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Enantioselective Hydrosilylation of Imines Catalyzed by Chiral Zinc Acetate Complexes

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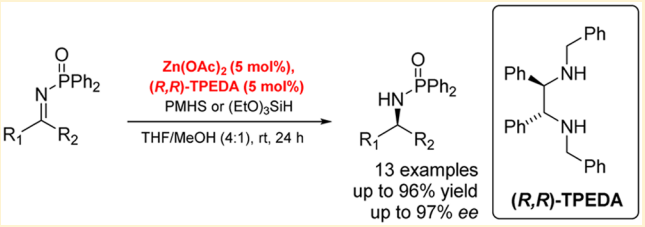
Supporting Information

ABSTRACT: A series of zinc acetate complexes with optically pure diphenylethanediamine (DPEDA)-derived ligands have been employed as enantioselective catalyst for the hydrosilylation of various imines. High control of stereoselectivity (up to 97% *ee*) and excellent yields (up to 96%) were gained for a broad range of *N*-phosphinoylimines by using (*R*,*R*)-*N*,*N*′-dibenzyl-1,2-diphenylethane-1,2-diamine. This is the first successful application of an air-stable and environmentally friendly chiral $Zn(OAc)_2$ complex instead of the previously used harmful diethylzinc in the asymmetric reduction of the C═N double bond.



Chiral secondary amines are significant synthetic targets and useful synthons for numerous drugs and natural products.[1] Their exceptional importance for the manufacture of pharmaceuticals and agrochemicals stimulates intensive progress in the development of methods for laboratory and large-scale synthesis of enantiopure amines. Recently, several catalytic methodologies for reduction of the double C═N have been established with considerable efficiency.[2−4] In the number, asymmetric hydrosilylation provides an important alternative for other methods because of mild conditions and application of safe, easy to handle, inexpensive hydrosilanes.[5]

While transition-metal-catalyzed asymmetric hydrosilylation of ketones based on noble metals such as Rh, Ru, and Ir is well established,[5] the arsenal of known catalysts for hydrosilylation of imines is far more limited. Previously proposed catalytic systems derived from rhodium, ruthenium, and iridium complexes with diferrocene or diphosphine ligands afforded corresponding amines with moderate to low enantioselectivities only.[6−8] More active catalysts containing Ti-, Cu-, and Rh-based chiral Lewis acids required stochiometric loading of the Lewis acids, multistep synthesis of chiral ligands, or special preparation of substrates.[9−11] Therefore, the development of cheaper and general catalytic systems for the enantioselective reduction of imines is still highly desired and deserves special attention.

One of the most promising, yet still unexplored, alternatives is application of chiral zinc catalysts.[12] Recently, environmentally benign and less expensive earth-abundant metals such as Zn[13] and Fe[14] have been exhaustively explored in asymmetric synthesis. Replacing toxic and expensive noble metals by zinc-based catalysts is one of the most important issues for pharmaceutical research nowadays.

The use of Zn-catalyzed enantioselective hydrosilylation of aryl-alkyl ketones developed by Mimoun[15] and further extended to imines by Yun[16] made a breakthrough in practical hydrosilylation. The highly enantioselective reduction of imines was achieved by using Zn-diamine complexes in protic media (MeOH). However, according to this protocol, a typical catalyst system is formed *in situ* from equimolar amounts of hazardous and unstable dialkylzinc and secondary diamines.[17]

The first application of zinc salt in asymmetric hydrosilylation of imines was reported by Ireland et al. in 2004.[18] Enantioselective reduction of imines by using polymethylhydrosiloxane (PMHS) as a reducing agent in the presence of $Zn(OTf)_2$ resulted in the formation of chiral alkyl-aryl and cyclic amines with good yields, albeit low *ee*'s (ca. 30%). Driven by our interest in developing zinc-based catalysts for asymmetric transformations, we reported recently efficient hydrosilylation of ketones by using chiral $Zn(OAc)_2$-*pybox* ligands.[19] Now, we describe the first example of highly enantioselective hydrosilylation of imines catalyzed by a chiral catalyst composed of $Zn(OAc)_2$ instead of expensive, dangerous, and inconvenient $ZnEt_2$ with high impact on large-scale application in the industry (Scheme 1).

Initial optimization of the reaction conditions was carried out with a catalytic system composed of $Zn(OAc)_2$ (5 mol %) and various diamine ligands in a mixture of THF/MeOH as a solvent at room temperature in the presence of 3 equiv of PMHS (Scheme 1). After many trials, we selected derivatives of (*R*,*R*)-1,2-diphenylethane-1,2-diamine (DPEDA, **L1**) as the most promising candidates for further studies.

To our delight, using (*R*,*R*)-**L1** and zinc acetate as *in situ* generated catalyst and *N*-phosphinoylimine (**1**) as a probe substrate resulted in a formation of the desired amine (**5**) in good yield and *ee* (68%, Table 1, entry 1). Data collected in Table 1 indicate that slightly varying the ligand structure had tremendous impact on the reaction enantioselectivity. From among the tested benzyl and *o*-substituent benzyl derivatives of

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Scheme 1. Diamine Ligands Used in This Study on Asymmetric Hydrosilylation

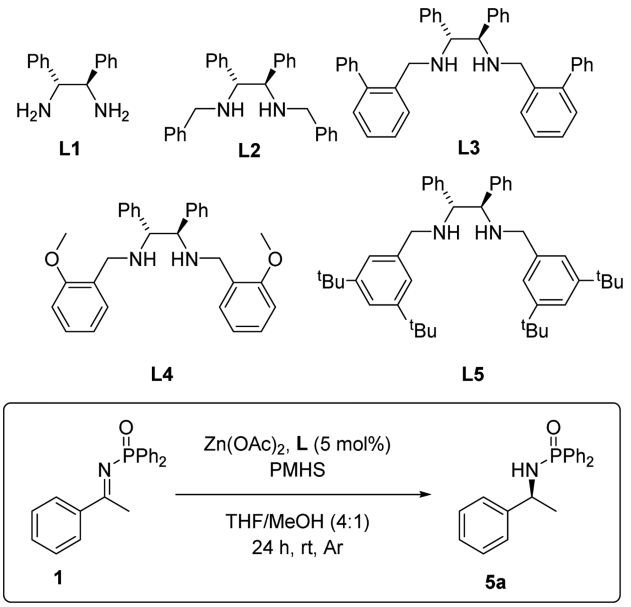
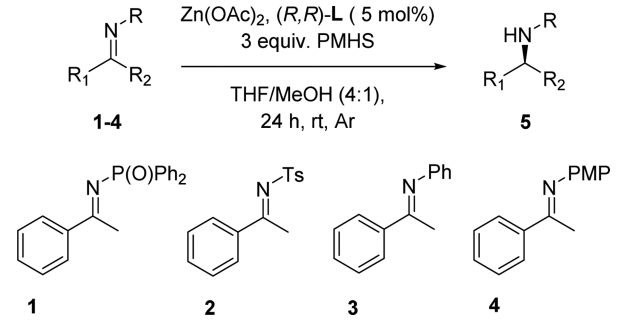


Table 1. Asymmetric Hydrosilylation of Various Imines Catalyzed by Zinc Acetate with Derivatives of (*R,R*)-DPEDA Ligands[a]



entry	substrate	ligand	yield [%][b]	ee [%][c]
1	**1**	**L1**	78	68
2	**1**	**L2**	80	96
3	**1**	**L3**	n.d.	
4	**1**	**L4**	n.d.	
5	**1**	**L5**	40	98
6	**2**	**L2**	90	75
7	**3**	**L2**	n.d.	
8	**4**	**L2**	n.d.	

[a]Reaction conditions: $Zn(OAc)_2$ (5 mol %) and chiral ligand (**L**, 5 mol %) were stirred in 0.4 mL of THF during 30 min. Then, imine (0.44 mmol) in 0.4 mL of THF, silane and 0.2 mL of MeOH were successively added. Reactions were carried out for 24 h at rt under an inert atmosphere. [b]Isolated yields after column chromatography. [c]Determined by HPLC.

DPEDA (**L2**–**L4**), only ligand **L2** gave the desired product in very good isolated yield and high enantioselectivity (96%, entry 2). Interestingly, application of *o*-substituted ligands (**L3**, **L4**) was unsuccessful. However, application of a more bulky ligand with *tert*-butyl substituents (**L5**) resulted in excellent enantioselectivity (up to 98% *ee*) but poor conversion, unfortunately. Despite the fact that hydrosilylation of imine **1** to the corresponding amine **5** was not complete in 24 h and prolongation of the reaction time had only little effect on the conversion, this highly promising attempt with diamine **L2**-$Zn(OAc)_2$ encouraged us to pursue further optimization of the reaction conditions.

The choice of the substituent attached to the imine nitrogen atom was then studied. This revealed that only imines with diphenylphosphinoyl (**1**) and tosyl (**2**) groups showed significant reactivity, whereas the imines **3** and **4** were unreactive (Table 1, entries 7, 8).

The ratio of silane/substrate, used solvent as well as catalysts loading proved to be important parameters for the process optimization. Data collected in Table 2 show that the application of ca. 3 equiv of PMHS in a combination with 5 mol % of Zn-**L2** catalyst in THF/MeOH solvent gave the highest enantioselectivity (96%, entry 1). The amount of this particular silane (PMHS, ca. 3 equiv) seems to be crucial for the reaction yield as diminished addition of reducing agent (ca. 2 equiv, entry 2) resulted in inferior efficiency. Similarly, the decrease of the catalyst amount from 5 mol % to 2.5 mol % or 1 mol % lowered both yields and *ee*'s (entries 3, 4). Surprisingly, increasing the amount of the catalyst to 10 mol % prevented formation of the product (entry 5). This tendency could be overcome by using an additional amount of PMHS (4–6 equiv, entry 6). This observation suggests that the $Zn(OAc)_2$-based catalyst utilizes polymethylhydroxysilane (PMHS) for the formation of zinc hydride, which is not efficiently regenerated in the catalytic cycle.

Thus, 5 mol % of catalyst loading was found to be the best catalyst loading under elaborated reaction conditions with PMHS. Interestingly, in contrast to our predecessors,[16,17] we observed similar reaction efficiency for the reduction performed in THF without any additive of protic solvents (Table 2, entry 7). This interesting reaction condition was maintained for the reduction performed in the presence of triethoxysilane, leading to desired amine **5** with 89% *ee* (entry 11). We also tested other commercially available silanes to perform the catalytic reduction of imines under milder reaction conditions. Results summarized in Table 2 undoubtedly confirmed that the highest control of the stereoselectivity is achieved only with PMHS in THF/MeOH solution (entries 1–6) or triethoxysilane in THF (entry 11). The latter reaction conditions were more efficient in the light of the lower amount of used reducing agent (2 equiv only). Thus, we can state that alcohol additives are not necessary to enhance reaction rates of the zinc-catalyzed reduction of imines.

With optimized reaction conditions, various *N*-phosphinoylimines were reduced by using 5 mol % loading of catalyst, 3 equiv of PMHS, and THF/MeOH mixture (4:1) as a solvent (Method A). Alternative reactions were also carried out with 2 equiv of $(EtO)_3SiH$ in dry THF (Method B).

In all cases, corresponding products were isolated with good to high yield and high enantioselectivity. For most tested substrates, reactions performed in the presence of $(EtO)_3SiH$ (Method B) resulted in the better yields than those with PMHS as hydrogenating agent (Scheme 2). Reduction of phenylmethyl phosphinoylimine provided amine **5a** with high *ee* (up to 96%). Exchange of the methyl group with ethyl decreased only the yield of the reaction when PMHS was used as hydrogenating agent (product **5b**). Substrates bearing an electron-withdrawing group attached to the aromatic ring were smoother reduced than imines possessing an electron-donating group, but *ee* values were high in most cases (entries **5c**–**i**). Low yields for *N*-phosphinoylimines having an activated

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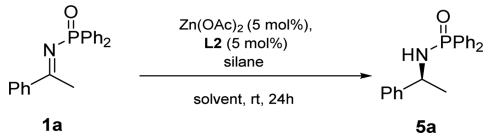
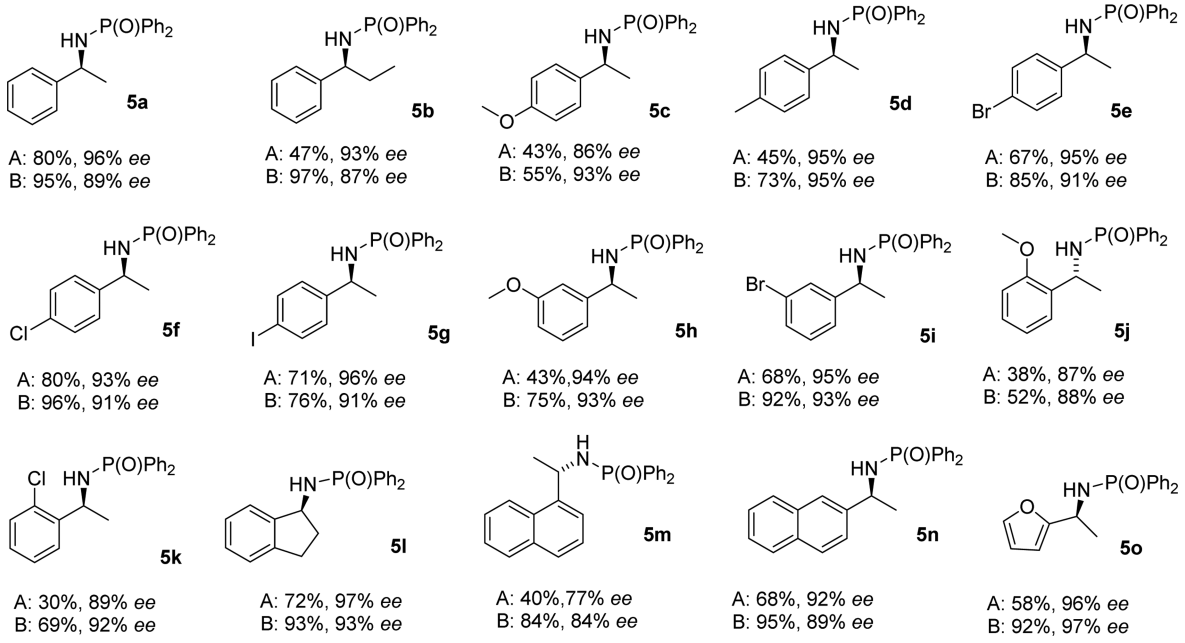
Table 2. Asymmetric Hydrosilylation of *N*-Phosphinoylimines with $Zn(OAc)_2$: Studies on Catalyst Loading and Solvent Effect[a]



entry	silane	solvent	cat. [mol %]	yield [%][b]	ee [%][c]
1	PMHS	THF/MeOH (4:1)	5	80	96
2	PMHS[d]	THF/MeOH (4:1)	5	30	94
3	PMHS	THF/MeOH (4:1)	2.5	60	80
4	PMHS	THF/MeOH (4:1)	1	44	76
5	PMHS	THF/MeOH (4:1)	10	trace	
6	PMHS[e]	THF/MeOH (4:1)	10	80	91
7	PMHS	THF	5	70	91
8	$(EtO)_2MeSiH$	THF/MeOH (4:1)	5	65	79
9	$(EtO)_2MeSiH$	THF	5	52	86
10	$(EtO)_3SiH$	THF/MeOH (4:1)	5	36	70
11	$(EtO)_3SiH$	THF	5	95	89
12	$(EtO)_3SiH$	THF	2.5	38	94
13	$(EtO)_3SiH$	THF	10	70	94

[a]Reaction conditions: $Zn(OAc)_2$ (5 mol %) and **L2** (5 mol %) were stirred in 0.4 mL of THF during 30 min. Then, imine (0.44 mmol) in 0.4 mL of THF, silane (0.08 mL, ca. 3 equiv of PMHS or 2 equiv of $(EtO)_2MeSiH$ or $(EtO)_3SiH$), and 0.2 mL of MeOH were successively added. Reactions were carried out for 24 h at rt under an inert atmosphere. [b]Isolated yields after column chromatography. [c]Determined by HPLC. [d]2 equiv of silane was used. [e]6 equiv of silane was used.

Scheme 2. Asymmetric Hydrosilylation of Various *N*-Phosphinoylimines Catalyzed by $Zn(OAc)_2$-L2 Complex with PMHS in THF/MeOH (Method A) and $(EtO)_3SiH$ in THF (Method B)



ring could be caused by a much stronger Zn−N bond due to higher electron density on the nitrogen atom. As a result, in this particular case, the activity of the catalyst was decreased. Moreover, the $Zn(OAc)_2$-**L2** catalyst showed the same effectiveness in the reduction of substrates possessing groups placed in *ortho* (**5j**−**k**), *meta* (**5h**−**i**), and *para* (**5c**−**g**) positions. The hydrosilylation reactions of heteroaromatic and bicyclic *N*-phosphinoylimines were also carried out with excellent *ee* values (**5l**−**o**).

An important application of our methodology would be its use in the synthesis of pharmaceuticals or biologically active compounds. Several primary amines being drugs and herbicide precursors can be easily obtained from corresponding imines by using an elaborated methodology. For example, the 3-hydroxy-substituted amine **5h** is a desired substrate for Rivastigmine synthesis,[20] and 4-chloro-substituted amine **5f** is a key intermediate in the synthesis of agricultural fungicide Capropamid.[21] The 1-naphthalen structure of amine **5m** can be found in Cinacalcet,[22] while amine **5l** is a useful intermediate in the synthesis of Rasagiline.[23]

As was previously confirmed, application of protic solvent was not necessary for the formation of amines with high efficiency and stereoselectivity. This observation is in contrast to previously reported studies of the hydrosilylation reaction of

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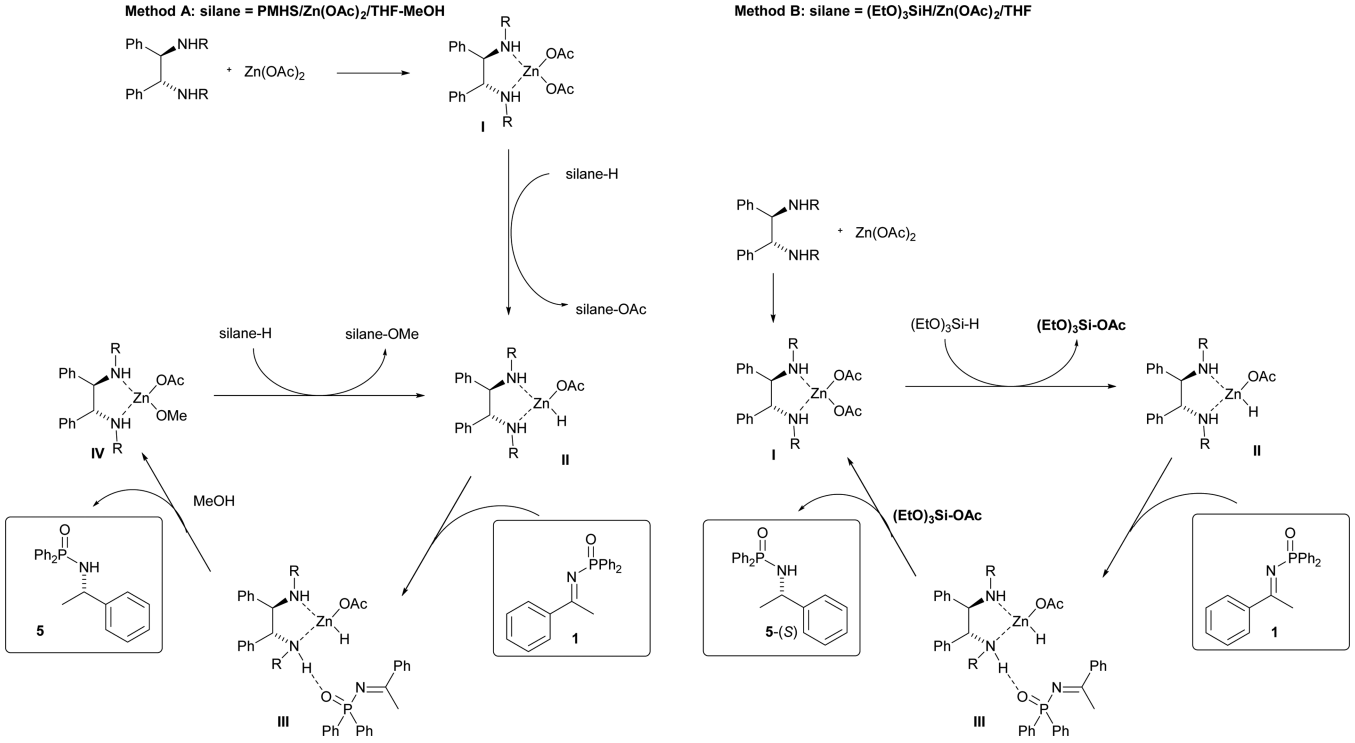
Scheme 3. Mechanistic Proposal for the Hydrosilylation of *N*-Phosphinoylimine Catalyzed by Chiral Zn-Diamine Complex



N-phosphinoylimines where diethylzinc-based catalysts required the presence of protic solvent, mostly THF/MeOH (4:1).[16] It was assumed that some additive of alcohol is responsible for the formation of alkoxide zinc species, which facilitate cleavage of the strong Zn−N bond during the catalytic cycle. On the basis of the previously postulated mechanism,[17] we propose a possible catalytic cycle for the zinc-catalyzed hydrosilylation of *N*-phosphinoylimine depicted in Scheme 3. Zinc complex **I** is formed directly from diamine and zinc acetate in the first step. This, in turn, undergoes the reaction with silane to provide the Zn-hydrido species **II** being the effective reducing agent. When PMHS is used as a reducing agent (Schemes 2 and 3, Method A), the reaction is more efficient with methanolic solution. Initially formed silane acetate should be transformed into silane-OMe and facilitate the presumable turnover-limiting catalyst regeneration step in MeOH. This is in accordance with the conclusion presented previously by Yun[16a] and Kwit.[17c] From our results and in analogy to the previously proposed mechanism for hydrosilylation of imines, we can assume that the first amount of silane is used for the formation of the Zn-hydrido species **II**. This step utilizes silane, and this explains why application of higher catalyst loading stops the reaction cycle (Table 2, entry 5) by withdrawing silane, which is necessary for the next reaction steps.

The use of dry THF instead of the mixture of THF/MeOH as a solvent decreased the yield for the reaction performed with PMHS.[24] Surprisingly, application of monomeric triethoxysialne was more efficient in THF in comparison to THF/MeOH media. Moreover, the reduction using $(EtO)_3SiH$ gave nearly quantitative conversion in a shorter time (24 h). This observation suggests that the acetate ions in the reaction mixture play the same role as methanol yet work more efficiently, supporting release of the free *N*-phosphinoylated amine at the end of the reaction. This can be described as follows: application of triethoxysilane does not require methanol, and Zn-hydrido species **II** can be efficiently regenerated in a catalytic cycle based on acetate transfer from $(EtO_3)SiOAc$ to catalyst (Scheme 3, Method B). This tendency was previously postulated by Shibasaki and used in a catalytic enantioselective Mannich-type reaction of ketoimines.[25] Finally, chiral (*R*,*R*)-ligand based **II** delivers hydride from the *Re*-face of the imine substrate (**III**), resulting in a formation of (*S*)-**5**.

To conclude, we developed a highly active zinc catalyst for efficient asymmetric hydrosilylation of *N*-phosphinoylimines. The proposed methodology offers the application of more stable $Zn(OAc)_2$ instead of $ZnEt_2$ together with safe and inexpensive hydrosilanes such as PMHS or $(EtO)_3SiH$ without any loss in reaction yield and enantioselectivity. We also confirmed that the usage of protic solvent is not required in the hydrosilylation reaction catalyzed by zinc acetate. The proposed catalyst reduced various aromatic imines, derived from acetophenone as well as heteroaromatic and bicyclic *N*-phosphinoylimines with excellent *ee*'s.

EXPERIMENTAL SECTION

General Information. All starting materials and reagents were purchased from commercial sources and used without purification. Dry THF was distilled from potassium to prior to use. TLC analysis of reaction mixtures was performed on silica gel 60F254 TLC plates. Chromatography was carried out on 60 silica gel. ^1H and ^{13}C NMR spectra were recorded with 600 MHz and referenced relative to tetramethylsilane (δ = 0 ppm) for ^1H NMR, and $CDCl_3$ (δ = 77.16 ppm) for ^{13}C NMR. Data are reported as follows: chemical shift, multiplicity (br s = broad singlet, s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, m = multiplet) and integration. IR spectra were recorded at an ATR FTIR spectrometer. Optical rotations were measured at room temperature with a digital polarimeter. HPLC analysis were performed using AD-H and OD-H columns with UV detection at 206 nm. All catalytic reactions were performed under an inert atmosphere.

Synthesis of Ligands. Ligands **L2**−**L5** were synthesized according to the literature procedure.[26] (*R*,*R*)-1,2-Diphenylethylenediamine (1.0

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equiv) and K_2CO_3 (4.0 equiv) were dissolved in 0.5 mL of dry DMF. Next, to the solution was added dropwise the corresponding arylmethyl halide (2.0 equiv), and the mixture was stirred at rt for 16 h. After this time, 5 mL of water was added and the reaction mixture was extracted with diethyl ether (3 × 5 mL). The combined organic layers were washed with water (3 × 5 mL) and dried over anhydrous Na_2SO_4. The solvent was evaporated, and the residue was purified by column chromatography on silica gel with hexane−ethyl acetate as eluent.

(1*R*,2*R*)-*N*,*N*′-Dibenzyl-1,2-diphenylethane-1,2-diamine (L2).[26] The product was obtained starting from benzyl chloride as a white solid after purification by column chromatography on silica gel Hx−AcOEt (4:1) (91 mg, 49%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.32−7.26 (m, 4H), 7.23 (m, 6H), 7.18−7.10 (m, 6H), 7.06−7.00 (m, 4H), 3.71 (s, 2H), 3.66 (d, J = 13.4 Hz, 2H), 3.49 (d, J = 13.4 Hz, 2H), 2.15 (s, 2H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 141.2, 140.6, 128.3, 128.1, 128.0, 128.0, 126.9, 126.8, 68.4, 51.4; IR (ATR) 3312, 3085, 3062, 3028, 2887, 2827, 2750 cm^{-1}; $[\alpha]_D^{20}$ = −25.1 (c = 1.0, $CHCl_3$); HRMS $[M + H]^+$ calcd for $C_{28}H_{29}N_2$ 393.2331, found 393.2317.

(1*R*,2*R*)-*N*,*N*′-Bis(2-methoxybenzyl)-1,2-diphenylethane-1,2-diamine (L3).[27] The product was obtained starting from *o*-methoxybenzyl chloride as a colorless oil after purification by column chromatography on silica gel Hx−AcOEt (4:1) (130 mg, 61%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.20−7.05 (m, 14H), 6.83 (t, J = 7.4, 2H), 6.75 (d, J = 8.0 Hz, 2H), 3.74−3.66 (m, 4H), 3.61 (s, 6H), 3.41 (d, J = 13.5 Hz, 2H), 2.45−1.99 (s, 2H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 157.6, 129.7, 128.0, 127.9, 126.7, 120.1, 110.0, 68.3, 55.0, 47.1; IR (ATR) 3314, 3060, 3026, 2924, 2834, 1725 cm^{-1}; $[\alpha]_D^{20}$ = −38.0 (c = 1.0, $CHCl_3$); HRMS $[M + H]^+$ calcd for $C_{30}H_{33}N_2O_2$ 453.2542, found 453.2533.

(1*R*,2*R*)-*N*,*N*′-Bis(2-phenylbenzyl)-1,2-diphenylethane-1,2-diamine (L4).[16a] The product was obtained starting from 2-(chloromethyl)-1,1′-biphenyl as a colorless oil after purification by column chromatography on silica gel Hx−AcOEt (9:1) (167 mg, 65%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.34−7.27 (m, 6H), 7.27−7.15 (m, 12H), 7.10−7.03 (m, 6H), 6.82 (m, 4H), 3.51 (d, J = 12.5 Hz, 2H), 3.43 (s, 2H), 3.30 (d, J = 12.5 Hz, 2H), 1.90 (s, 2H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 142.1, 141.1, 141.1, 137.8, 130.1, 130.0, 129.0, 128.0, 127.9, 127.8, 127.3, 126.9, 126.8, 126.7, 68.8, 49.3; IR (ATR) 3311, 3058, 3024, 2952, 2922, 2850 cm^{-1}; $[\alpha]_D^{20}$ = −26.5 (c = 1.0, $CHCl_3$); HRMS $[M + H]^+$ calcd for $C_{40}H_{37}N_2$ 545.2957, found 545.2952.

(1*R*,2*R*)-*N*,*N*′-Bis(3,5-di-*tert*-butylbenzyl)-1,2-diphenylethane-1,2-diamine (L5).[26] The product was obtained starting from 3,5-di-*tert*-butylbenzyl bromide as a white solid after purification by column chromatography on silica gel Hx−AcOEt (15:1) (187 mg, 65%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.28 (t, J = 1.7 Hz, 2H), 7.19−7.12 (m, 6H), 7.08−7.02 (m, 8H), 3.73 (s, 2H), 3.63 (d, J = 13.0 Hz, 2H), 3.49 (d, J = 13.0 Hz, 2H), 2.11 (s, 2H), 1.28 (s, 36H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 150.6, 141.5, 139.7, 128.1, 127.9, 126.8, 122.4, 120.8, 68.48, 52.1, 34.8, 31.5; IR (ATR) 3359, 3023, 2965, 2949, 2901, 2862 cm^{-1}; $[\alpha]_D^{20}$ = −10.9 (c = 1.0, $CHCl_3$); HRMS $[M + H]^+$ calcd for $C_{44}H_{61}N_2$ 617.4835, found 617.4842

Synthesis of *N*-Phosphinoylimines. *Preparation of Ketoximes.* *N*-Phosphinoylimines were synthesized from the corresponding oximes by the modification of the literature procedure.[28] A suspension of hydroxylamine hydrochloride (1.6 equiv), and NaOAc (2.0 equiv) in 80% aqueous EtOH (20 mL) was stirred at rt for 30 min. After this time, ketone (1.0 equiv) was added and the reaction mixture was heated gently to reflux for 1 h. Following cooling to rt, the solvent was evaporated under vacuum and the residue was purified by column chromatography with hexane−ethyl acetate (9:1) as eluent, to provide crystalline oxime with quantitative yield.

Preparation of N-Phosphinoylimines.[29] In the round bottle flask under an inert atmosphere, oxime (1.0 equiv) was dissolved in a mixture of dry DCM/Hx (1:1) and cooled to −40 °C. To the reaction mixture was added TEA (1.1 equiv) dropwise, followed (after 10 min) by addition of Ph_2PCl (1.1 equiv). After adding was finished, the reaction mixture was gradually warmed to room temperature and stirred overnight. When the reaction was completed, the contents of the flask were poured over ice and the aqueous phase was extracted with DCM (3 × 15 mL). The combined organic layers were washed with water and brine and dried over anhydrous Na_2SO_4.The solvents were evaporated under reduced pressure to afford the crude ketimine, which was purified by column chromatography on silica gel with DCM−Acetone (9:1 to 4:1) as eluent.

The spectral characteristics of *N*-phosphinoylimines **1a**,[29] **1b**,[29] **1c**,[29] **1d**,[30] **1e**,[30] **1f**,[30] **1g**,[11] **1h**,[30] **1i**,[30] **1j**,[30] **1k**,[31] **1l**,[32] **1m**,[30] **1n**,[30] and **1o**[30] were consistent with those reported previously in the literature. Racemates of *N*-phosphinoylated amines were prepared by reduction of the corresponding imines using $NaBH_4$.

General Procedure for Asymmetric Hydrosilylation of *N*-Phosphinoylimines: Method A. In the small round-bottom flask with a magnetic stir bar under an inert atmosphere were dissolved in 0.4 mL of freshly distilled THF $Zn(OAc)_2$ (4.1 mg; 0.022 mmol) and **L2** (8.61 mg; 0.022 mmol). After 30 min, the solution of the corresponding *N*-phosphinoylimine (0.44 mol; c = 0.44 mol/L), PMHS (80 μL, 3 equiv), and 0.2 mL of dry methanol was added successively. The reaction mixture was stirred at room temperature for 24 h. After the indicated time, the reaction mixture without any workup was purified by column chromatography on silica gel with DCM−Acetone (9:1) as eluent.

General Procedure for Asymmetric Hydrosilylation of *N*-Phosphinoylimines: Method B. In the small round-bottom flask with a magnetic stir bar an under inert atmosphere were dissolved in 0.6 mL of freshly distilled THF $Zn(OAc)_2$ (4.1 mg; 0.022 mmol) and **L2** (8.61 mg; 0.022 mmol). After 30 min, the solution of the corresponding *N*-phosphinoylimine (0.44 mol, c = 0.44 mol/L) and $(EtO)_3SiH$ (162 μL, 2 equiv) was added successively. The reaction mixture was stirred at room temperature for 24 h. After this time, the reaction mixture without any workup was purified by column chromatography on silica gel with DCM−Acetone (9:1) as eluent.

5a *(S)-(−)-N-(1-Phenylethyl)-diphenylphosphinamide.*[33] **5a** was obtained from **1a**[29] as a colorless solid, 134 mg, yield 95%, *ee* 89% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 15.5 min (minor) (*R*), t_S = 20.6 min (major); $[\alpha]_D^{20}$ = −35.5 (c = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = +38.3 (for enantiomer *R* in EtOH).

5b *(S)-(−)-N-(1-Phenylpropyl)-diphenylphosphinamide.*[33] **5b** was obtained from **1b**[29] as a colorless solid, 143 mg, yield 97%, *ee* 87% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.7 mL/min, UV = 206 nm, 21 °C, t_R = 13.9 min (minor), t_S = 18.4 min (major); $[\alpha]_D^{20}$ = −20.8 (c = 1.0, $CHCl_3$).

5c *(S)-(−)-N-(1-(4-Methoxylphenyl)-ethyl)-diphenylphosphinamide.*[33] **5c** was obtained from **1c**[29] as a light yellow solid, 85 mg, yield 55%, *ee* 93% by HPLC Chiralpak AD-H Hexane−2-Propanol (90:10), flow 0.7 mL/min, UV = 206 nm, 21 °C, t_S = 41.1 min (major), t_R = 46.3 min (minor); $[\alpha]_D^{20}$ = −19.9 (c = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = −66.4 (in MeOH).

5d *(S)-(−)-N-(1-(4-Methylphenyl)ethyl)-diphenylphosphinamide.*[33] **5d** was obtained from **1d**[30] as a colorless solid, 108 mg, yield 73%, *ee* 95% by HPLC Chiralcel OD-H Hexane−2-Propanol = 90:10, flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 15.8 min (minor), t_S = 18.2 min (major); $[\alpha]_D^{20}$ = −36.5 (c = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = −66.5 (in MeOH).

5e *(S)-(−)-N-(1-(4-Bromophenyl)ethyl)-diphenylphosphinamide.*[16] **5e** was obtained from **1e**[30] as a colorless solid, 150 mg, yield 85%, *ee* 91% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.7 mL/min, UV = 206 nm, 21 °C, t_R = 14.8 min (minor), t_S = 17.1 min (major); $[\alpha]_D^{20}$ = −42.6 (c = 1.0, $CHCl_3$).

5f *(S)-(−)-N-(1-(4-Chlorophenyl)ethyl)-diphenylphosphinamide.*[33] **5f** was obtained from **1f**[30] as a colorless solid, 137 mg, yield 96%, *ee* 91% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 27.4 min (minor), t_S = 32.6 min (major); $[\alpha]_D^{20}$ = −55.7 (c = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = −73.4 (in MeOH).

5g *(S)-(−)-N-(1-(4-Iodophenyl)ethyl)-diphenylphosphinamide.*[11] **5g** was obtained from **1g**[11] as a light yellow solid, 148 mg, yield 76%, *ee* 91% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10),

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flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 21.0 min (minor), t_S = 23.9 min (major); $[\alpha]_D^{20}$ = −33.7 (*c* = 1.0, $CHCl_3$).

5h *(S)-(−)-N-(1-(3-Methoxylphenyl)ethyl)-diphenylphosphinamide.*[33] **5h** was obtained from **1h**[30] as a colorless solid, 115 mg, yield 75%, *ee* 93% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 23.8 min (minor), t_S = 35.5 min (major); $[\alpha]_D^{20}$ = −71.0 (*c* = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = −52.1 (in MeOH).

5i *(S)-(−)-N-(1-(3-Bromophenyl)ethyl)-diphenylphosphinamide.* **5i** was obtained from **1i**[30] as a colorless solid; 162 mg, yield 92%, *ee* 93% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 18.6 min (minor), t_S = 24.7 min (major); $[\alpha]_D^{20}$ = −39.5 (*c* = 1.0, $CHCl_3$); ^{1}H NMR (300 MHz, CDCl3): δ = 1.54 (d, 3H), 3.17−3.22 (m, 1H), 4.32−4.40 (m, 1H), 7.13−7.22 (m, 2H), 7.34−7.64 (m, 8H), 7.76−7.82 (m, 2H), 7.86−7.93 (m, 2H) ppm. ^{13}C NMR (151 MHz, CDCl3): δ = 25.0, 122.7, 125.0, 128.5, 128.7,128.8, 129.3, 130.4, 132.1, 132.5, 133.9, 147.5 ppm. HRMS (ESI-TOF): calcd. for $C_{20}H_{19}BrNNaPO$ $[M + Na]^+$: 422.0285 found 422.0279.

5j *(R)-(+)-N-(1-(2-Methoxylphenyl)ethyl)-diphenylphosphinamide.*[34] **5j** was obtained from **1j**[30] as a yellowish solid, 80 mg, yield 52%, *ee* 88% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_S = 21.2 min (minor), t_R = 23.3 min (major); $[\alpha]_D^{20}$ = +4.2 (*c* = 1.0, $CHCl_3$), Lit.[34] $[\alpha]_D^{20}$ = −22.1 (for *S* enantiomer in MeOH).

5k *(S)-(−)-N-(1-(2-Chlorophenyl)ethyl)-diphenylphosphinamide.*[35] **5k** was obtained from **1k**[31] as a colorless solid, 98 mg, yield 69%, *ee* 92% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 20.9 min (minor), t_S = 23.3 min (major); $[\alpha]_D^{20}$ = −13.6 (*c* = 1.0, $CHCl_3$).

5l *(S)-(−)-N-(1-Indanamine)-diphenylphosphinamide.*[16] **5l** was obtained from **1l**[32] as a colorless solid, 136 mg, yield 93%, *ee* 93% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 22.8 min (minor), t_S = 38.1 min (major); $[\alpha]_D^{20}$ = −47.7 (*c* = 1.0, $CHCl_3$).

5m *(S)-N-(+)-(1-(1-Naphthyl)ethyl)-diphenylphosphinamide.*[33] **5m** was obtained from **1m**[30] as a colorless solid, 137 mg, yield 84%, *ee* 84% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 22.9 min (minor), t_S = 29.4 min (major); $[\alpha]_D^{20}$ = +56.9 (*c* = 1.0, $CHCl_3$).

5n *(S)-(−)-N-(1-(2-Naphthyl)ethyl)-diphenylphosphinamide.*[33] **5n** was obtained from **1n**[30] as a light yellow solid, 155 mg, yield 95%, *ee* 89% by HPLC Chiralcel OD-H Hexane−2-Propanol (90:10), flow 0.5 mL/min, UV = 206 nm, 21 °C, t_R = 21.6 min (minor), t_S = 29.3 min (major); $[\alpha]_D^{20}$ = −89.3 (*c* = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = −77.8 (in MeOH).

5o *(S)-(−)-N-(1-Furylethyl)-diphenylphosphinamide.*[33] **5o** was obtained from **1o**[30] as a colorless solid, 126 mg, yield 92%, *ee* 97% by HPLC Chiralpak AD-H Hexane−2-Propanol (90:10), flow 0.7 mL/min, UV = 206 nm, 21 °C, t_R = 23.6 min (minor), t_R = 26.0 min (major); $[\alpha]_D^{20}$ = −88.4 (*c* = 1.0, $CHCl_3$); Lit.[11] $[\alpha]_D^{20}$ = −42.1 (in MeOH).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02613.

^{1}H and ^{13}C NMR spectra and HPLC data (PDF)

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Notes

The authors declare no competing financial interest.

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