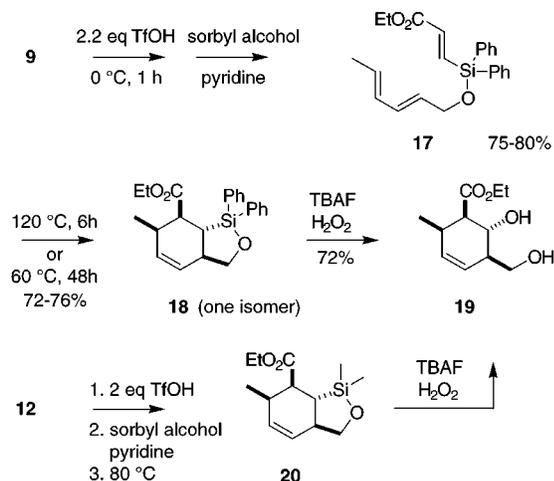
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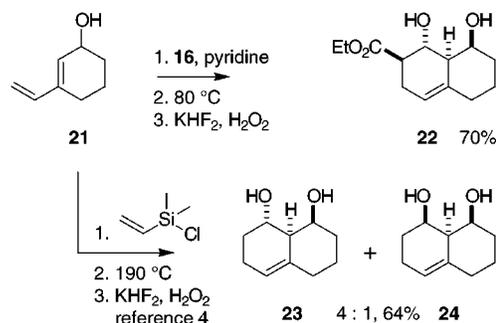
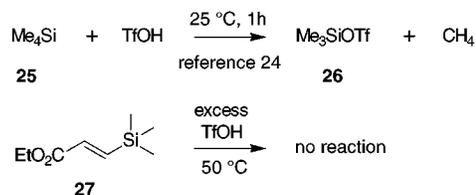
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**Scheme 3. Protonation Protects the Acrylate****Scheme 4. One-Flask Conversion of **9** and **12** to Silyl Ethers Followed by Cycloaddition and Oxidation**

This process was evaluated by proton NMR. Addition of 1 equiv of triflic acid to acrylate **9** in deuteriochloroform at ambient temperature led to minor changes in the proton NMR spectrum attributed to simple protonation of the carbonyl (**13**). Following addition of a second equivalent of acid, substantial changes in the chemical shift of the alkene proton signals were observed, accompanied by the appearance of a prominent singlet at 7.3 ppm consistent with the formation of benzene and triflate **16**. This transformation was very clean and complete within minutes at room temperature.<sup>18</sup>

Isolation of **16** is unnecessary. After addition of triflic acid at 0 °C, treatment with pyridine<sup>19</sup> and sorbyl alcohol directly forms silyl ether **17** (Scheme 4). The use of phenyl groups on silicon, rather than methyl groups, leads to substantial hydrolytic stability for this silyl ether, and it can be purified by silica gel chromatography in good overall yield. Warming this triene leads to Diels–Alder adduct **18** as a single isomer, and Tamao–Fleming oxidation<sup>20–22</sup> then yields the known diol **19**.<sup>3</sup> Substitution of dimethylphenylsilane **12** for triphenylsilyl **9** led to similar results, except that the hydrolytically more labile dimethylsilyl ether intermediate (**1b**) was not purified, but cyclized directly to give **20**.<sup>3</sup>

Secondary alcohol **21** reacted smoothly but more slowly with triflate **16** and, after heating to 80 °C overnight and

**Scheme 5. Secondary Alcohols Also React Well with **16******Scheme 6. Acrylate **27** Is Stable to Triflic Acid**

Tamao–Fleming oxidation, gave diol **22** as a single isomer. Use of an unadorned vinyl silane lead to a mixture of the isomeric products **23** and **24** (Scheme 5).<sup>4</sup>

A potentially simpler and “greener”<sup>23</sup> approach to dimethylsilyltriflate **5** (X = OTf, R = CH<sub>3</sub>) is the protolytic cleavage of a methyl group instead of phenyl group. Alkyls are the most difficult of groups to remove from silicon with acid,<sup>14</sup> yet tetramethylsilane evolves methane rapidly and quantitatively on treatment with triflic acid, forming trimethylsilyl triflate **26** (Scheme 6).<sup>24</sup> Although vinyl groups are protolytically cleaved from silanes much more easily than methyl groups,<sup>14,17</sup> initial protonation of the carbonyl of **27** was expected to protect the acrylate. Surprisingly, this protonation protects all of the groups on silicon; with a large excess of triflic acid, silane **27** was stable at 50 °C for several hours without noticeable decomposition (NMR).

The general method described here should allow a variety of functionalized silyl acrylate derivatives to be rapidly and easily prepared without the need for isolation of reactive intermediates. The crystalline and easily synthesized **9** is particularly convenient. With the increasingly common use of organosilane reagents, we anticipate that this chemistry will find broad application.

**Acknowledgment** is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, and to the NSF (CHE9712772) for support of this research. NMR spectrometers used in this research were purchased with funds from the NSF (CHE9413510). The authors thank Ian Fleming for helpful discussions.

**Supporting Information Available:** Characterization data and procedures for the synthesis of **9**, **12**, **17–19**, and **22**, and proton NMR spectra for **9**, **12**, **13**, **16–19**, and **22**.

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