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

Jesse R. McAtee,^a Sarah B. Krause,^a and Donald A. Watson^{a,*}

^a Department of Chemistry and Biochemistry, University of Delaware, Newark, Delaware 19716, USA Fax: (+1)-302-831-6335; e-mail: dawatson@udel.edu

Received: May 2, 2015; Revised: May 21, 2015; Published online: July 14, 2015

Dedicated to Prof. Stephen L. Buchwald on the occasion of his 60th birthday.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201500436.

Abstract: Recently we reported a second generation ligand, bis(3,5-di-*tert*-butylphenyl)(*tert*-butyl)-phosphine, for the preparation of allylsilanes 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 the widely available palladium pre-catalyst, tris(dibenzylidene-acetone)dipalladium(0) $[Pd_2(dba)_3]$. 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.

Keywords: alkenes; palladium; silyl-Heck reaction; vinylsilanes

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

In our initial report, we described the formation of trimethylvinylsilanes from stryene derivatives and Me₃SiI.^[3a] The optimal ligand in this palladium-catalyzed transformation was identified as *t*-BuPPh₂, 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 $Pd_2(dba)_3$ (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 a 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 *t*-BuPPh₂ also converts terminal alkenes bearing allylic hydrogen atoms (α olefins) to the corresponding allylsilanes 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 allylsilanes 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 exogeneous ligands.

As such, we have reinvestigated the silylation of styrene derivatives by Me_3SiI 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 $Pd_2(dba)_3$ 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-





Figure 1. Improved synthesis of vinylsilanes using our second generation catalyst.

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% t- $BuPPh_2$ in toluene at 50 °C, this transformation can be carried out in 98% isolated yield (Table 1, entry 1).^[3a] With 2.5 mol% $Pd_2(dba)_3$ (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% $Pd_2(dba)_3$ (DCE at 40 °C, conditions similar to those used in our second generation allylsilane 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%), a 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 $Pd_2(dba)_3$, the use of *t*-BuPPh₂ under the same conditions provides only 75% of the desired product (entry 5).

Using the catalyst derived from $Pd_2(dba)_3$ 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 silvl-Heck reactions, this catalyst system was tolerant of a wide range of functional groups, including aryl chlorides, aryl fluorides, esters, ethers, tertiary amines, silvl 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 Me₃SiI 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-BuPPh₂.^[13]

We also briefly examined the use of the $Pd_2(dba)_3/$ ligand **2** catalyst system for the silylation of α -olefins. Using 1-decene as a model system, this catalyst system provided the desired allylsilane **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 those 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*-BuPPh₂ (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 $Pd_2(dba)_3/ligand$ **2** catalyst system, we also wished to examine if vinylsilanes containing groups other than trimethylsilane could be prepared using palladium catalysis. Previously, Me₃SiI 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

Table 1. Interplay of palladium precatalyst and ligand on yield.

	t-	Bu	cat. [P Me ₃ S solvent, tem	d]/ligand sil, Et ₃ N perature, 24 h t-Bu	SiMe ₃	
Entry	Me ₃ SiI	Solvent	Temperature	Ligand	[Pd]	Yield of 3
1	2.0 equiv.	PhMe	50°C	10.5 mol% <i>t</i> -BuPPh ₂	5 mol% 1	98%
2	2.0 equiv.	PhMe	50°C	10.5 mol% t-BuPPh ₂	$2.5 \text{ mol}\% \text{ Pd}_2(\text{dba})_3$	12%
3	1.4 equiv.	DCE	40°C	7.5 mol% 2	$2.5 \text{ mol}\% \text{ Pd}_2(\text{dba})_3$	91%
4	1.4 equiv.	DCE	40°C	5 mol% 2	2.5 mol% $Pd_2(dba)_3$	99%
5	1.4 equiv.	DCE	40°C	5 mol% <i>t</i> -BuPPh ₂	2.5 mol% $Pd_2(dba)_3$	75%

© 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Table 2.	Scope	of the	second	generation	silyl-Heck	reaction
to form	vinylsil	anes.				

	2.5 mol% Pd ₂ (dba) _{3,} 5 mol% liga 1.4 equiv. Me ₃ Sil, Et ₃ N	ind	,SiMe₂
Ar 🔨	DCE. 40 °C. 24 h		Ar 🗸 🕬

Entry	Product	Yield with <i>t</i> -BuPPh2 ^[a]	Yield with 2 ^[b]
1	t-Bu SiMe ₃	75%	99%
2	SiMe ₃	65%	96%
3	CI SiMe ₃	52% ^[c]	98% ^[c]
4	F 6 SiMe ₃	79%	96%
5	EtO ₂ C 7	67%	94%
6	MeO 8	98% ^[c]	96% ^[c]
7	Me ₂ N 9 SiMe ₃	88%	96%
8	TBSO 10	76% ^[c]	97% ^[c]
9	SiMe ₃	83% ^[c]	97% ^[c]
10	SiMe ₃	67%	99%
11	BPin 13	61% ^[c]	99%[c]
12	Me SiMe ₃ Me	37% ^[c]	88%[c]
13	Me ₃ Si 15	74%	95%

[a] Yield determined using NMR against internal standard.
 [b] Isolated yield.

^[c] Using 2.0 equiv. Me₃SiI.

in fluoride-promoted Hiyama cross-coupling reactions),^[14] phenyl groups (which are excellent substrates for both oxidation and acylation),^[10,p,2] and 5methyl-2-furyl groups (which can be oxidized under extremely mild conditions).^[15] **Table 3.** Reactions of α -olefins.



Entry	Temperature	Catalyst	rield of 16
1	40°C	2.5 mol% $Pd_2(dba)_3$	87% ^[a]
		5 mol% 2	
2	r.t.	$2.5 \text{ mol}\% \text{ Pd}_2(\text{dba})_3$	trace ^[b]
		5 mol% 2	
3	40°C	$2.5 \text{ mol}\% \text{ Pd}_2(\text{dba})_3$	20% ^[b]
		5 mol% t-BuPPh ₂	
4	r.t.	2 mol% 1	98% ^[a,c]
		3 mol% 2	

^[a] Isolated yield.

^[b] Yield determined using NMR against internal standard.

^[c] Ref.^[3c]

To this end, we were pleased to find that $Bn(Me)_2SiI$, $Ph(Me)_2SiI$ and (5-methyl-2-furyl)- $(Me)_2SiI$ could all be used in the reaction with 4-*tert*-butylstyrene, leading to the corresponding *trans*-vinyl-silanes (**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 a trace of product **20** was observed. None-theless, 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 $Pd_2(dba)_3$ precatalyst. Thus, silylation of styrene derivatives



^[a] Using 2.0 equiv. Me₃Sil.

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

Adv. Synth. Catal. 2015, 357, 2317-2321

© 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Jesse R. McAtee et al.

using this technology is now possible using completely bench-stable and commercially available catalytic precursors. Furthermore, 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 $Pd_2(dba)_3$ (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 under vacuum. The crude residue was purified by flash column chromatography, vacuum distillation, or sublimation to yield the pure products.

Acknowledgements

The University of Delaware (UD), the Research Corporation (Cottrell Scholars Program), and the NSF (CAREER CHE1254360) are gratefully acknowledged for support. NMR and MS data were acquired at UD on instruments obtained with the assistance of NSF (NSF CHE0421224, CHE1229234 and CHE0840401) and NIH (NIH P20M103541, P20M104316, P30M110758, S10RR02692, and S10OD016267) funding.

References

[1] a) M. A. Brook, Silicon in Organic, Organometallic, and Polymer Chemistry, Wiley, Chichester, 2000; b) I. Fleming, A. Barbero, D. Walter, Chem. Rev. 1997, 97, 2063-2192; c) M. J. Curtis-Long, Y. Aye, Chem. Eur. J. 2009, 15, 5402-5416; d) T. Hiyama, E. Shirakawa, Organosilicon Compounds, in: Cross-Coupling Reactions, (Edf.: N. Miyaura), Springer Verlag, Berlin, Heidelberg, 2002, Vol. 219, pp 61-85; e) Y. Nakao, T. Hiyama, Chem. Soc. Rev. 2011, 40, 4893-4901; f) S. E. Denmark, J. H.-C. Liu, Angew. Chem. 2010, 122, 3040-3049; Angew. Chem. Int. Ed. 2010, 49, 2978-2986; g) K. Aikawa, Y. Hioki, K. Mikami, J. Am. Chem. Soc. 2009, 131, 13922-13923; h) D. A. Evans, Y. Aye, J. Am. Chem. Soc. 2006, 128, 11034-11035; i) K. Mikami, H. Wakabayashi, T. Nakai, J. Org. Chem. 1991, 56, 4337-4339; j) N. Asao, T. Shimada, Y. Yamamoto, J. Am. Chem. Soc. 1999, 121, 3797-3798; k) N. Asao, K. Nabatame, Y. Yamamoto, *Chem. Lett.* **2001**, *30*, 982–983; l) V. J. Meyer, M. Niggemann, *Eur. J. Org. Chem.* **2011**, *2011*, 3671–3674; m) Y. Nishimoto, M. Kajioka, T. Saito, M. Yasuda, A. Baba, *Chem. Commun.* **2008**, 6396–6398; n) R. Takeuchi, N. Ishii, M. Sugiura, N. Sato, *J. Org. Chem.* **1992**, *57*, 4189–4194; o) P. Pawluć, J. Szudkowska, G. Hreczycho, B. Marciniec, *J. Org. Chem.* **2011**, *76*, 6438–6441; p) M. Yamane, K. Uera, K. Narasaka, *Bull. Chem. Soc. Jpn.* **2005**, *78*, 477–486; q) M. M. Doyle, W. R. Jackson, P. Perlmutter, *Aust. J. Chem.* **1989**, *42*, 1907–1918; r) V. Gouverneur, B. Greedy, *Chem. Eur. J.* **2002**, *8*, 766–772; s) B. Greedy, V. Gouverneur, *Chem. Commun.* **2001**, 233–234; t) P. Pawluć, G. Hreczycho, J. Szudkowska, M. Kubicki, B. Marciniec, *Org. Lett.* **2009**, *11*, 3390–3393.

- [2] G. R. Jones, Y. Landais, *Tetrahedron* 1996, 52, 7599– 7662.
- [3] a) J. R. McAtee, S. E. S. Martin, D. T. Ahneman, K. A. Johnson, D. A. Watson, Angew. Chem. 2012, 124, 3723–3727; Angew. Chem. Int. Ed. 2012, 51, 3663–3667;
 b) S. E. S. Martin, D. A. Watson, J. Am. Chem. Soc. 2013, 135, 13330–13333; c) J. R. McAtee, G. P. A. Yap, D. A. Watson, J. Am. Chem. Soc. 2014, 136, 10166–10172; d) S. E. S. Martin, D. A. Watson, Synlett 2013, 24, 2177–2182.
- [4] For a nickel-catalyzed silyl-Heck reaction see: J. R. McAtee, S. E. S. Martin, A. P. Cinderella, W. B. Reid, K. A. Johnson, D. A. Watson, *Tetrahedron* 2014, 70, 4250–4256.
- [5] For early papers and process related to the silyl-Heck reaction see: a) H. Yamashita, T. Kobayashi, T. Hayashi, M. Tanaka, Chem. Lett. 1991, 20, 761–762; b) H. Yamashita, M. Tanaka, K. Honda, J. Am. Chem. Soc. 1995, 117, 8873–8874; c) N. Chatani, N. Amishiro, S. Murai, J. Am. Chem. Soc. 1991, 113, 7778–7780; d) N. Chatani, N. Amishiro, T. Morii, T. Yamashita, S. Murai, J. Org. Chem. 1995, 60, 1834–1840; e) J. Terao, K. Torii, K. Saito, N. Kambe, A. Baba, N. Sonoda, Angew. Chem. 1998, 110, 2798–2801; Angew. Chem. Int. Ed. 1998, 37, 2653–2656; f) J. Terao, Y. Jin, K. Torii, N. Kambe, Tetrahedron 2004, 60, 1301–1308.
- [6] Y. Pan, G. B. Young, J. Organomet. Chem. 1999, 577, 257–264.
- [7] a) C. Amatore, A. Jutand, F. Khalil, M. A. M'Barki, L. Mottier, *Organometallics* 1993, *12*, 3168–3178; b) I. J. S. Fairlamb, *Org. Biomol. Chem.* 2008, *6*, 3645–3656.
- [8] a) D. A. Watson, M. Su, G. Teverovskiy, Y. Zhang, J. García-Fortanet, T. Kinzel, S. L. Buchwald, *Science* 2009, *325*, 1661–1664; b) H. G. Lee, P. J. Milner, M. T. Colvin, L. Andreas, S. L. Buchwald, *Inorg. Chem. Acta.* 2014, *422*, 188–192.
- [9] Part 300683, Aspira Scientific, Milpitas, CA.
- [10] a) A. F. Littke, G. C. Fu, Angew. Chem. 2002, 114, 4350–4386; Angew. Chem. Int. Ed. 2002, 41, 4176–4211;
 b) U. Christmann, R. Vilar, Angew. Chem. 2005, 117, 370–378; Angew. Chem. Int. Ed. 2005, 44, 366–374;
 c) G. C. Fu, Acc. Chem. Res. 2008, 41, 1555–1564;
 d) D. S. Surry, S. L. Buchwald, Chem. Sci. 2011, 2, 27–50.
- [11] Ligand 2: Part 300685, Aspira Scientific, Milpitas, CA.
- [12] As determined by NMR and GC analysis.

- [13] In addition to lower yields, t-BuPPh₂ provides much less consistent results under these conditions (with runto-run yields sometimes varying by more than 40%). With ligand 2, yields of vinylsilanes were reproducible within 1–2% over multiple runs.
- [14] a) S. Denmark, S. Tymonko, J. Am. Chem. Soc. 2005, 127, 8004–8005; b) B. M. Trost, M. R. Machacek, Z. T. Ball, Org. Lett. 2003, 5, 1895–1898.
- [15] a) W. Adam, A. Rodriguez, *Tetrahedron Lett.* 1981, 22, 3505–3508; b) M. C. Norley, P. J. Kocieński, A. Faller, *Synlett* 1994, 77–78.