

Enantioselective Synthesis of α -Aminosilanes by Copper-Catalyzed Hydroamination of Vinylsilanes**

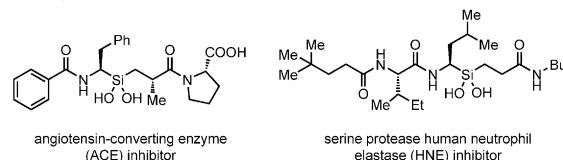
Nootaree Niljianskul, Shaolin Zhu, and Stephen L. Buchwald*

Abstract: The synthesis of α -aminosilanes by a highly enantio- and regioselective copper-catalyzed hydroamination of vinylsilanes is reported. The system employs Cu-DTBM-SEGPHOS as the catalyst, diethoxymethylsilane as the stoichiometric reductant, and *O*-benzoylhydroxylamines as the electrophilic nitrogen source. This hydroamination reaction is compatible with differentially substituted vinylsilanes, thus providing access to amino acid mimics and other valuable chiral organosilicon compounds.

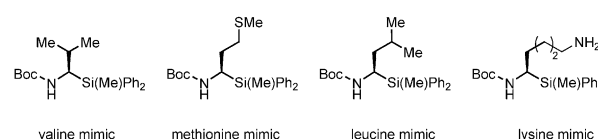
Organosilicon compounds have recently gained prominence within the field of medicinal chemistry. Silicon is often used as an isostere for carbon due to its similar valency and tetrahedral bonding pattern.^[1] In addition, because of its larger covalent radius, electropositive/lipophilic nature, and low intrinsic toxicity, silicon is complementary to carbon and is valuable in pharmaceutical research.^[2] Among the many subclasses of organosilicon compounds, chiral α -aminosilanes in particular have demonstrated significant bioactivities.^[2,3] Several potent inhibitors of proteolytic enzymes possess the α -aminosilane motif, and α -aminosilanes have been incorporated into peptide isosteres (Scheme 1).^[2–4] Thus, the development of robust methods for the construction of chiral α -aminosilanes is an important area of research.

Although there has been progress in the synthesis of racemic α -aminosilanes,^[5,6] enantioselective approaches remain limited. Previous methods include asymmetric deprotonation followed by reverse aza-Brook rearrangement [Scheme 2, Eq. (1)].^[7] Other approaches have utilized the chiral auxiliary bearing aldimines developed by Davis or Ellman in conjunction with silyllithium reagents [Eq. (2)].^[3,8] Recently, Oestreich and co-workers reported an elegant process catalyzed by a chiral N-heterocyclic carbene/copper complex using Suginome's Ph(Me)₂SiBpin reagent [Eq. (3)].^[8] However, these methods have limitations with

■ Silanediol protease inhibitors:

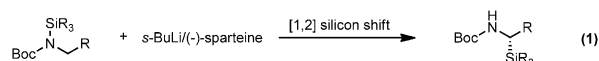


■ Chiral diarylsilyl amino acid analogues:

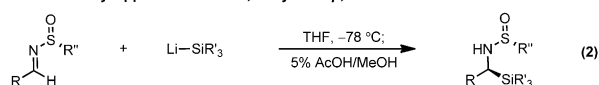


Scheme 1. Examples of silicon-containing peptidomimetics and amino acids. Boc = *tert*-butoxycarbonyl.

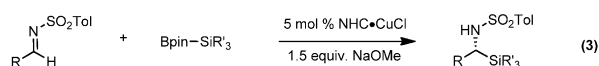
Reverse aza-Brook Rearrangement Approach: Voyer, Sieburth



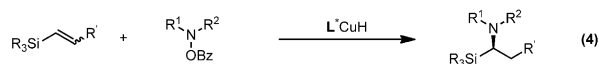
Chiral Auxiliary Approach: Scheidt, Skrydstrup, Sieburth



Cu-catalyzed Approach: Oestreich



CuH-catalyzed Hydroamination of Vinyl Silanes: This Work



Scheme 2. Previous approaches towards the synthesis of chiral α -aminosilanes and the development of our strategy. Bpin = pinacolborane, Bz = benzoyl, Tol = tolyl.

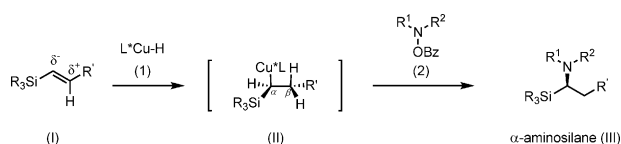
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respect to the scope of the amine, and, with the exception of the report by Oestreich and co-workers, require the use of a stoichiometric chiral auxiliary or reagent.

Recently, we, as well as Hirano, Miura, and co-workers, reported the CuH-catalyzed asymmetric Markovnikov hydroamination of styrenes.^[9] We felt that this method, when applied to vinylsilane substrates, would allow the generation of a broad range of chiral α -aminosilanes [Eq. (4)]. As vinylsilanes are readily prepared and bench-stable, they are attractive as starting materials for the synthesis of α -aminosilanes.^[10] The intermolecular hydroamination of vinylsilanes would likely, based on literature precedent, proceed regiose-



Scheme 3. Regioselectivity in the hydroamination of β -vinylsilanes.

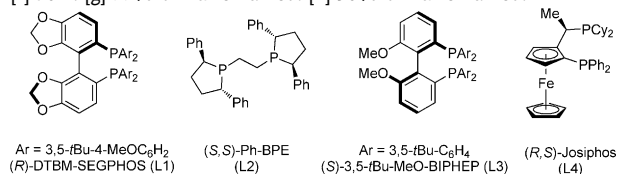
lectively to give chiral α -aminosilanes (**III**), via the α -silylalkylcopper intermediate **II** (Scheme 3),^[11] on reaction with the *O*-benzoylhydroxylamine electrophile **2**.^[9]

We began our investigation by examining the hydroamination of (*E*)-vinylsilane **1a** using conditions previously developed for the hydroamination of styrene (Table 1).^[9] The

Table 1: Reaction optimization.^[a]

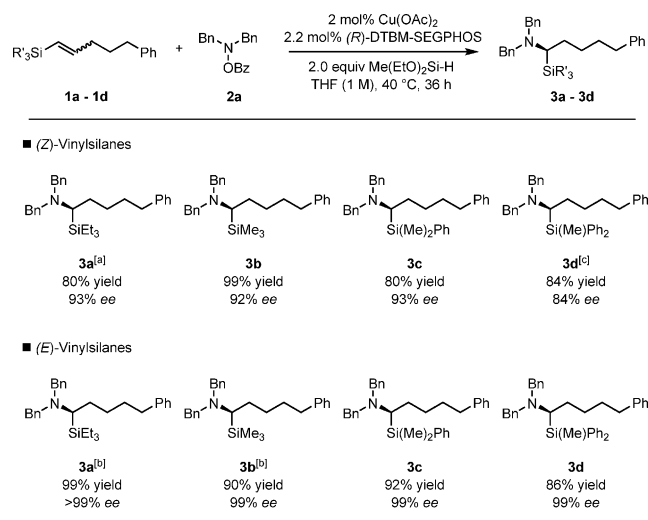
Entry	Solvent	L	Yield 3a [%] ^[b]	ee [%] ^[c]
1	THF	L1	> 99	> 99
2	cyclohexane	L1	> 99	> 99
3	Et ₂ O	L1	> 99	> 99
4	toluene	L1	> 99	> 99
5	CH ₂ Cl ₂	L1	0 ^[e,f,g]	–
6	THF	L2	37 ^[f]	95
7	THF	L3	92 ^[d]	98
8	THF	L4	0 ^[e,f,h]	–

[a] Reaction conditions: **1a** (0.5 mmol), **2a** (0.6 mmol), Cu(OAc)₂ (0.02 mmol), ligand (0.022 mmol), solvent (1 mL). [b] Yields of isolated products. [c] Determined by HPLC analysis on a chiral stationary phase. [d] 16 h. [e] Yield determined by GC (dodecane as internal standard). [f] 36 h. [g] 77% of **1a** remained. [h] 96% of **1a** remained.



reaction furnished α -aminosilane **3a** regioselectively in quantitative yield with > 99% ee after 8 h (entry 1). Switching the solvent to cyclohexane, diethyl ether, or toluene (entries 2–4) had no effect, but no conversion was seen in dichloromethane (entry 5). We also examined other chiral ligands that were previously shown to be effective in reactions catalyzed by a copper(I) hydride complex (entries 6–8).^[9b,17] However, the use of (*R*)-DTBM-SEGPHOS was found to give the highest reactivity and selectivity.

We next investigated the influence of the nature of the silyl group and olefin geometry on the reactivity and enantioselectivity (Scheme 4). The reaction was compatible with vinylsilanes containing triethylsilyl (**3a**), trimethylsilyl (**3b**), dimethylphenylsilyl (**3c**), and methylphenylsilyl groups (**3d**).^[18] In all cases, the reactions proceeded regioselectively to give α -aminosilane products. Interestingly, we found: 1) both *E* and *Z* isomers provided the same enantio-



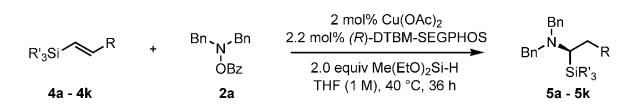
Scheme 4. Influence of the silyl group and olefin geometry on yield and enantioselectivity. Reaction conditions: **1a–1d** (1 mmol), **2a** (1.2 mmol), Cu(OAc)₂ (0.02 mmol), (*R*)-DTBM-SEGPHOS (0.022 mmol), THF (1 mL), 40 °C, 36 h. Yields are of isolated products (average of two runs). [a] Cu(OAc)₂ (0.04 mmol), (*R*)-DTBM-SEGPHOS (0.044 mmol). [b] 8 h. [c] Cu(OAc)₂ (0.04 mmol), (*R*)-DTBM-SEGPHOS (0.044 mmol), THF (0.5 mL, 2 M). Bn = benzyl.

meric product, and 2) *E* substrates invariably reacted faster and with a higher level of enantioselectivity than the corresponding *Z* substrates.

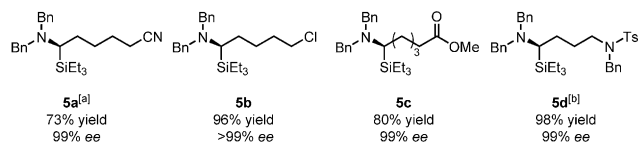
Thus, we chose to examine the scope of the hydroamination of (*E*)-vinylsilanes. This method accommodates a broad range of functional groups (Scheme 5). Vinylsilanes containing a nitrile (**5a**), an alkyl chloride (**5b**), an ester (**5c**), a sulfonamide (**5d**), a *tert*-butyldimethylsilyl ether (**5e**), and an allylic ether moiety (**5f**) were readily handled. No competitive elimination of alkoxide was observed with an ether (**5f**).^[19] Additionally, we applied our method to the synthesis of α -amino acid mimics by hydroamination of a secondary benzylamine (**5i**), a β,β -disubstituted vinylsilane (**5j**), and a β -isopropyl-substituted vinylsilane (**5k**), to provide mimics of lysine, valine, and leucine, respectively.

The compatibility of this reaction with a variety of *O*-benzoylhydroxylamine electrophiles was then examined (Scheme 6). Acyclic dialkyl (**6a**), cyclic dialkyl (**6b**), and alkylbenzylamine-based electrophiles (**6c**) were all suitable partners, delivering the hydroaminated products with high yields and enantioselectivities. In addition, a heterocycle-containing electrophile was tolerated (**6d**). Hydroamination to install a bis(*p*-methoxybenzyl)amino group was also successful (**6e**).

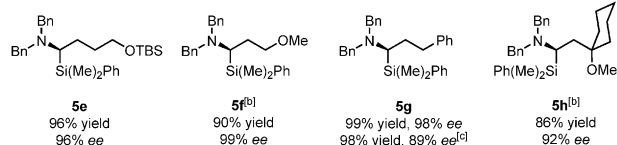
As previously mentioned (Scheme 4), the *E* and *Z* substrates provide the same enantiomer of the product. However, *E* substrates react faster and afford a higher level of enantioselectivity than the corresponding *Z* substrates. We thus wondered whether, in the case of (*Z*)-alkenes, most of the hydroamination product was formed by isomerization of the slower reacting *Z* isomer, followed by transformation of the nascent *E* isomer. We investigated this possibility through the use of a deuterated silane reagent. In this case, L*Cu-D



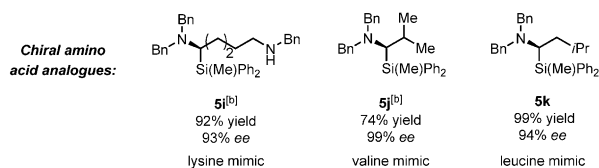
■ Vinyl Triethylsilanes



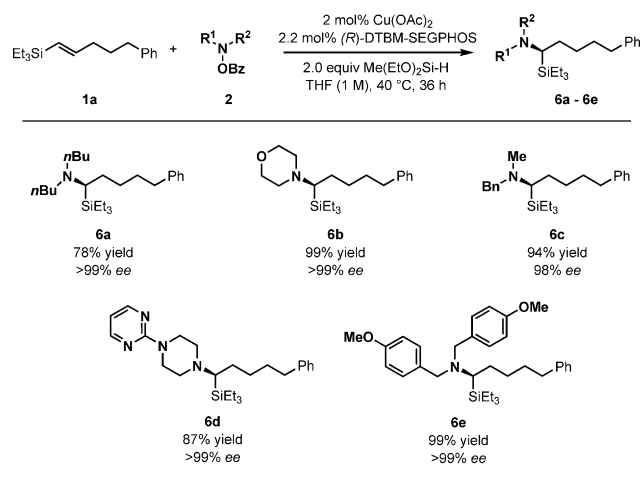
■ Vinyl Dimethylphenylsilanes



■ Vinyl Diphenylmethylsilanes



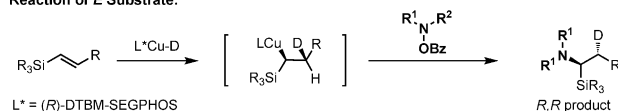
Scheme 5. Hydroamination of (*E*)-vinylsilanes. Reaction conditions: **4a–4k** (1 mmol), **2a** (1.2 mmol), Cu(OAc)₂ (0.02 mmol), (*R*)-DTBM-SEGPHOS (0.022 mmol), THF (1 mL), 40 °C, 36 h. Yields are of isolated products (average of two runs). [a] 16 h reaction time. [b] Cu(OAc)₂ (0.04 mmol), (*R*)-DTBM-SEGPHOS (0.044 mmol), THF (1 mL, 1 M). [c] From (*Z*)-**4g**. TBS = *tert*-butyldimethylsilyl, Ts = *p*-toluenesulfonyl.



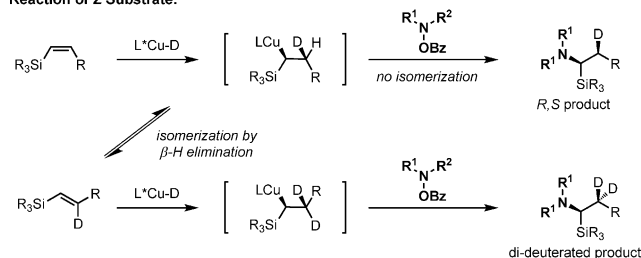
Scheme 6. Scope of *O*-benzoylhydroxylamine electrophiles. Reaction conditions: **1** (1 mmol), **2a** (1.2 mmol), Cu(OAc)₂ (0.02 mmol), (*R*)-DTBM-SEGPHOS (0.022 mmol), THF (1 mL), 40 °C, 36 h. Yields are of isolated products (average of two runs).

would form and the olefin would insert into it through a *syn*-addition process (Scheme 7). For the more reactive *E* substrate, subsequent reaction with the *O*-benzoylhydroxylamine would generate the *R,R* product. For the *Z* substrate, if no isomerization occurs, the reaction should generate the

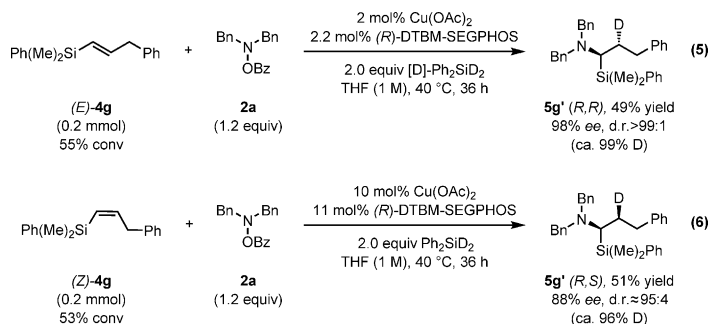
Reaction of *E* Substrate:



Reaction of *Z* Substrate:



Scheme 7. Possible reaction pathways.

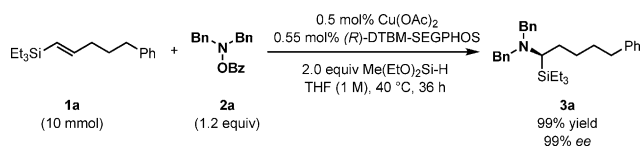


Scheme 8. Deuterium-labeling experiments.

R,S product. However, if the *Z* substrate undergoes Cu-catalyzed isomerization to the *E* alkene prior to reaction with *O*-benzoylhydroxylamine, the major product would contain approximately two deuterium atoms.

Deuterium-labeling experiments (Scheme 8) revealed that the hydroamination of (*E*)-**4g** was completely diastereoselective with about 99% deuterium incorporation^[20] to give the monodeuterated *R,R* isomer **5g'** [Eq. (5)]. The reaction was also diastereoselective for (*Z*)-**4g**, and gave the monodeuterated *R,S* isomer **5g'** with about 96% deuterium incorporation [Eq. (6)].^[20] The stereochemical result and the presence of the monodeuterated product from the *Z* substrate indicates that most of the product does not form by isomerization of the substrate to the *E* isomer.

Lastly, to demonstrate the scalability of this transformation, we carried out the hydroamination of **1a** with Bn₂N-OBz (**2a**) on a 10 mmol scale (Scheme 9). Full conversion of the vinylsilane was achieved with a catalyst loading of only 0.5 mol%. The yield and the enantioselectivity was the same as for the 1 mmol scale reaction (Table 1).



Scheme 9. Large-scale hydroamination reaction of (*E*)-triethylsilylvinylsilane.

In summary, we have developed an enantioselective Cu-catalyzed hydroamination of vinylsilanes. The reaction proceeds in a regioselective manner to provide enantioenriched α -aminosilanes in high yield with outstanding levels of enantioselectivity. The method is applicable to a variety of substrates, and provides rapid access to a family of valuable chiral organosilicon building blocks and bioactive molecules.

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- [20] See the Supporting Information section II, part C for a detailed analysis.