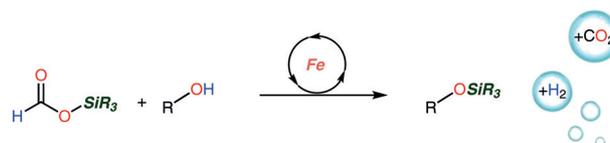


Iron-Catalyzed Silylation of Alcohols by Transfer Hydrosilylation with Silyl Formates

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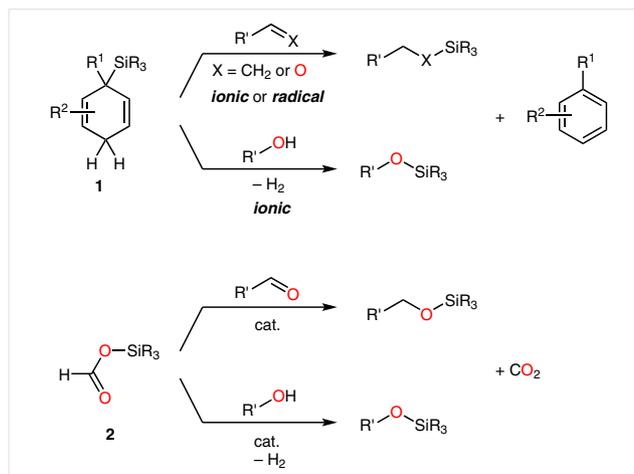
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Abstract An iron catalyst is shown for the first time to promote transfer hydrosilylation with silyl formates and is utilized for the silylation of alcohols. Attractive features of this protocol include the use of an earth-abundant transition-metal catalyst, mild reaction conditions, and the release of gases as the only byproducts (H_2 and CO_2).

Key words silylation, iron catalysis, silanes, alcohols, silyl formates, hydrosilanes, CO_2

Transfer hydrosilylation consists in the formal transfer of a hydrosilane moiety (R_3SiH) from a silicon reagent (that bears no Si–H bond) to a substrate.¹ It is reminiscent of transfer hydrogenation where a hydrogen donor (e.g., isopropanol or formic acid) is used to deliver an equivalent of H_2 to reduce a C=C or C=O unsaturation.² Although the two methodologies are conceptually related, examples of transfer hydrosilylation reactions have only been disclosed recently with the use of silicon-substituted cyclohexa-1,4-dienes (1,4-CHDN, **1**) able to deliver a hydrosilane equivalent with the concomitant release of a benzene derivative (Scheme 1). While Studer *et al.* explored the radical activation of these hydrosilane surrogates in the transfer hydrosilylation of alkenes,^{3,4} Oestreich *et al.* exploited their ionic activation for the transfer hydrosilylation of carbonyls, alcohols, and alkenes.^{5–7} In 2016, Cantat *et al.* introduced a new type of hydrosilane surrogates with the use of silyl formates (**2**, R_3SiOCHO).⁸ While silyl formates are usually observed as products or intermediates in the hydrosilylation of CO_2 ,^{9–12} the reversible decarboxylation reaction was used to promote the transfer hydrosilylation of aldehydes (Scheme 1).⁸ An advantage of this methodology is the release of a gaseous byproduct, CO_2 . Earlier this year, the same methodology was employed to convert alcohols into silyl ethers by de-

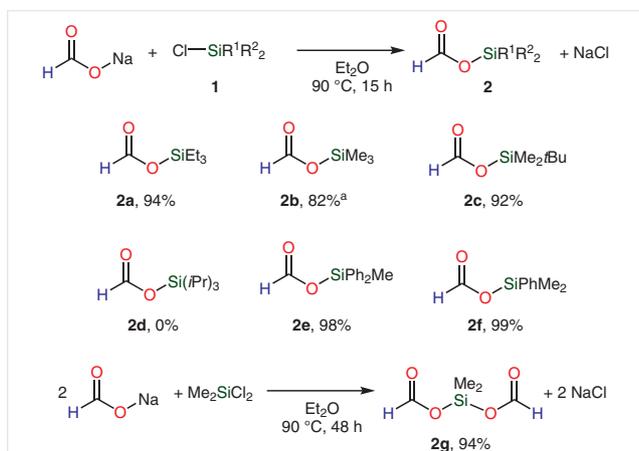
hydrogenative and decarboxylative silylation of O–H bonds with silyl formates.¹³ Importantly, the use of silyl formates in transfer hydrosilylation reactions requires a catalyst able to promote the decarboxylation of a formate ligand, and the silylation of alcohols and aldehydes could only be achieved using molecular ruthenium(II) complexes.^{8,13} Further utilization of silyl formates would strongly benefit from the use of noble-metal-free catalysts and, herein, we show for the first time that iron complexes, supported by a chelating tetraphosphine ligand, enable the silylation of alcohols by transfer hydrosilylation with silyl formates. An improved synthesis of silyl formates is also reported.



Scheme 1 Surrogates of hydrosilanes used in transfer hydrosilylation

Although silyl formates can be obtained by catalytic hydrosilylation of CO_2 ,^{9–12} a more convenient access to these reagents relies on the silylation of formic acid with chlorosilanes, in the presence of an organic base, such as pyridine or triethylamine.⁸ Nevertheless, using this synthesis,

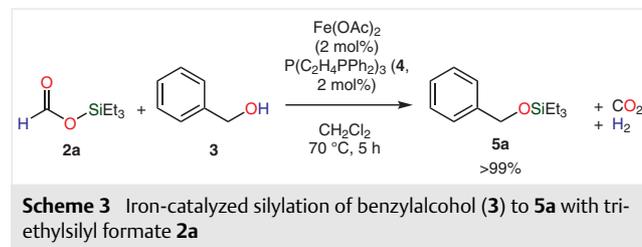
free formic acid can be found as an impurity in samples of silyl formates and the presence of such protic species influences the catalytic activity in transfer hydrosilylation. To circumvent this limitation, a new route was exploited where chlorosilanes are reacted with sodium formate in ethereal solutions (Scheme 2). Heating a Et_2O solution of Et_3SiCl at 90°C in the presence of 1.4 equiv NaOCHO after 12 h, results in the formation of Et_3SiOCHO (**2a**). After filtration aimed at removing the insoluble NaCl and NaOCHO precipitate and removal of the volatiles under reduced pressure, **2a** was isolated in 94% yield. The procedure was successfully applied to the synthesis of a variety of silylformates, including trimethylsilyl (**2b**), *tert*-butyldimethylsilyl (TBDMS, **2c**), diphenylmethylsilyl (DPMS, **2e**), and phenyldimethylsilyl (PDMS, **2f**) substituents. The yield is somewhat lower for **2b** (82%), compared to **2c,e-g** (92–99%), because of the high volatility of the product and TMS-Cl , and the reaction was carried out at 60°C . The bulky triisopropylsilyl (TIPS) formate (**2d**) could not be obtained in satisfactory yields and its synthesis was performed with formic acid, in the presence of triethylamine.⁸ Diethyldichlorosilane was efficiently converted into the bisformate derivative **2g** (94% yield) upon reaction with an excess sodium formate (Scheme 2). Silyl formates **2b** and to a lesser extent **2a** were found to be sensitive towards moisture as they are readily hydrolyzed to formic acid and silanols and siloxanes.



Scheme 2 Synthesis of silyl formates by salt metathesis from sodium formates and chlorosilanes. ^a The reaction was performed at 60°C .

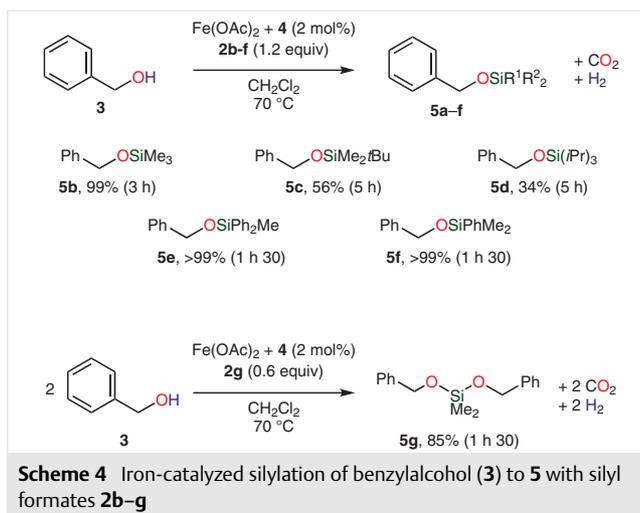
Having in hand a collection of silyl formates bearing different alkyl and aryl substituents on the silicon center, their reactivity was evaluated in the dehydrogenative and decarboxylative silylation of alcohols. Silyl ethers are useful chemicals, utilized for the temporary protection of alcohols but also for the synthesis of hybrid materials.^{14–16} Two main routes have been developed to access the O–Si linkage. They rely either on chlorosilanes or hydrosilanes. While the reaction between an alcohol and a chlorosilane, in the presence

of a base, generates a stoichiometric amount of a salt,^{17–19} the catalytic dehydrogenative silylation with hydrosilanes has the advantage of releasing H_2 gas as the only byproduct.^{20–26} This year, our group showed that replacing the hydrosilane reagent with a silyl formate enabled the silylation of a variety of alcohols when a catalytic amount of (triphos) $\text{Ru}(\text{OAc})_2$ (triphos = 1,1,1-tris(diphenylphosphinomethyl)ethane) was added.¹³ The role of the Ru catalyst is to promote the decarboxylation of a formate ligand to yield a reactive hydride complex. Based on this assumption, we turned our attention to iron catalysts that are able to engage in similar reaction paths. In particular, Laurency, Ludwig, Beller *et al.* demonstrated the potential of iron(II) salts supported by the tetraphosphine ligand $\text{P}(\text{C}_2\text{H}_4\text{PPh}_2)_3$ (**4**, also labelled PP_3) in the catalytic decomposition of formic acid to H_2 and CO_2 .²⁷ Capitalizing on this work, the silylation of benzylalcohol (**3**) was attempted with Et_3SiOCHO (**2a**), in the presence of 2 mol% $\text{Fe}(\text{OAc})_2$ and 2 mol% **4**. After 5 h at 70°C in CH_2Cl_2 , the reagents were fully consumed and **5a** was formed in quantitative yield (Scheme 3) [only 5% **5a** were observed in the absence of catalyst]. ^1H NMR and ^{13}C NMR spectra of the crude mixture also confirmed the production of H_2 and CO_2 as byproducts of the reaction. The formation of silyl ether **5a** from **2a** represents the second example of a dehydrogenative silylation of alcohols using silyl formates as surrogates of hydrosilanes.¹³ Although the reaction proceeded well in THF, acetonitrile or benzene, the best conversions were noticed in CH_2Cl_2 (see Supporting Information). Decreasing the reaction temperature to 25°C also enabled formation of **5a** in 98% yield, after a prolonged reaction time of 21 h. In comparison, (triphos) $\text{Ru}(\text{OAc})_2$ was found inactive at room temperature (RT).¹³



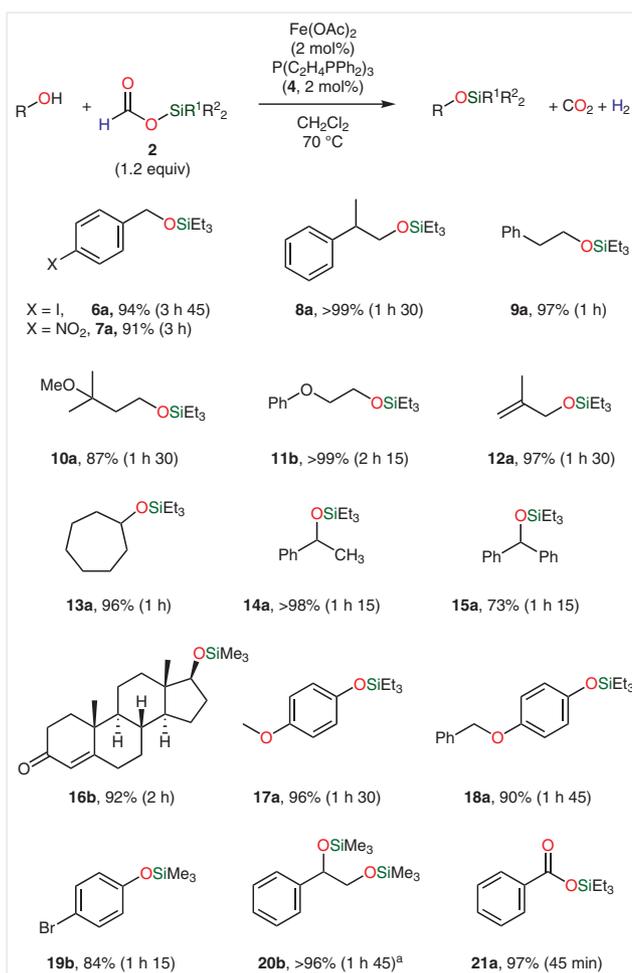
Scheme 3 Iron-catalyzed silylation of benzylalcohol (**3**) to **5a** with triethylsilyl formate **2a**

The influence of the silyl group was then investigated on the transfer hydrosilylation reaction. All the silyl formates **2a–g** successfully reacted with **3** to yield silyl ethers **5a–g**, respectively (Scheme 4). Full conversion of **3** was reached within 3 h at 70°C for the trimethylsilyl derivative **2b** while the production of the more congested congeners **5c** and **5d**, bearing TBDMS and TIPS groups, were limited to 56% and 34% yield, respectively, after 5 h. Interestingly, the aryl-substituted silyl formates **2e** and **2f** and the bis-formate **2g** were fully converted into the corresponding silyl ethers **5e–g** within only 1.5 h, presumably because of the enhanced acidic character at the silicon center.



The potential of the $\text{Fe}(\text{OAc})_2/\mathbf{4}$ catalytic system was further evaluated in the dehydrogenative and decarboxylative silylation of alcohols having various functional groups (Scheme 5). Aliphatic as well as aromatic alcohols were successfully silylated with Et_3SiOCHO (**2a**), as exemplified with the formation of **6a–15a** (from primary and secondary alcohols) and **17a,18a** (from phenols). Primary and secondary alcohols exhibit similar reactivities as attested with the formation of silyl ethers **8a** and **13a** in >96% yields from 2-phenyl-1-propanol and cycloheptanol, respectively. As such, the bis-silylation of the polyfunctional 1-phenyl-1,2-ethanediol to **20b** is readily achieved with 2 equiv **2b**. Importantly, the method is also tolerant to oxidizing functional groups such as iodo, nitro, keto, and vinyl groups (see **6a**, **7a**, **12a**, and **16b**). For example, despite the reductive conditions imposed by the combination of silyl formate **2b** and the $\text{Fe}(\text{OAc})_2/\mathbf{4}$ catalyst, the silylation of testosterone to **16b** is carried out in 92% yield within 2 h without reduction of the enone functionality. Overall, the $\text{Fe}(\text{OAc})_2/\mathbf{4}$ presents a catalytic activity and a reaction scope very similar to (triphos)Ru(OAc)₂, with the benefit of utilizing a first-row transition-metal complex. This is further confirmed with the isolation of silyl ester **21a** that can be obtained from the silylation of benzoic acid with **2a** and either the iron or ruthenium catalyst.¹³

Preliminary mechanistic investigations with (triphos)Ru(OAc)₂ have shown that the silylation of alcohols with silyl formates results from a two-step process where the metal complex first catalyzes a *trans*-silylation equilibrium between the reagents to yield the corresponding silyl ether and free formic acid.¹³ The ruthenium plays a second role by catalyzing the irreversible decomposition of formic acid to H₂ and CO₂, thereby driving the production of silyl ether to completion. The transient formation of free formic acid was observed by ¹H NMR spectroscopy upon silylation of **3** with silyl formate **2a** and $\text{Fe}(\text{OAc})_2/\mathbf{4}$ (Scheme 3), sug-



Scheme 5 Scope of the transfer dehydrogenative silylation of alcohols with silyl formates. Reagents and conditions: alcohol (0.50 mmol), silyl formate (0.60 mmol), $\text{Fe}(\text{OAc})_2$ (2 mol%), **4** (2 mol%), CH_2Cl_2 (2.0 mL; 0.25 M); 70 °C. Isolated yields are provided for reaction times indicated in brackets. ^a The stoichiometry was adapted with the use of 1.2 mmol **2a**.

gesting that the iron catalyst follows a similar reaction path. The hypothesis was further confirmed as $\text{Fe}(\text{OAc})_2/\mathbf{4}$ readily dehydrogenates formic acid to H₂ and CO₂, at 90 °C under base-free conditions in CH_2Cl_2 (see Supporting Information). To gain deeper insights into the nature of the active iron(II) species, the stoichiometric reaction between $\text{Fe}(\text{OAc})_2$, **4** and 2 equiv Et_3SiOCHO (**2a**) was carried out in CH_2Cl_2 at 70 °C. Rapid gas evolution indicated the transformation of the iron acetate complex. Isolation of the resulting iron complex by recrystallization from CH_2Cl_2 /pentane enabled the structure determination of **22** by X-ray diffraction (Figure 1). Compound **22** is an 18-electron iron(II) hydrido chloro complex supported by the tetraphosphine ligand **4**, coordinated with a $\kappa\text{-4}$ mode.^{28,29} The formation of **22** demonstrates the ability of $\text{Fe}(\text{OAc})_2/\mathbf{4}$ to yield iron-hydride species in the presence of silyl formates and this

chemical behavior is consistent with previous findings from Beller *et al.* on the reactivity of iron(II) complexes supported by **4** in the presence of formic acid.³⁰

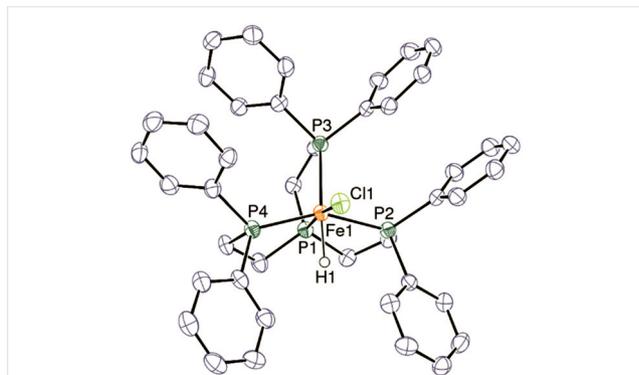
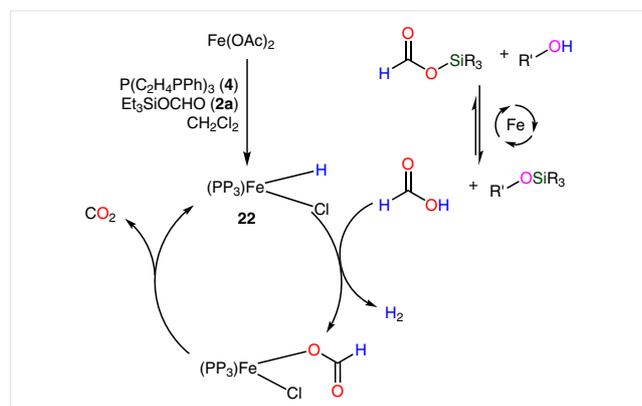


Figure 1 View of complex **22** ($[\text{Fe}(\mathbf{4})\text{HCl}]$). Displacement ellipsoids are drawn at the 50% probability level and carbon-bound hydrogen atoms are omitted.

The catalytic implication of **22** was tested in the silylation of **3**. As expected, **22** possesses a catalytic activity similar to $\text{Fe}(\text{OAc})_2/\mathbf{4}$ and the complex promotes the formation of **5a** in the reaction described in Scheme 3. Based on these data, a mechanistic proposal is drawn in Scheme 6: an active iron(II) hydride species (likely **22**) is formed from $\text{Fe}(\text{OAc})_2$ in the presence of **4** and the silyl formate reductant. The complex is then able to decompose HCO_2H by successive dehydrogenation and decarboxylation steps, in order to displace the equilibrium involving the alcohol, the silyl ether, and free formic acid to the formation of the silyl ether product.



Scheme 6 Proposed mechanism for the dehydrogenative and decarboxylative coupling of alcohols and silyl formates catalysed by $\text{Fe}(\text{OAc})_2/\mathbf{4}$

In conclusion, we have described an efficient synthetic route for the synthesis of silyl formates from chlorosilanes and sodium formates and the first iron catalysts able to utilize silyl formates as surrogates of hydrosilanes.³¹ $\text{Fe}(\text{OAc})_2$, supported by $\text{P}(\text{C}_2\text{H}_4\text{PPh}_2)_3$ (**4**), is an efficient catalyst for the dehydrogenative and decarboxylative silylation of alcohols

to silyl ethers. The iron catalyst exhibits a catalytic behavior similar to $(\text{triphos})\text{Ru}(\text{OAc})_2$ in this reaction and was shown to produce iron-hydride species in dichloromethane, in the presence of silyl formates. Further efforts are underway in our laboratories to exploit the reducing ability of such intermediates in new transfer hydrosilylation reactions.

Funding Information

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Supporting Information

Supporting information for this article is available online at <https://doi.org/10.1055/s-0036-1591508>.

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- (31) **General Procedure for the Synthesis of Silylformates (2)**
In a glovebox, a flame-dried round-bottom flask equipped with a Solv-seal connection and a J-Young valve was charged with sodium formate (42 mmol, 1.4 equiv) and suspended in Et₂O (30 mL, c 1 M). To the resulting suspension was added the silyl chloride **1** (30 mmol, 1 equiv). The flask was then sealed, brought out of the glovebox, and immersed in a pre-heated oil bath at 90 °C (oil temperature). Unless otherwise stated, the reactions were generally complete within 15 h. The mixture was then filtered over a sintered glass funnel and the solvent removed by distillation under vacuum at 0 °C. No other purification was needed. The formation of silyl formate was confirmed by ¹H, ¹³C NMR, and elemental analysis.

Analytical Data for 2e (Representative Example)

¹H NMR (200 MHz, *d*₈-THF): δ = 8.18 (s, 1 H), 7.71–7.56 (m, 4 H), 7.38 (m, 6 H), 0.85 (s, 3 H). ¹³C NMR (50 MHz, *d*₈-THF): δ = 160.88, 135.09, 134.47, 130.99, 128.53, –2.64. Anal. Calcd (%) for C₁₄H₁₄O₂Si (243.3 g mol⁻¹): C, 69.39; H, 5.82. Found: C, 69.03; H, 5.67.

General Procedure for the Transfer Hydrosilylation of Alcohols with Silylformates 5–21

In a glovebox, a flame-dried flask equipped with a J-Young valve was charged with Fe(OAc)₂ (1.7 mg, 0.01 mmol, 2 mol%) and P(C₂H₄PPh₂)₃ (**4**, 6.7 mg, 0.01 mmol, 2 mol%) followed by CH₂Cl₂ (2 mL, c 0.25 M). To the resulting white suspension were sequentially added the alcohol (0.5 mmol, 1 equiv) and the silyl formate **2** (0.6 mmol, 1.2 equiv per hydroxyl group) reagents. The flask was then sealed, brought out of the glovebox, and immersed in a pre-heated oil bath at 90 °C (oil temperature). A purple coloration appeared when heated. At this temperature, all the reactions were generally complete within 1.5 h with silyl formates **2**. The coloration observed turned from purple to bright orange. Yields of silyl ethers were determined after isolation and purification by column chromatography on silica gel.

Analytical Data for 16b (Representative Example)

¹H NMR (200 MHz, *d*₈-THF): δ = 5.59 (s, 1 H), 3.58 (m, 2 H), 1.89 (m, 14 H), 1.20 (s, 3 H), 1.12–0.78 (m, 4 H), 0.75 (s, 3 H), 0.06 (s, 9 H). ¹³C NMR (50 MHz, *d*₈-THF): δ = 195.30, 167.91, 122.75, 80.52, 53.42, 49.26, 41.92, 37.52, 35.86, 35.00, 34.79, 32.75, 31.49, 30.85, 29.81, 22.38, 19.69, 15.74, 9.80, –1.61. ESI-HRMS: *m/z* [M + H]⁺ calcd for C₁₄H₂₅O₂Si⁺: 361.2557; found: 361.2557.