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Pd-catalyzed synthesis of symmetrical and unsymmetrical siloxanes†

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A palladium-catalyzed arylation of hydrosiloxanes was developed for the synthesis of symmetrical and unsymmetrical siloxanes. Reactive functional moieties such as hydroxy or cyano groups were able to tolerate the reaction conditions and several novel unsymmetrical siloxanes were synthesized in moderate to high yield.

Siloxanes are of interest for use as, for example, liquid crystals,[1] starting materials for cross-coupling reactions,[2] and biologically active compounds.[3] Many synthetic methods have been reported, but most involve the dehydration of silanols to form Si–O–Si bonds in their final step (Fig. 1(a)).[4] In such cases, structural modification is required before the formation of Si–O–Si bonds. Furthermore, these methods use highly reactive organometallic reagents and chlorosilanes for the formation of Si–C bonds. Therefore, the synthesis of many kinds of siloxanes, especially unsymmetrical siloxanes, is relatively complicated. A promising and efficient alternative is the transition-metal-catalyzed arylation of hydrosilanes, which can be used to synthesize aryl or alkyl silanes. Hydrosilanes are generally reducing agents in the presence of transition metals because hydrogen has a greater electronegativity than silicon.[5] However, coupling reactions of hydrosilanes with aryl or alkyl halides have been shown to occur in the presence of specific palladium, rhodium, or platinum catalysts.[6,7] In this communication, we report the arylation of hydrosiloxanes to synthesize symmetrical and unsymmetrical siloxanes (Fig. 1(b)). This reaction enables the structural conversion of siloxanes after the formation of the Si–O–Si bonds.

We initially examined the double arylation reaction of 1,1,3,3-tetramethyldisiloxane (**1**) with various aryl iodides in the presence of $Pd(P(t\text{-}Bu)_3)_2$ and *N*,*N*-diisopropylethylamine, and moderate-to-high yields were achieved (Table 1). The reactivity of compound **1** was higher than those of simple alkyl or aryl hydrosilanes, and it enabled completion of the reaction relatively quickly (4 h). Our previous work has shown that simple alkyl or aryl hydrosilanes require longer time to complete Pd-catalyzed arylation under similar conditions.[6f–i] There are two reasons for the high

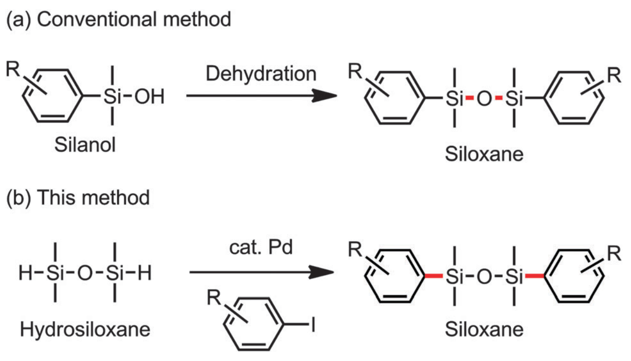
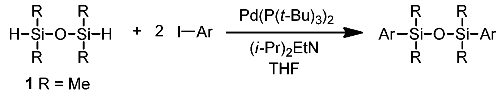
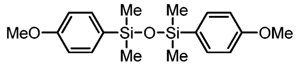


Fig. 1 Arylsiloxane preparation.

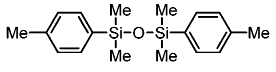
Table 1 Palladium-catalyzed double arylation of hydrosiloxane[a]



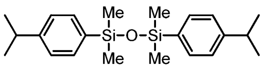
1 R = Me
2 R = Ph



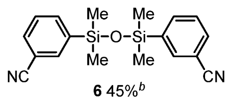
3 87%



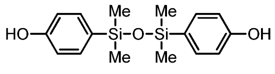
4 69%



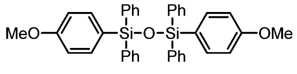
5 67%



6 45%[b]



7 64%



8 49%[b]

[a] Reaction conditions: $Pd(P(t\text{-}Bu)_3)_2$ (0.025 mmol), 1,1,3,3-tetramethyldisiloxane **1** or 1,1,3,3-tetraphenyldisiloxane **2** (0.50 mmol), Ar–I (1.25 mmol), $(i\text{-}Pr)_2EtN$ (2.0 mmol), THF (1.25 mL), 4 h. Isolated yields obtained after purification by preparative TLC (SiO_2) are listed. [b] Toluene was used as solvent instead of THF.

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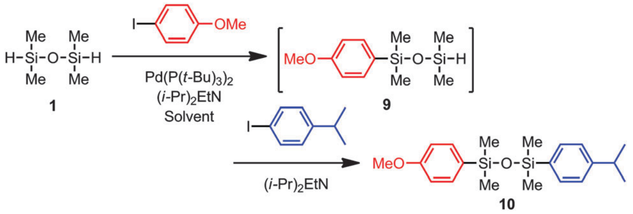
† Electronic supplementary information (ESI) available: Detailed experimental procedures and copies of ^{1}H and ^{13}C NMR. See DOI: 10.1039/c3cc46294c

reactivity of hydrosiloxanes: steric effects (compound **1** has less sterically hindered substituent groups adjacent to the Si–H bond) and the electron-withdrawing dimethylsiloxy (–OSiMe$_2$H) group. This group lowers the energy level of the σ* orbital of the Si–H bond to accelerate the oxidative addition of the Si–H bond to the Pd(0) species. It also lowers the reducing ability of Si–H, and so decreases the undesired reduction of aryl iodides. The electronic properties of the aromatic ring greatly affect the yield. Electron-rich aryl iodides gave good-to-high yields (**3**, **4**, **5**, and **7**) and electron-deficient aryl iodides gave lower yields (**6**). This trend is consistent with the results of our previous work.[6] In the case of the electron-deficient group, toluene was a more effective solvent than THF. Functional groups such as OH and CN tolerated these reaction conditions (**6** and **7**). Hydroxy groups are known to react with hydrosilanes in the presence of a transition metal to form silyl ether.[8] Therefore, the coupling of iodides and hydrosilanes (the desired reaction) is more reactive than that of hydroxyl groups and hydrosilanes (a side reaction). The double arylation of 1,1,3,3-tetraphenyldisiloxane (**2**) was also examined. The desired double arylated product was obtained in 49% yield in toluene. The double arylation of compound **2** took longer time and gave a lower yield than that of compound **1**; this was likely due to the steric bulkiness of the phenyl groups.

We next examined the stepwise arylation of compound **1** to synthesize unsymmetrical disiloxanes. A solution of Ar^1–I (aryl iodide for the first step), compound **1**, *N*,*N*-diisopropylethylamine, and a catalytic amount of Pd(P(*t*-Bu)$_3$)$_2$ was stirred for several hours to produce the mono-arylated product **9** *in situ*. After consumption of Ar^1–I was confirmed by GC–MS, Ar^2–I (aryl iodide for the second step) was added to the solution, and the mixture was stirred until the mono-arylated product **9** was consumed and unsymmetrical disiloxane **10** was produced. The results of reaction conditions screening using 4-iodoanisole and 4-iodocumene as model substrates are summarized in Table 2. The stepwise arylation of compound **1** proceeded in higher yields in less polar solvents, with toluene being the best (entry 5). Cooler reactions gave higher yields because the reduction of aryl iodides and the double arylation of Ar^1–I were suppressed at lower temperatures (entry 6).

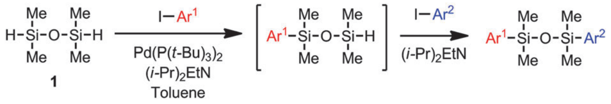
Table 2 Optimization of reaction conditions for palladium-catalyzed stepwise arylation of 1,1,3,3-tetramethyldisiloxane[a]

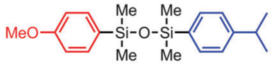


Entry	Solvent	Temperature	Yield[b] (%)
1	THF	rt	53
2	CH$_2$Cl$_2$	rt	60
3	CH$_3$CN	rt	53
4	NMP	rt	39
5	Toluene	rt	70
6	**Toluene**	**0 °C**	**84**

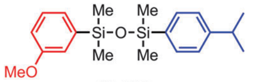
[a] Reaction conditions: (i) Pd(P(*t*-Bu)$_3$)$_2$ (0.025 mmol), 1,1,3,3-tetramethyldisiloxane **1** (0.75 mmol), 4-iodoanisole (0.50 mmol), (i-Pr)$_2$EtN (1.0 mmol), solvent (1.0 mL), 2 h; (ii) 4-iodocumene (1.0 mmol), (i-Pr)$_2$EtN (2.0 mmol), additional 1 d. [b] GC yield with dodecane as internal standard.

Table 3 Palladium-catalyzed stepwise arylation of 1,1,3,3-tetramethyldisiloxane (scope of the substrate)[a]





10 68%



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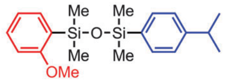
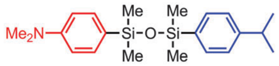
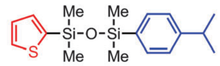


12 82%



13 44%



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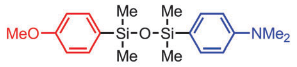
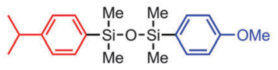


15 37%

16 62%

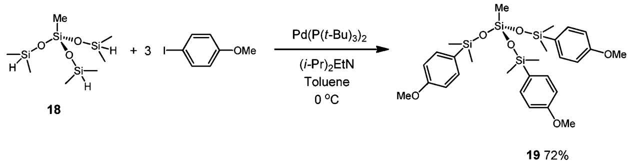


17 55%

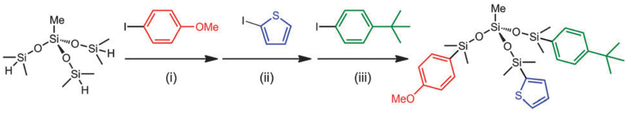
[a] Reaction conditions: (i) Pd(P(*t*-Bu)$_3$)$_2$ (0.050 mmol), 1,1,3,3-tetramethyldisiloxane **1** (1.5 mmol), Ar^1–I (1.0 mmol), (i-Pr)$_2$EtN (2.0 mmol), toluene (2.0 mL), 0 °C, 2 h; (ii) Ar^2–I (2.0 mmol), (i-Pr)$_2$EtN (4.0 mmol), additional 1–2 d. Isolated yields obtained after purification by preparative TLC (SiO$_2$) are listed.

Under the optimized reaction conditions (entry 6), we investigated the scope of the stepwise arylation of compound **1** (Table 3). *para*-, *meta*-, and *ortho*-substituted aryl iodides could be used for the first arylation (**10–12**). *ortho*-Substituted aryl iodide gave high yield despite steric hindrance (**12**). Heterocycles such as thiophene could also be used for the stepwise arylation (**14**). Changing the order of addition of the aryl iodides resulted in a slightly decreased yield (**10** *vs.* **17**). Several kinds of aryl iodides, including those with a reactive cyano group, could be used for the second arylation (**10**, **15**, and **16**).

These promising results suggested the possibility of triple arylation. The coupling of 3-((dimethylsilyl)oxy)-1,1,3,5,5-pentamethyltrisiloxane (**18**) and 3.5 equivalents of 4-iodoanisole gave the triple arylated product **19** in 72% yield (Scheme 1). The triple stepwise arylation of compound **18** was also carried out and the



Scheme 1 Palladium-catalyzed triple arylation of hydrosiloxane. Reaction conditions: Pd(P(*t*-Bu)$_3$)$_2$ (0.025 mmol), 3-((dimethylsilyl)oxy)-1,1,3,5,5-pentamethyltrisiloxane **18** (0.50 mmol), 4-iodoanisole (1.75 mmol), (i-Pr)$_2$EtN (3.0 mmol), toluene (1.75 mL), 0 °C, 1 d. Isolated yield obtained after purification by preparative TLC (SiO$_2$) is listed.



18

20 20%

Scheme 2 Palladium-catalyzed triple-stepwise arylation of hydrosiloxane. Reaction conditions: (i) Pd(P(t-Bu)$_3$)$_2$ (0.025 mmol), 3-((dimethylsilyl)oxy)-1,1,3,5,5-pentamethyltrisiloxane **18** (0.75 mmol), 4-iodoanisole (0.50 mmol), (i-Pr)$_2$EtN (1.0 mmol), toluene (2.25 mL), 0 °C, 2 h; (ii) (i-Pr)$_2$EtN (1.75 mmol), 2-iodothiophene (0.875 mmol), 0 °C, 4 h; (iii) (i-Pr)$_2$EtN (1.75 mmol), 1-(*tert*-butyl)-4-iodobenzene (0.875 mmol), 0 °C, 1 d. Isolated yield obtained after purification by preparative TLC (SiO$_2$) followed by preparative HPLC (ODS) is listed.

desired product **20** was synthesized in 20% yield (Scheme 2). Despite the low yield of product **20**, this synthetic method has the advantage of producing such complicated molecules in one step from commercially available starting materials.

In conclusion, we developed a novel method for the preparation of symmetrical and unsymmetrical siloxanes. The simplicity of the one-pot process and the resulting high yields make this procedure a good method for the synthesis of siloxanes. It can also be used to convert siloxanes to more complicated molecules after the formation of the Si–O–Si bonds. Further applications of this method to the synthesis of other hydrosilanes are currently under study.

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