Iron Catalysis

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Efficient Hydrosilylation of Carbonyl Compounds with the Simple Amide Catalyst $[Fe\{N(SiMe_3)_2\}_2]$**

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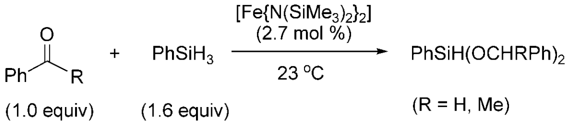
The hydrosilylation of carbonyl groups is an important synthetic transformation that is widely employed in the laboratory and in industry.[1] This reaction features high atom economy and combines reduction of the carbonyl functionality with alcohol protection in a single step.[1] The alkoxysilane products are valuable synthetic intermediates and monomers for organosilane polymers and materials. The most common and active catalysts for this reaction are based on precious metals, such as rhodium and ruthenium.[1] However, the high cost of these metals and concerns about trace toxic metal impurities in the organic products have focused considerable attention on the development of alternative catalysts.[2] In particular, catalysts based on iron are highly attractive, since this metal is abundant, inexpensive, and relatively nontoxic.[3] Recently, Nishiyama and coworkers[4a–c] and Beller and co-workers[4d–f] reported the use of $Fe(OAc)_2$ (5 mol %) combined with nitrogen-, phosphorus-, or sulfur-based ligands for the hydrosilylation of carbonyl functionalities[4] at 65 °C. Chirik and co-workers also demonstrated an efficient hydrosilylation system based on bis(imino)pyridine iron dialkyl complexes.[5] Although considerable savings can be achieved by the use of inexpensive metals, specialized ligands and activators may lead to substantial costs.[6,7]

During our attempts to develop new iron catalysts, we obtained the unusual δ-agostic iron η^1-silane complex $[(MeQn_2SiH)Fe\{N(SiMe_3)_2\}_2]$ (Qn = 8-quinolyl).[8] When the reactivity of this complex toward carbonyl compounds was tested, it became apparent that the $MeQn_2SiH$ ligand readily dissociated as a free species in solution, and further heating of the reaction mixture at 60 °C produced the hydrosilylation product.[8] Thus, we investigated the simple iron(II) silylamide $[Fe\{N(SiMe_3)_2\}_2]$[9] as a reactive, low-coordination-number catalyst precursor for transformations involving hydrosilanes. Herein we report the use of $[Fe\{N(SiMe_3)_2\}_2]$ as a simple, cost-effective, environmentally benign, and highly active catalyst for the hydrosilylation of organic carbonyl groups. At mild temperatures (ca. 23 °C), catalyst loadings as low as 0.01 mol % may be used.

The addition of acetophenone (37 equiv) and $PhSiH_3$ (58 equiv) to $[Fe\{N(SiMe_3)_2\}_2]$ in C_6D_6 resulted in the rapid consumption of acetophenone at room temperature [Eq. (1)]. Analysis of the products by NMR spectroscopy revealed an approximately 1:6.5 ratio of $PhSiH_2(OCHMePh)$ and $PhSiH(OCHMePh)_2$. Under similar conditions, benzaldehyde was readily reduced to $PhHSi(OCH_2Ph)_2$ as the dominant product within 3 h (ca. 90 %).



(1)

Secondary silanes are also suitable substrates for hydrosilylation catalyzed by $[Fe\{N(SiMe_3)_2\}_2]$. With Ph_2SiH_2 as the reductant, aldehydes and ketones underwent facile catalytic hydrosilylation at 23 °C to cleanly afford the corresponding silyl ethers $Ph_2SiHOCHRR'$ (Table 1). Thus, rapid hydrosilylation of benzaldehyde and acetophenone occurred at 23 °C, with a catalyst loading of 2.7 mol % (Table 1, entries 1 and 2). With 0.31 mol % of the catalyst, the hydrosilylation of acetophenone proceeded to completion within 1.1 h (Table 1, entry 3). Acetophenone underwent highly efficient hydrosilylation with a catalyst loading of just 0.03 mol % (Table 1, entry 4). Even in the presence of 0.01 mol % of $[Fe\{N(SiMe_3)_2\}_2]$, the complete hydrosilylation of *p*-methoxyacetophenone (10000 turnovers) occurred in less than 17 h at 23 °C (Table 1, entry 5).

The alkyl-substituted ketones 3-pentanone and cyclohexanone were rapidly reduced at 23 °C (Table 1, entries 6 and 7). At a catalyst loading of 0.03 mol %, cyclohexanone underwent rapid and clean hydrosilylation in 20 h at 23 °C (Table 1, entry 8). Under similar conditions, the hydrosilylation of 3-pentanone was initially very rapid, with a turnover rate of $> 40\ min^{-1}$, and then slowed down, although 2200 turnovers had been reached after 20 h (Table 1, entry 9).

Notably, 5-hexen-2-one, cyclopropyl phenyl ketone, *p*-bromoacetophenone, and *p*-dimethylaminobenzaldehyde were conveniently hydrosilylated to the corresponding silylethers: the C=C, cyclopropyl, bromoaryl, and dimethylamino groups were not affected (Table 1, entries 10–13). *p*-Cyanoacetophenone was viewed as a more challenging substrate, as the nitrile functionality could potentially trap the unsaturated iron center; however, this compound underwent hydrosilylation with a catalyst loading of 1.2 mol % in 17 h (Table 1, entry 14).

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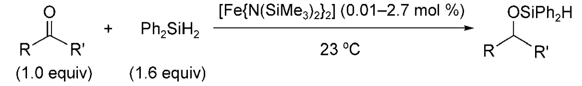
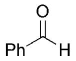
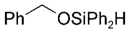
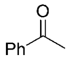
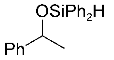
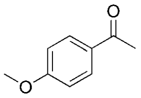
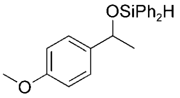
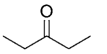
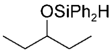
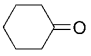
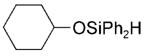
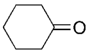
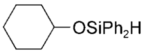
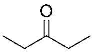
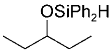
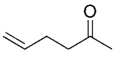
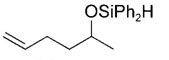
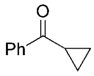
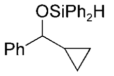
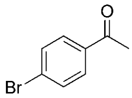
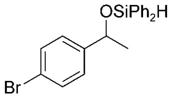
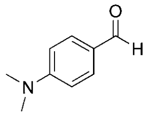
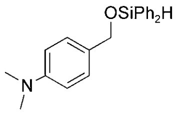
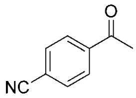
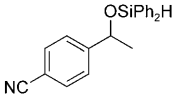
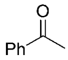
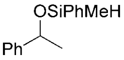
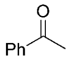
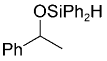
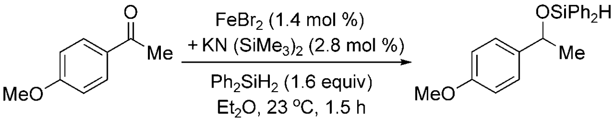
Table 1: Hydrosilylation of ketones under the catalysis of $[Fe\{N(SiMe_3)_2\}_2]$.[a]



Entry	Cat. [mol %]	Substrate	*t* [h]	Conv.[b] [%]	Product
1	2.7		2	> 98	
2	2.7		0.7	> 98	
3	0.31		1.1	> 98	
4	0.03		18	> 98	
5	0.01		2.2 17	41 > 98	
6	2.7		0.7	> 98	
7	2.7		0.7	> 98	
8	0.03		0.7 4 20	26 61 > 98	
9	0.03		0.3 20	26 67	
10	1.0		1.2 5.5	88 95	
11	0.23		9 28	70 96	
12	0.76		1	> 98	
13	0.54		0.5	> 98	
14	1.2		17	> 98	
15[c]	2.7		0.7	> 98	
16[d]	0.55	 (neat)	0.5	> 98	

[a] Reaction conditions: substrate (0.49–1.47 mmol), Ph_2SiH_2 (1.6 equiv), 23 °C, C_6D_6. [b] Conversion was determined by NMR spectroscopy on the basis of the consumption of the aldehyde/ketone, and the identity of the product was confirmed by GC–MS. [c] $PhMeSiH_2$ was used instead of Ph_2SiH_2. [d] The reaction was carried out without a solvent.

$PhMeSiH_2$ was also found to be effective for the hydrosilylation of acetophenone (Table 1, entry 15). Interestingly, these reactions occur readily in the absence of a solvent. Thus, the solvent-free hydrosilylation of acetophenone was complete in less than 0.5 h with a catalyst loading of 0.55 mol% (Table 1, entry 16). A catalyst generated in situ from $FeBr_2$ and $KN(SiMe_3)_2$ also proved effective [Eq. (2)].[10] Finally, in light of recent studies on the effects of other metal contaminants in iron-catalyzed cross-coupling reactions,[11] we tested a catalyst synthesized from $FeBr_2$ of 99.999% purity (see the Supporting Information). This catalyst was found to be equally effective.



(2)

More sterically demanding silanes, such as (trip)$PhSiH_2$ (trip = 2,4,6-$i$$Pr_3C_6H_2$), Ph_3SiH, and Et_3SiH, were not effective for this reaction. For example, under identical conditions (23 °C, 2.7 mol% Fe loading), no catalysis was observed after 1 day. Heating of the reaction mixture of 3-pentanone and Et_3SiH to 60 °C resulted in the precipitation of insoluble Fe species, and no catalytic hydrosilylation was observed.

The reaction solutions remained transparent throughout the catalysis, and mercury had no effect on the reactions of entries 2 and 8.[12] These observations are consistent with a homogeneous catalytic system. The observation that no ring-opening product formed during the hydrosilylation of cyclopropyl phenyl ketone is inconsistent with a radical mechanism.[13] The stoichiometric reaction of $[Fe\{N(SiMe_3)_2\}_2]$ with Ph_2SiH_2 (3 equiv) was slow at 23 °C (ca. 36% conversion after 21 h), whereas the addition of acetophenone resulted in rapid consumption of $[Fe\{N(SiMe_3)_2\}_2]$ and the formation of $HN(SiMe_3)_2$. In situ monitoring of the operating catalytic system by NMR spectroscopy also revealed the formation of $HN(SiMe_3)_2$ at early stages in the catalysis. The generated $HN(SiMe_3)_2$ could serve as a labile ligand to support a highly reactive iron complex, which may initiate hydrosilylation reactions. The mechanism of this catalysis remains largely undefined, but future efforts will focus on obtaining more mechanistic information.

Thus, $[Fe\{N(SiMe_3)_2\}_2]$, a simple iron complex known for over two decades,[9] has proven to be a readily accessible catalyst precursor for the efficient hydrosilylation of carbonyl functionalities at room temperature. This $[Fe\{N(SiMe_3)_2\}_2]$/Ph_2SiH_2 system is one of the most active iron-based catalytic systems for the hydrosilylation of ketones. Importantly, no special neutral donor ligand or activator is required. Furthermore, this system tolerates a variety of functional groups, such as ether, olefin, cyclopropyl, bromoaryl, dimethylamino, and even nitrile groups. The iron catalyst can be generated in situ, and the reaction can be carried out without a solvent; thus, this catalyst may provide a simple, economically and environmentally attractive alternative to catalytic systems currently employed for the hydrosilylation of ketones. Furthermore, $[Fe\{N(SiMe_3)_2\}_2]$ appears to be a fundamentally new type of iron-based hydrosilylation catalyst, and this finding should stimulate further interest in the exploration of simple metal amides[14] as catalyst precursors for transformations involving hydrosilanes. Future studies will address the scope and mechanism of this catalytic hydrosilylation.

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Keywords: carbonyl compounds · homogeneous catalysis · hydrosilylation · iron · metal amides

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[10] In a control experiment, multiple products were obtained from acetophenone (1 equiv) and Ph_2SiH_2 (1.6 equiv) when $KN(SiMe_3)_2$ (2.8 mol %) was used under similar reaction conditions.

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