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Simplified Preparation of Trialkylvinylsilanes via the Silyl-Heck Reaction Utilizing a Second Generation Catalyst

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Abstract

Recently we reported a second-generation ligand, bis(3,5-di-*tert*-butylphenyl)(*tert*-butyl)phosphine, for the preparation of allyl silanes using the silyl-Heck reaction. We now show that this new ligand also provides superior reactivity in the preparation of vinylsilanes from styrene derivatives. For the first time, this new ligand provides exceptionally high yields of trialkylvinylsilanes using a widely available palladium pre-catalyst, Pd₂(dba)₃. Finally, we demonstrate that this new catalyst system is able to form more highly decorated all carbon substituted vinylsilanes that have been shown to possess superior reactivity in oxidation and cross coupling reactions.

Graphical Abstract

Keywords

silyl-Heck reaction; vinylsilane; alkene; palladium

Vinylsilanes are potent nucleophiles in a wide variety of carbon-carbon and carbon-heteroatom bond forming reactions.^[1] Additionally, the carbon-bound silicon is readily oxidized, allowing vinylsilanes to serve as masked carbonyl groups.^[2] We have previously described a silyl-Heck reaction, which allows for the preparation of unsaturated

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Dedicated to Prof. Stephen L Buchwald on the Occasion of his 60th Birthday

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organosilanes from simple alkenes and electrophilic silanes under palladium-catalysis.^{[3], [4], [5]}

In our initial report, we described the formation of trimethylvinylsilanes from styrene derivatives and Me₃SiI.^[3a] The optimal ligand in this palladium-catalyzed transformation was identified as ^tBuPPh₂, which provided high yields (up to 98% isolated) of the desired products across a range of styrene derivatives. These transformations, however, required the use of (COD)Pd(CH₂SiMe₃)₂ (**1**) as the palladium pre-catalyst.^[6] Other more common and more stable palladium(0) sources, such as Pd₂(dba)₃ (dba = dibenzylideneacetone), provided significantly lower yields (ca. 10%) under comparable conditions. We attribute the poor performance of this latter complex to competitive, non-productive ligation of dba to the metal center.^[7]

Although complex **1** is easily prepared on gram scale,^[3a, 8] is air stable, and has recently become commercially available,^[9] it is slightly thermally sensitive. This liability potentially limits the adoption of the silyl-Heck reaction in some situations. We thus have sought alternative catalytic conditions for the transformation that utilize more readily handled reagents.

In our initial study, we also reported that the palladium catalyst formed using ^tBuPPh₂ also convert terminal alkenes bearing allylic hydrogen atoms (α -olefins) to the corresponding allyl silanes using the silyl-Heck reaction, albeit in modest yields.^[3a] More recently, we have developed a second-generation ligand **2** (Figure 1) for the formation of allyl silanes in very high yields.^[3c] Although ligand **2** was designed to promote oxidative addition of the Si–I bond by increasing both the size and electron-richness of the phosphine center,^[10] we recognized that these properties might also inhibit deleterious binding of exogenous ligands.

As such, we have reinvestigated the silylation of styrene derivatives by Me₃SiI using our second-generation ligand **2**. We now report that very high yields of the desired vinylsilanes can be obtained when this ligand is used in combination with the widely available and bench stable Pd₂(dba)₃ precatalyst. We demonstrate that this ligand provides vastly superior yields of vinylsilanes with this precatalyst, compared to the first generation ligand. These new conditions allow the preparation of vinylsilanes from styrene derivatives using the silyl-Heck reaction with completely bench-stable and commercially available catalytic precursors.^[11]

As a model system to examine the interplay of the ligand and palladium precatalyst, we investigated the conversion of 4-*tert*-butylstyrene to vinylsilane **3** using Me₃SiI in the presence of Et₃N. As we have previously reported, with use of 5 mol % **1** and 10.5 mol % ^tBuPPh₂ in toluene at 50 °C, this transformation can be carried out in 98% isolated yield (Table 1, entry 1).^[3a] With 2.5 mol % Pd₂(dba)₃ (5 mol % Pd), only 12% of **3** is observed under otherwise identical conditions (entry 2). In contrast, with the use of second-generation ligand **2** (7.5 mol %) and 2.5 mol % Pd₂(dba)₃ (DCE at 40 °C, conditions similar to those use in our second-generation allyl silane synthesis),^[3c] 91% of the desired product is observed along with trace amounts of starting material (entry 3).^[12] With lower ligand loading (5 mol %), quantitative yield of silane **3** and no remaining alkene is observed (entry 4). Demonstrating that it is ligand **2**, and not just the altered conditions, that account for the

improved reactivity using $\text{Pd}_2(\text{dba})_3$, the use of $t\text{BuPPh}_2$ under the same conditions provides only 75% of the desired product (entry 5).

Using the catalyst derived from $\text{Pd}_2(\text{dba})_3$ and ligand **2**, excellent yields of vinylsilanes were obtained with a broad range of styrenes (Table 2). The product from the model reaction (**3**) was isolated in 99% yield (entry 1). Simple styrene gives rise to trimethylsilane **4** in 96% isolated yield (entry 2). Like the earlier generation silyl-Heck reactions, this catalyst system was tolerant of a wide range of functional groups, including aryl chlorides, aryl fluorides, esters, ethers, tertiary amines, silyl ethers, dioxalanes, strained rings and boronic esters (entries 3–11). Both electron-poor and electron-rich aromatic styrenes were well tolerated (entries 5–7), as were sterically hindered substrates (entry 12). Finally, even complex molecules such as natural product derivatives could be functionalized (entry 13). In all cases, uniformly high yields of the vinylsilane were observed, and in all cases, only the *trans*-isomer of the product was detected. In some cases, as noted in Table 2, 2 equivalents of Me_3SiI were required to achieve the observed yields.

Consistent with the results shown in Table 1, across the substrates examined, the second-generation ligand provide far superior results compared to $t\text{BuPPh}_2$.^[13]

We also briefly examined the use of the $\text{Pd}_2(\text{dba})_3$ /ligand **2** catalyst system for the silylation of α -olefins. Using 1-decene as a model system, this catalyst system provided desired allyl silane **16** in 87% yield, with the mass balance being decene isomers (Table 3, entry 1). The *E/Z* and allyl/vinyl selectivities in the reaction were nearly identical to that which we have previously reported.^[3a, c] At room temperature, however, only trace reactivity was observed (entry 2). Although this catalyst system is much more efficient than that employing $t\text{BuPPh}_2$ (entry 3), it remains significantly less effective than with the use of precatalyst **1** and ligand **2** under our previously reported conditions (entry 4).^[3c]

Given the greater reactivity of the $\text{Pd}_2(\text{dba})_3$ /ligand **2** catalyst system, we also wished to examine if vinylsilanes containing groups other than trimethyl silane could be prepared using palladium catalysis. Previously, Me_3SiI has proven to be the only mono-electrophilic silane with sufficient reactivity to participate in palladium-catalyzed silyl-Heck reactions. In particular, we wished to prepare vinylsilanes bearing benzyl groups (which have been shown to be highly effective in fluoride-promoted Hiyama cross-coupling reactions),^[14] phenyl groups (which are excellent substrates for both oxidation and acylation),^{[10, p], [2]} and 5-methyl-2-furyl groups (which can be oxidized under extremely mild conditions).^[15]

To this end, we were pleased to find that $\text{Bn}(\text{Me})_2\text{SiI}$, $\text{Ph}(\text{Me})_2\text{SiI}$ and (5-methyl-2-furyl) $(\text{Me})_2\text{SiI}$ could all be used in the reaction with 4-*tert*-butyl-styrene, leading to the corresponding *trans*-vinylsilanes (**17–19**) in high yield (Figure 2). Unfortunately, the new ligand does not completely solve steric limitations with respect to the silyl electrophile. With use of Et_3SiI only trace product **20** was observed. Nonetheless, the ability to prepare functionalized vinylsilanes using the palladium-catalyzed silyl-Heck reaction marks a significant advance in the utility of this methodology.

In conclusion, we have now shown that our second-generation ligand effectively promotes the preparation of vinylsilanes from styrene derivatives via the silyl-Heck reaction using the

bench stable Pd₂(dba)₃ precatalyst. Thus, silylation of styrene derivatives using this technology is now possible using completely bench-stable and commercially available catalytic precursors. Further, this new catalyst system expands the scope of vinylsilanes that can be prepared using this method.

Experimental Section

General Procedure

In a nitrogen-filled glovebox Pd₂(dba)₃ (25.0 μmol, 2.5 mol %), phosphine **2** (50.0 μmol, 5.0 mol %), dichloroethane (1.0 mL), triethylamine (1.0 mL), trimethylsilyl iodide (0.2 mL, 1.4 mmol, 1.4 equiv.) and alkene (1.0 mmol, 1 equiv) were added to a 4.0 mL vial containing a magnetic stir bar. The vial was sealed with a Teflon lined cap and removed from the glovebox. The vial was then placed in a 40 °C oil bath and the mixture was allowed to stir for 24 h. The vial was then cooled to room temperature, and opened to air. The reaction was quenched with ~0.5 mL of brine and diluted with ~1 mL diethyl ether. The layers were separated and the aqueous layer was extracted with a second ~1 mL of diethyl ether. The combined organic layers were dried over anhydrous magnesium sulfate, filtered, and concentrated *in vacuo*. The product was purified by flash column chromatography, vacuum distillation, or sublimation to yield the pure products.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Improved Synthesis of Vinylsilanes Using Second-Generation Catalyst.

Figure 2.
Second-generation silyl-Heck reaction for the synthesis of functionalized vinylsilanes.

Table 1

Interplay of Palladium Precatalyst and Ligand on Yield.

entry	Me ₃ SiH	solvent	temp	ligand	[Pd]	yield 3
1	2.0 eq	PhMe	50 °C	10.5 mol % <i>t</i> BuPPh ₂	5 mol % 1	98%
2	2.0 eq	PhMe	50 °C	10.5 mol % <i>t</i> BuPPh ₂	2.5 mol % Pd ₂ (dba) ₃	12%
3	1.4 eq	DCE	40 °C	7.5 mol % 2	2.5 mol % Pd ₂ (dba) ₃	91%
4	1.4 eq	DCE	40 °C	5 mol % 2	2.5 mol % Pd ₂ (dba) ₃	99%
5	1.4 eq	DCE	40 °C	5 mol % <i>t</i> BuPPh ₂	2.5 mol % Pd ₂ (dba) ₃	75%

Table 2

Scope of second-generation silyl-Heck reaction to form vinylsilanes.

$$\text{Ar-CH=CH}_2 \xrightarrow[\text{DCE, 40 } ^\circ\text{C, 24 h}]{\substack{2.5 \text{ mol } \% \text{ Pd}_2(\text{dba})_3, 5 \text{ mol } \% \text{ ligand} \\ 1.4 \text{ equiv Me}_3\text{SiH, Et}_3\text{N}}} \text{Ar-CH=CH-SiMe}_3$$

entry	product	yield with <i>t</i> BuPPh ₂ ^a	yield with 2 ^b
1	3	75%	99%
2	4	65%	96%
3	5	52% ^c	98% ^c
4	6	79%	96%
5	7	67%	94%
6	8	98% ^c	96% ^c
7	9	88%	96%
8	10	76% ^c	97% ^c
9	11	83% ^c	97% ^c
10	12	67%	99%

entry	product	yield with <i>t</i> BuPPh ₂ ^a	yield with 2 ^b
11		61% ^c	99% ^c
12	13	37% ^c	88% ^c
13	14	74%	95%
	15		

^aYield determined using NMR against internal standard.

^bIsolated yield.

^cUsing 2.0 equiv Me₃SiI.

Table 3Reactions of α -Olefins.

entry	temp	catalyst	yield 16
1	40 °C	2.5 mol % Pd ₂ (dba) ₃ 5 mol % 2	87% ^a
2	rt	2.5 mol % Pd ₂ (dba) ₃ 5 mol % 2	trace ^b
3	40 °C	2.5 mol % Pd ₂ (dba) ₃ 5 mol % ^t BuPPh ₂	20% ^b
4	rt	2 mol % 1 3 mol % 2	98% ^{a,c}

^a Isolated yield.^b Yield determined using NMR against internal standard^c Reference 3c.