

COMMUNICATION

 View Article Online
 View Journal | View Issue

 Regiocontrol in the cobalt-catalyzed
 hydrosilylation of alkynes†

 Guojiao Wu, Uttam Chakraborty and Axel Jacobi von Wangelin *

 Cite this: *Chem. Commun.*, 2018, 54, 12322

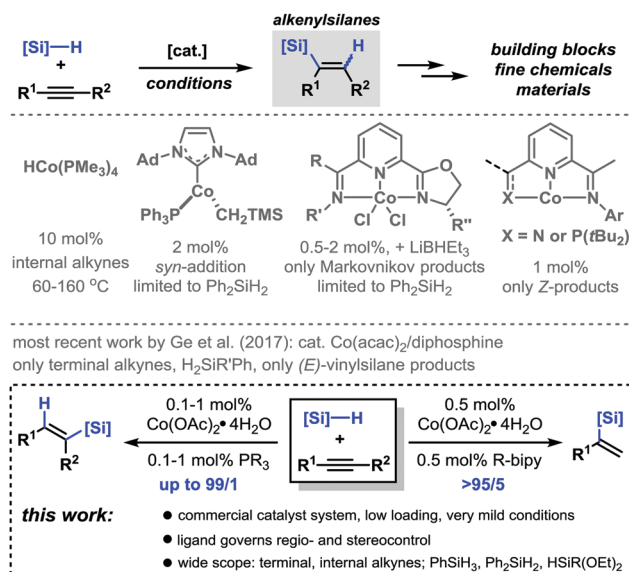
 Received 7th September 2018,
 Accepted 4th October 2018

DOI: 10.1039/c8cc07267a

rsc.li/chemcomm

Hydrofunctionalizations of unsaturated hydrocarbons are key strategies for the synthesis of functionalized building blocks. Here, we report highly versatile cobalt-catalyzed hydrosilylations of alkynes that operate with minute amounts of the inexpensive, bench-stable pre-catalyst $\text{Co}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ under mild conditions (0.1–1 mol%, THF, r.t., 1 h). Near-perfect regiocontrol/stereocontrol was induced by the choice of the ligand: bidentate phosphines afforded (*E*)- β -vinylsilanes; α -vinylsilanes formed with bipyridine ligands.

Alkenylsilanes constitute versatile building blocks in the realm of fine chemicals and materials synthesis by virtue of their dense poly-functionalization.¹ The combination of a polarized alkene moiety, a Si center, and the substituents at alkene and silicon offer ample opportunities for post-synthesis manipulations. Hydro-silylations of alkynes enable a most straightforward and atom-economic synthesis of alkenylsilanes in the presence of the noble metal catalysts Ru, Rh, and Pt.^{2–4} Only few protocols rely on the use of inexpensive and environmentally benign 3d base metal catalysts.⁵ Despite the recent progress in the field, the precise control of regioselectivity and stereoselectivity remains a challenge of utmost importance. Cobalt catalysts were demonstrated to exhibit especially high activity and tolerance of functional groups in hydrosilylations of alkenes.⁶ Much less attention has been directed towards cobalt-catalyzed hydrosilylations of alkynes which often require high catalyst loadings, complex ligands, and harsh conditions or showed poor regio/stereocontrol or a limited substrate scope with regard to alkynes and silanes (Scheme 1, top).^{7–12} Very recently, Ge *et al.* reported Co-catalyzed hydrosilylations to give (*Z*)-vinylsilanes in the presence of pyridine-2,6-diimines.¹³ We believed that a most user-friendly protocol would combine the following criteria: (i) high catalytic activity of a commercial catalyst system under very mild conditions; (ii) control of regioselectivity and stereoselectivity by the choice of the ligand, and (iii) a wide



Scheme 1 Cobalt-catalyzed hydrosilylations of alkynes.

substrate scope involving terminal and internal alkynes and trihydrosilanes. Documented herein are the benefits of a versatile regiodivergent and stereoselective hydrosilylation of alkynes in the presence of only 0.1–1 mol% $\text{Co}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ and commercial phosphine or bipyridine ligands (Scheme 1, bottom).

An initial evaluation of parameters in the model reaction between phenylacetylene (**1a**) and phenylsilane (**2a**) in the presence of the bench-stable and inexpensive $\text{Co}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ revealed very good regioselectivity and stereoselectivity toward (*E*)-styrylsilane with various commercial phosphine ligands (Table 1, entries 1–7). With only 0.1 mol% $\text{Co}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}/\text{dppb}$, an isolated yield of 86% was obtained with very high stereoselectivity (>50/1 *E/Z*) and regiocontrol (1/49 α/β). A complete reversal of regioselectivity was observed upon employment of bipyridine ligands (up to 25/1 α/β , entries 8–12). These results are a significant extension of previous reports with N,N,N-ligands that resulted in poor regio-selectivity with PhSiH_3 .¹² The strict

Department of Chemistry, University of Hamburg Martin Luther King Pl. 6, 20146 Hamburg, Germany. E-mail: axel.jacobi@uni-hamburg.de

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c8cc07267a

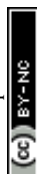


Table 1 Optimization of reaction conditions^a

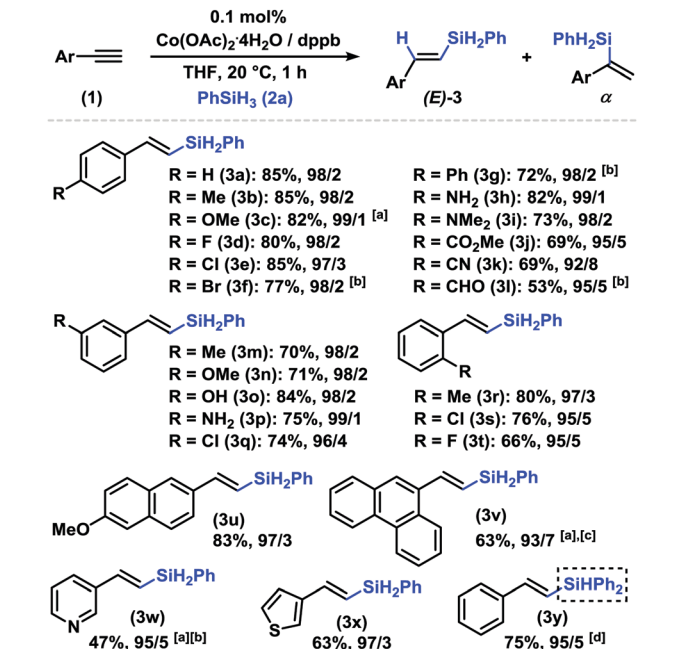
Entry	Ligand	Yield ^b [%]	<i>E/Z/α</i> ^b	
1		<i>n</i> = 1	72	87/0/13
2		<i>n</i> = 2	81	97/0/3
3		<i>n</i> = 3	95	98/0/2
4	Dppf	92	97/0/3	
5	DPEphos	90	98/0/2	
6	Xantphos	89	87/2/11	
7 ^c	Dppb	94 (86) ^d	98/0/2	
8	2,2'-Bipyridine (bipy)	75	10/0/90	
9	4-OMe-bipy	66	4/0/96	
10	4-Me-bipy	70 (60) ^d	5/0/95	
11	4- <i>t</i> Bu-bipy	64	5/0/95	
12	1,10-Phenanthroline	61	10/0/90	
13	L1 or L2 or L3	0	—	
14	2,2';6',2''-Terpyridine	0	—	

^a Conditions: **1a** (0.40 mmol), **2a** (0.48 mmol), Co(OAc)₂·4H₂O (0.5 mol%), ligand (0.5 mol%), 0.5 mL THF, 20 °C, under N₂ (1 h w/PR₃, 3 h with N,N-ligands). ^b Yield and product ratios from quantitative GC-FID vs. internal *n*-dodecane. ^c 0.1 mol% Co(OAc)₂·4H₂O (in 10 μL methanol), 0.1 mol% dppb, 1 h. ^d Isolated yields in parentheses.

ligand control of this protocol is further documented by the lack of catalytic activity in the presence of other N,N-ligands such as (pyridin-2-yl)methanimine, butane-2,3-diimine, and terpyridine (entries 13 and 14).

Various arylacetylenes underwent clean formation of (*E*)-alkenylsilanes in good yields, very high stereoselectivities (> 50/1 *E/Z*) and regioselectivities (> 18/1 β/α) with only 0.1 mol% Co(OAc)₂·4H₂O and dppb at r.t. (Scheme 2). Diverse substitution patterns (incl. *ortho*-substituents) and functional groups (OH, NH₂, nitrile, ester, aldehyde, thiophene, and pyridine) were tolerated. No dehalogenation was observed with halides (Br, Cl, and F). The same conditions were successfully applied to hydrosilylations with monohydrosilanes and dihydrosilanes (*i.e.* (EtO)₃SiH and Ph₂SiH₂). An extension of the methodology to terminal and internal alkyl alkynes was realized with cobalt/diphosphine catalyst systems (entries 5 and 6 in Table 1 and ESI†). Terminal alkynes exhibited the highest reactivities, very high stereoselectivities (> 50/1 *E/Z*), and very high regioselectivities (up to 99/1 β/α) toward (*E*)-alkenyl-silanes in the presence of 1 mol% Co(OAc)₂·4H₂O and DPEphos (Scheme 3, top). Silyl ethers, halides, nitriles, and ester moieties were tolerated. Free OH groups inhibited the conversion. The protocol was also applied to hydrosilylation with diphenylsilane (**5m**).

Internal alkynes successfully reacted under slightly modified conditions with Xantphos as a ligand (Scheme 3, bottom). Highly selective *syn*-hydrosilylation was operative with all substrates.

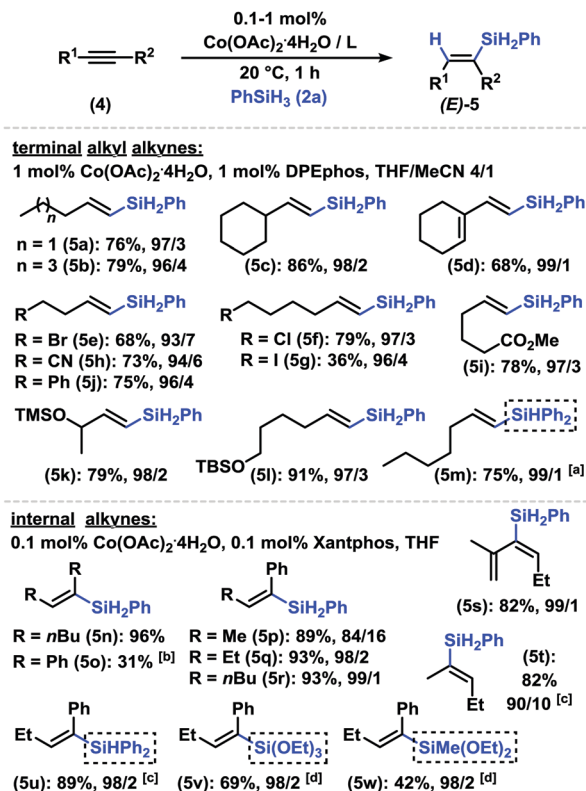


Scheme 2 Hydrosilylation of terminal aryl alkynes. Conditions: **1** (0.4 mmol), **2a** (0.48 mmol), Co(OAc)₂·4H₂O (0.1 mol%), dppb (0.1 mol%), 0.5 mL THF, 20 °C, under N₂, 1 h. Isolated yields are given. *E/Z* ratios were determined by quantitative GC-FID vs. internal *n*-dodecane. ^a 3 h. ^b Co(OAc)₂·4H₂O (0.5 mol%), dppb (0.5 mol%). ^c Co(OAc)₂·4H₂O (1 mol%), dppb (1 mol%). ^d Xantphos.

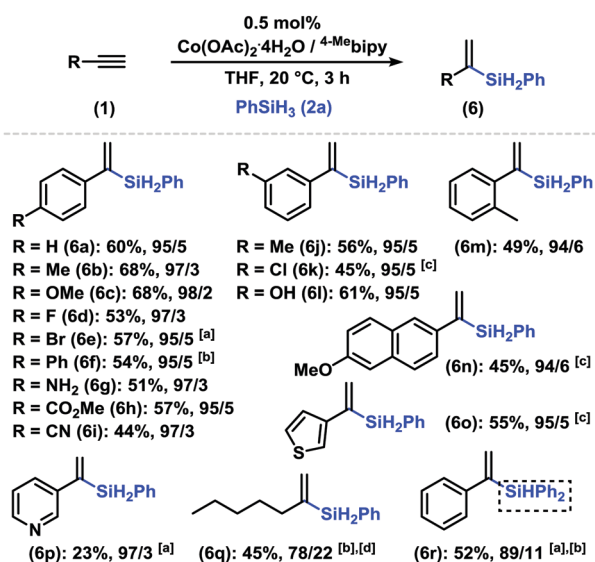
Unsymmetrical alkynes engaged in the regioselective addition of the silyl moiety to the less bulky C atom (Ph, *i*-Pr vs. alkyl; alkyl vs. Me). This is also manifested in the series of 2-alkyl phenylacetylenes with increasing regioselectivities in the order Me < Et < *n*Bu (**5p**, **5q**, and **5r**). The conjugated enyne 2-methylhex-1-ene-3-yne cleanly afforded the desired 3-silyl product **5s**. The hydrosilylation of the sterically rather unbiased 2-pentyne gave impressive regio-selectivity (9/1) and stereoselectivity. Ph₂SiH₂, HSi(OEt)₃, and HSiMe(OEt)₂ fared equally well. Steric silanes (HSiEt₃ and HSi(OiPr)₂Me₂) gave complex product mixtures, possibly from rapid alkyne (cyclo)oligomerizations. We further explored the regioselective α-silylation of terminal alkynes (entries 8–12, Table 1). The Co/2,2'-bipyridine catalysts enabled a reversal of regio-selectivity to cleanly afford 1-phenylvinyl silanes which constitute important synthetic building blocks (Scheme 4).¹ The reaction displayed compatibility with Br, NH₂, ester, nitrile, and free OH functional groups. 2-Ethynyl-6-methoxynaphthalene, 3-ethynylthiophene, and 3-ethynylpyridine gave slightly lower conversions (**6n**, **6o**, and **6p**). Internal alkynes reacted poorly (~10% yield, low regiocontrol).

The versatility of the derived alkenylsilanes for further manipulations is exemplified in Scheme 5. Sequential hydro-silylations afforded a divinylsilane (87/13 β/α) via the alkenyl-silane **3a**. Substitution of the hydride at Si with Grignard reagents is a robust method of silane functionalization. With PhMgBr, tertiary silane **3a** was obtained in 74% yield. Tamao oxidation of vinylsilane **6a** gave the corresponding phenone in 81% yield. Further alkenylsilane reactions of high utility include electrophilic and nucleophilic olefin additions, silyl substitutions, oxidations, cross-couplings, hydro-functionalizations and polymerizations.¹

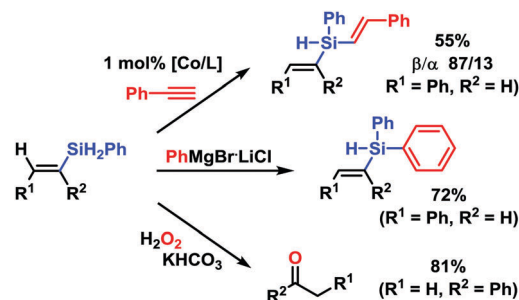




Scheme 3 Hydrosilylation of alkynes. Conditions: **4** (0.4 mmol), **2a** (0.48 mmol), Co(OAc)₂·4H₂O (0.1 or 1 mol%), ligand (0.1 or 1 mol%), 0.5 mL solvent, 1 h, under N₂. Isolated yields are given. Product ratios *E*/*α* were determined by quantitative GC-FID vs. internal *n*-dodecane. ^aXantphos. ^bCo(OAc)₂·4H₂O (0.5 mol%). ^cCo(OAc)₂·4H₂O (1 mol%). ^dCo(OAc)₂·4H₂O (0.5 mol%), 0.5 mL MeCN, 60 °C, 2 h.

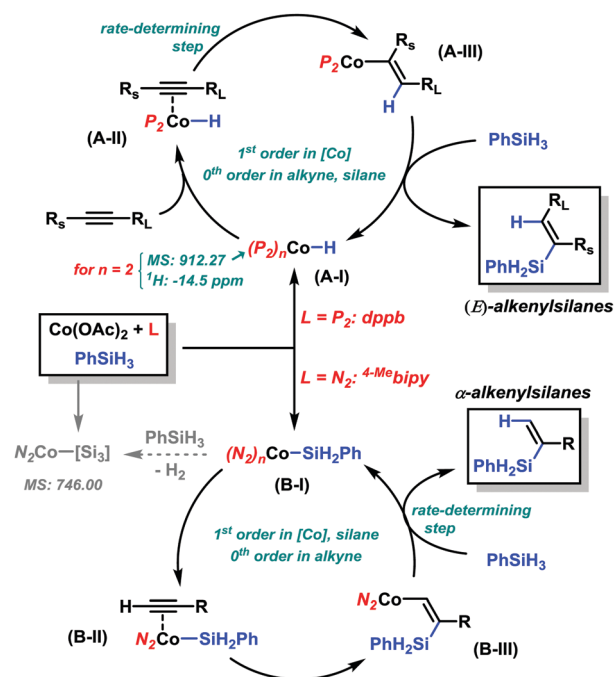


Scheme 4 Markovnikov hydrosilylation of arylacetylenes. Conditions: **1** (0.4 mmol), **2a** (0.48 mmol), Co(OAc)₂·4H₂O (0.1 or 1 mol%), ligand (0.1 or 1 mol%), 0.5 mL solvent for 1 h under N₂. Isolated yields are given. The product ratios *α*/*E* were determined by GC analysis. ^a50 °C. ^b6 h. ^c**2a** (1.5 equiv.). ^d4-Me-bipy as a ligand (0.5 mol%).



Scheme 5 Post-synthesis manipulations of (*E*)-alkenyl silanes.

In extension of literature precedents and our own preliminary mechanistic data derived from the optimization experiments, substrate scope, and regiochemical and stereochemical course of the cobalt-catalyzed hydrosilylation reactions, we performed key mechanistic studies on the nature of catalytic intermediates (Scheme 6).^{6,10–15} In full accord with the literature,^{6g} the reduction of Co(OAc)₂ by the silane in the presence of diphosphine ligands (L = P₂) was observed by MS and NMR. We postulate the formation of the monohydrido species L_nCoH (A-I). Indeed, the penta-coordinate complex (dppb)₂CoH was observed in LIFDI-MS spectra (*m/z* 912.27) and showed a characteristic ¹H NMR resonance at –14.5 ppm (see the ESI† for details). Coordination of the alkyne (A-II) and migratory insertion into the Co–H bond constitute the elemental steps that govern the regioselectivity and stereoselectivity of the reaction. The preferential addition of the cobalt complex to the less hindered side of the alkyne bearing the smaller substituent R_s affords the more stable alkenylcobalt species A-III. Formal transmetalation to Si results in the formation of the (*E*)-alkenylsilane and regeneration of the active species A-I. The reaction is first order in



Scheme 6 Proposed reaction mechanisms of hydrosilylation catalysed by (diphosphine)cobalt complexes (top) and (bipy)cobalt complexes (bottom).

the cobalt catalyst and zero order in phenylacetylene and silane (see the ESI†), which suggests that the alkyne insertion into Co–H is rate-determining. A different mechanistic scenario appears to be operative with bipy ligands ($L = N_2$, Scheme 6, bottom). The reductive formation of a silylcobalt complex LCo–Si (B-I) is in full agreement with the literature.^{6c,6f,11} 1H NMR spectra of the reaction of $Co(OAc)_2 \cdot 4H_2O / ^4Me$ bipy with $PhSiH_3$ (1:1:10) documented the anticipated formation of a paramagnetic species. The presence of silylcobalt complexes was suggested by LIFDI-MS measurements of the catalyst mixture which exhibited the trisilyl complex $(^4Me$ bipy)₂Co(SiHPhSiHPhSiH₂Ph) (m/z 746.00). Such oligosilane complexes constitute key intermediates in silane dehydro-coupling and oligomerization reactions and were also observed with other metals.¹⁵ The same paramagnetic oligosilyl complex was independently formed by the reaction of equimolar $Co(OAc)_2 \cdot 4H_2O$ and 4Me bipy with 5 equiv. of $PhSiH_3$. The dehydrocoupling could be reversed by the addition of $LiAlH_4$ (2.5 equiv. per [Co]) which resulted in the generation of $PhSiH_3$ (see the ESI† for details). The silylcobalt complex B-I is postulated to engage in alkyne coordination followed by regioselective and stereo-selective 1,2-*syn*-insertion. The resultant *syn*-alkenylcobalt complex B-III releases α -alkenylsilane upon reaction with $PhSiH_3$. This hydrosilylation reaction is first order in [Co] and silane and zero order in phenylacetylene (see the ESI†). This indicates a rate limitation by the product release step.

In conclusion, a highly versatile cobalt-catalyzed hydrosilylation has been developed that enables precise regiocontrol by the choice of the ligand. The catalysts exhibit superior activity over the current state-of-the-art, operating under very mild conditions (20 °C, 1 h) with only 0.1–1 mol% catalyst loading. The catalysts are based on commercial and inexpensive components: the bench-stable $Co(OAc)_2 \cdot 4H_2O$ and the ligand dppb or 4Me bipy. The mild conditions allow a wide substrate scope (terminal and internal alkynes, various silanes) and the tolerance of sensitive functional groups (halides, aldehydes, esters, nitriles, NH_2 , and OH). Key mechanistic studies support the notion of a mechanistic dichotomy: the ligand dppb enables highly selective formation of (*E*)-alkenyl-silanes via anti-Markovnikov hydrosilylation. A full regiochemical switch is effected by the ligand 4Me bipy which selectively delivers Markovnikov products. The former pathway involves the formation of hydrido-cobalt catalyst species, while the latter mode of reactivity is most likely based on silylcobalt species. The high functional group tolerance and mild reaction conditions make these protocol highly attractive for complex molecule synthesis with great utility for medicinal and materials chemistry endeavours.

This work was supported by the Deutsche Forschungsgemeinschaft (JA 1107/6-1) and the European Research Council (CoG 683150).

Conflicts of interest

There are no conflicts to declare.

Notes and references

- (a) E. Langkopf and D. Schinzer, *Chem. Rev.*, 1995, **95**, 1375; (b) I. Fleming, A. Barbero and D. Walter, *Chem. Rev.*, 1997, **97**, 2063; (c) I. Ojima, Z. Li and J. Zhu, *The Chemistry of Organic Silicon Compounds*, Wiley, Hoboken, 2003, pp. 1687; (d) S. E. Denmark and R. F. Sweis, *Metal-Catalyzed Cross-Coupling Reactions*, Wiley-VCH, Weinheim, 2nd edn, 2008, pp. 163.
- (a) C. S. Arico and L. R. Cox, *Org. Biomol. Chem.*, 2004, **2**, 2558; (b) S. V. Maifeld, M. N. Tran and D. Lee, *Tetrahedron Lett.*, 2005, **46**, 105; (c) M. Nagao, K. Asano, K. Umeda, H. Katayama and F. Ozawa, *J. Org. Chem.*, 2005, **70**, 10511; (d) S. Ding, L. Song, L. W. Chung, X. Zhang, J. Sun and Y. D. Wu, *J. Am. Chem. Soc.*, 2013, **135**, 13835; (e) R. Gao, D. R. Pahls, T. R. Cundari and C. S. Yi, *Organometallics*, 2014, **33**, 6937; (f) S. Ding, L. J. Song, Y. Wang, X. Zhang, L. W. Chung, Y. D. Wu and J. Sun, *Angew. Chem., Int. Ed.*, 2015, **54**, 5632; (g) Y. Mutoh, Y. Mohara and S. Saito, *Org. Lett.*, 2017, **19**, 5204.
- (a) A. Mori, E. Takahisa, Y. Yamamura, T. Kato, A. P. Mudalige, H. Kajiro, K. Hirabayashi, Y. Nishihara and T. Hiyaama, *Organometallics*, 2004, **23**, 1755; (b) G. T. S. Andavan, E. B. Bauer, C. S. Letko, T. K. Hollis and F. S. Tham, *J. Organomet. Chem.*, 2005, **690**, 5938; (c) T. Sanada, T. Kato, M. Mitani and A. Mori, *Adv. Synth. Catal.*, 2006, **348**, 51; (d) J. P. Morales-Cerón, P. Lara, J. López-Serrano, L. L. Santos, V. Salazar, E. Alvarez and A. Suárez, *Organometallics*, 2017, **36**, 2460.
- (a) M. Chauhan, B. J. Hauck, L. P. Keller and P. Boudjouk, *J. Organomet. Chem.*, 2002, **645**, 1; (b) W. Wu and C.-J. Li, *Chem. Commun.*, 2003, 1668; (c) H. Aneetha, W. Wu and J. G. Verkade, *Organometallics*, 2005, **24**, 2590; (d) A. Hamze, O. Provot, J.-D. Brion and M. Alami, *Tetrahedron Lett.*, 2008, **49**, 2429; (e) A. Hamze, O. Provot, J.-D. Brion and M. Alami, *J. Organomet. Chem.*, 2008, **693**, 2789; (f) G. Berthon-Gelloz, J.-M. Schumers, G. D. Bo and I. E. Markó, *J. Org. Chem.*, 2008, **73**, 4190; (g) J. Hu, F. Li and T. S. A. Hor, *Organometallics*, 2009, **28**, 1212; (h) Y. Kawasaki, Y. Ishikawa, K. Igawa and K. Tomooka, *J. Am. Chem. Soc.*, 2011, **133**, 20712; (i) R. Cano, M. Yus and D. J. Ramón, *ACS Catal.*, 2012, **2**, 1070.
- For Fe, see: (a) C. Belger and B. Plietker, *Chem. Commun.*, 2012, **48**, 5419; (b) M. D. Greenhalgh, D. J. Frank and S. P. Thomas, *Adv. Synth. Catal.*, 2014, **356**, 584; (c) J. H. Docherty, J. Peng, A. P. Dominey and S. P. Thomas, *Nat. Chem.*, 2017, **9**, 595. For Ni catalysts, see: (d) K. Tamao, M. Asahara and A. Kawachi, *J. Organomet. Chem.*, 1996, **521**, 325; (e) A. Tillack, S. Pulst, W. Baumann, H. Baudisch, K. Kortus and U. Rosenthal, *J. Organomet. Chem.*, 1997, **532**, 117; (f) M. J. Chaulagain, G. M. Mahandr and J. Montgomery, *Tetrahedron Lett.*, 2006, **62**, 7560; (g) J. Berding, J. A. Van Paridon, V. H. S. Van Rixel and E. Bouwman, *Eur. J. Inorg. Chem.*, 2011, 2450. For Co catalysts, see ref. 8–14.
- For selected examples: (a) Z. Mo, Y. Liu and L. Deng, *Angew. Chem., Int. Ed.*, 2013, **52**, 10845; (b) C. Chen, M. B. Hecht, A. Kavara, W. W. Brennessel, B. Q. Mercado, D. J. Weix and P. L. Holland, *J. Am. Chem. Soc.*, 2015, **137**, 13244; (c) X. Du, Y. Zhang, D. Peng and Z. Huang, *Angew. Chem., Int. Ed.*, 2016, **55**, 6671; (d) D. Noda, A. Tahara, Y. Sunada and H. Nagashima, *J. Am. Chem. Soc.*, 2016, **138**, 2480; (e) C. H. Schuster, T. Diao, I. Pappas and P. J. Chirik, *ACS Catal.*, 2016, **6**, 2632; (f) A. D. Ibrahim, S. W. Entsminger, L. Zhu and A. R. Fout, *ACS Catal.*, 2016, **6**, 3589; (g) C. Wang, W. J. Teo and S. Ge, *ACS Catal.*, 2017, **7**, 855; (h) Y. Liu and L. Deng, *J. Am. Chem. Soc.*, 2017, **139**, 1798; (i) K. L. Lee, *Angew. Chem., Int. Ed.*, 2017, **56**, 3665; (j) B. Raya, S. Jing, V. Balasanthiran and T. V. RajanBabu, *ACS Catal.*, 2017, **7**, 2275; for review, see (k) J. Su and L. Deng, *ACS Catal.*, 2016, **6**, 290–300.
- T. Konno, K. Taku, S. Tamada, K. Moriyasu and T. Ishihara, *Org. Biomol. Chem.*, 2009, **7**, 1167.
- (a) M. Isobe, R. Nishizawa, T. Nishikawa and K. Yoza, *Tetrahedron Lett.*, 1999, **40**, 6927; (b) S. Tojo and M. Isobe, *Tetrahedron Lett.*, 2005, **46**, 381; (c) K.-H. Huang and M. Isobe, *Eur. J. Org. Chem.*, 2014, 4733.
- L. Yong, K. Kirleis and H. Butenschön, *Adv. Synth. Catal.*, 2006, **348**, 833.
- Z. Mo, J. Xiao, Y. Gao and L. Deng, *J. Am. Chem. Soc.*, 2014, **136**, 17414.
- (a) J. Guo and Z. Lu, *Angew. Chem., Int. Ed.*, 2016, **55**, 10835; (b) Z. Zuo, J. Yang and Z. Huang, *Angew. Chem., Int. Ed.*, 2016, **55**, 10839; (c) J. Guo and Z. Lu, *Angew. Chem., Int. Ed.*, 2017, **56**, 615.
- A. Rivera-Hernández, B. J. Fallon, S. Ventre, C. Simon, M.-H. Tremblay, G. Gontard, E. Derat, M. Amatore, C. Aubert and M. Petit, *Org. Lett.*, 2016, **18**, 4242.
- (a) W. J. Teo, C. Wang, Y. W. Tan and S. Ge, *Angew. Chem., Int. Ed.*, 2017, **56**, 4328; (b) X. Du, W. Hou, Y. Zhang and Z. Huang, *Org. Chem. Front.*, 2017, **4**, 1517; (c) C. Wu, W. J. Teo and S. Ge, *ACS Catal.*, 2018, **8**, 5896.
- C. C. H. Atienza, T. Diao, K. J. Weller, S. A. Nye, K. M. Lewis, J. G. P. Delis, J. L. Boyer, A. K. Roy and P. J. Chirik, *J. Am. Chem. Soc.*, 2014, **136**, 12108.
- (a) M. D. Spencer, Q. D. Shelby and G. S. Girolami, *J. Am. Chem. Soc.*, 2007, **129**, 1860; (b) E. E. Smith, G. Du, P. E. Fanwick and M. M. Abu-Omar, *Organometallics*, 2010, **29**, 6527.

