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Acceleration Effects of Phosphine Ligands on the Rhodium-Catalyzed Dehydrogenative Silylation and Germylation of Unactivated C(sp^3)−H Bonds

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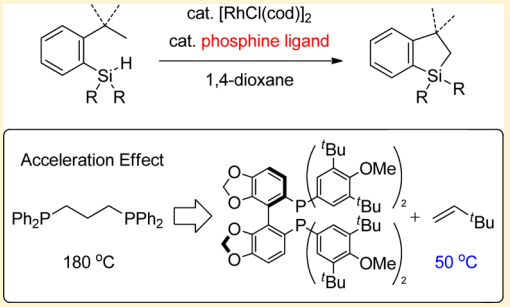
Supporting Information

ABSTRACT: The current work describes the marked rate of acceleration caused by phosphine ligands on the rhodium-catalyzed dehydrogenative silylation and germylation of unactivated C(sp^3)−H bonds. The reactivity was affected by the steric and electronic nature of the phosphine ligands. The use of the bulky and electron-rich diphosphine ligand (*R*)-DTBM-SEGPHOS was highly effective to yield the dehydrogenative silylation products selectively in the presence of a hydrogen acceptor. An appropriate choice of C_2-symmetric chiral diphosphine ligand enables the asymmetric dehydrogenative silylation via the enantioselective desymmetrization of the C(sp^3)−H bond. The unprecedented catalytic germylation of C(sp^3)−H bonds with dehydrogenation was also examined with the combination of the rhodium complex and a wide bite angle diphosphine ligand to provide the corresponding 2,3-dihydrobenzo[*b*]germoles in good yield.



INTRODUCTION

Investigation of new catalyst systems for the improvement of reaction efficiency and selectivity is one of the most important research topics in synthetic chemistry. Transition-metal-catalyzed dehydrogenative silylation of C−H bonds is a straightforward, atom-efficient, and environmentally friendly method for the synthesis of organosilicon compounds and has received intensive interest.[1−3] In addition to the unique function of organosilicon compounds themselves, they can be used as useful intermediates because silyl groups can be easily converted to various functional groups by Hiyama cross-coupling[4] and Tamao−Fleming oxidation,[5] etc. Although organosilicon compounds can be synthesized via bond-forming reactions with reactive functional groups, molecules containing the proper substituents are not always readily available and sometimes must be prepared through additional synthetic steps from commercially available building blocks. Thus, the development of efficient silylation methods for ubiquitous C−H bonds is highly desirable. There are many reports on the dehydrogenative silylation of aromatic C(sp^2)−H bonds without any directing groups,[1] whereas silylation of aliphatic C(sp^3)−H bonds is still limited from the viewpoint of substrate scope.[6−9] In most cases, activated C(sp^3)−H bonds at the benzylic position,[7] or located adjacent to boron or nitrogen atoms,[8] are used as substrates. Generally, C(sp^3)−H bonds are highly unreactive due to their thermal stability and low polar nature.

Seminal work on the dehydrogenative silylation of unactivated C(sp^3)−H bonds was reported by Berry et al.[9a] They found Ru(*p*-cymene)(H)$_2$(SiEt$_3$)$_2$ and Cp*Rh(H)$_2$(SiEt$_3$)$_2$ (Cp* = η^5-C$_5$Me$_5$) complexes were effective for the dehydrogenative silylation of the C(sp^3)−H bond adjacent to a silicon atom. Since then, Tilley et al. reported that the rare-earth-metal complex, Cp*$_2$ScH, could catalyze the dehydrogenative silylation of methane gas (150 atm) with H_2SiPh_2.[9b] These works clearly imply that π-coordinated six-electron-donor ligands are highly important to overcome this unfavorable thermodynamic transformation. Recently, Hartwig et al. disclosed the iridium-catalyzed hydroxyl group-directed dehydrogenative silylation of C(sp^3)−H bonds, in which the phenanthroline-based nitrogen ligand, 3,4,7,8-tetramethyl-1,10-phenanthroline, was reported to be optimal.[9c] The utility of nitrogen ligands can be understood by considering the fact that nitrogen- and oxygen-containing heterocycles have been frequently employed as directing groups for dehydrogenative C−H bond silylation[7c,e,8,9f] since the seminal work on C−H bond functionalization by Murai et al.[10] In contrast, the use of phosphorus atom-based ligands on the dehydrogenative silylation of C(sp^3)−H bonds is limited to the reactions with RhCl(CO)(PMe$_3$)$_2$,[7a] Ni(PEt$_3$)$_4$,[7b] and Ru(H)$_2$(CO)(PPh$_3$)$_3$.[8a] Nevertheless, phosphorus ligands have been well investigated as

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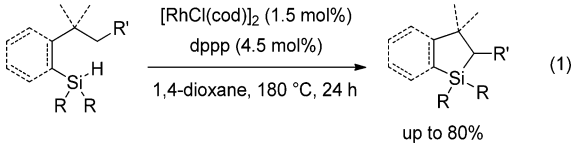
one of the most important and effective ligands in modern organic synthesis.[11]

In 2013, we reported the rhodium-catalyzed synthesis of 2,3-dihydrobenzo[*b*]siloles via the intramolecular dehydrogenative silylation of 2-alkylphenylsilanes (eq 1).[9d] The combination of



(1)

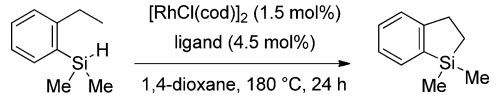
$[RhCl(cod)]_2$ and bidentate phosphines was found to be effective to construct five-membered silicon-containing heterocycles. Although the silylation occurred even at less reactive secondary C(sp^3)−H bonds,[9a,d−f] the reaction required high temperature to overcome the low reactivity of the C−H bond, which detracts from its synthetic utility. Recently, Hartwig et al. reported that rhodium or iridium complexes with C_2-symmetric bisphosphines are useful for hydroarylation of olefins and dehydrogenative silylation of C(sp^2)−H bonds. These studies stimulated us to reexamine the reaction conditions of dehydrogenative silylation of C(sp^3)−H bonds carefully to improve the reaction efficiency. We envisioned that the precursors, 2-alkylphenylsilanes, are suitable to study the effect of phosphine ligands since they do not contain any heteroatoms, such as nitrogen and oxygen, which potentially coordinate with a metal center.

The present study describes the acceleration effect of phosphine ligands on the rhodium-catalyzed dehydrogenative silylation of C(sp^3)−H bonds. Bulky and electron-rich C_2-symmetric diphosphine ligands were found to be effective, and the reaction temperature was markedly decreased compared with our previous report.[9d] The proper choice of phosphine ligands also enabled the unprecedented enantioselective silylative desymmetrization as well as the dehydrogenative germylation of C(sp^3)−H bonds.

RESULTS AND DISCUSSION

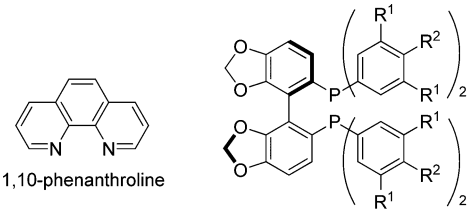
The effect of phosphine ligands on the dehydrogenative silylation of 2-(dimethylsilyl)ethylbenzene (**1a**) was first studied with a catalytic amount of $[RhCl(cod)]_2$ in 1,4-dioxane at 180 °C (Table 1). The monodentate phosphine ligands, such as PPh_3, PCy_3, $PMePh_2$, and P(*o*-Tol)$_3$, were ineffective, and the yields of 2,3-dihydrobenzo[*b*]silole (**2a**) were less than 30% (entries 1−4).[12] In contrast, bidentate diphosphines were found to be effective (entries 5−8). Employing dppp and dppbz as ligands, **2a** was obtained in 70% yields (entries 6 and 8). On the other hand, nitrogen-based bidentate ligands, including TMEDA and 1,10-phenanthroline, previously reported as effective ligands for the iridium-catalyzed hydroxyl group-directed dehydrogenative silylation,[9c] were less reactive, with more than half of starting hydrosilane **1a** recovered (entries 9 and 10). Although the typical C_2-symmetric bisphosphines, BINAP and (*R*)-SEGPHOS, were less effective, the yield was increased to 72% when electron-rich and wide-bidentate phosphine, (*R*)-DTBM-SEGPHOS, was used as a ligand (entries 11−13). The catalytic activity of other rhodium and iridium precursors, $[Rh(OMe)(cod)]_2$, $[IrCl(cod)]_2$, and $[Ir(OMe)(cod)]_2$, with (*R*)-DTBM-SEGPHOS was also tested, and the combination of $[RhCl(cod)]_2$ and (*R*)-DTBM-SEGPHOS was found to be the most effective.

Table 1. Effect of Ligands on the Dehydrogenative Silylation of the C(sp^3)−H Bond



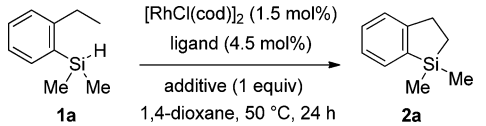
entry	ligand	recov of **1a**[a] (%)	yield of **2a**[a] (%)
1[b]	PPh_3	78	18
2[b]	PCy_3	17	19
3[b]	$PMePh_2$	18	10
4[b]	P(*o*-Tol)$_3$	28	29
5	dppe	0	50
6	dppp	11	70
7	dppf	0	44
8	dppbz	0	70
9	TMEDA	67	7
10	1,10-phenanthroline	44	29
11	*rac*-BINAP	0	38
12	(*R*)-SEGPHOS	54	23
13	(*R*)-DTBM-SEGPHOS	0	72

[a]Determined by ^{1}H NMR. [b]Ligand (9 mol %).



Based on these results, we chose dppp, dppbz, and (*R*)-DTBM-SEGPHOS as ligands and studied other parameters further. We found the efficiency of the reaction was significantly improved by the addition of hydrogen acceptors, and the reaction temperature could be markedly decreased from 180 to 50 °C. For example, 2,3-dihydrobenzo[*b*]silole **2a** was isolated in 77% yield when 1 equiv of 3,3-dimethyl-1-butene was added under the reaction conditions described in Table 1, entry 13 (Table 2, entry 1). On the other hand, the reaction did not occur at all even with 3,3-dimethyl-1-butene when dppp or dppbz were employed as ligands at 50 °C (entries 2 and 3). Although norbornene can be used as a hydrogen acceptor, the yield was decreased to 40% due to the competitive hydro-

Table 2. Effect of Hydrogen Acceptors



entry	ligand	additive	yield of **2a**[a] (%)
1	(*R*)-DTBM-SEGPHOS	3,3-dimethyl-1-butene	81 (77)
2	dppp	3,3-dimethyl-1-butene	0
3	dppbz	3,3-dimethyl-1-butene	0
4	(*R*)-DTBM-SEGPHOS	norbornene	40
5	(*R*)-DTBM-SEGPHOS	1,5-cyclooctadiene	0
6	(*R*)-DTBM-SEGPHOS	1,4-cyclohexadiene	0
7	(*R*)-DTBM-SEGPHOS		0

[a]Determined by ^{1}H NMR. Isolated yield is in parentheses.

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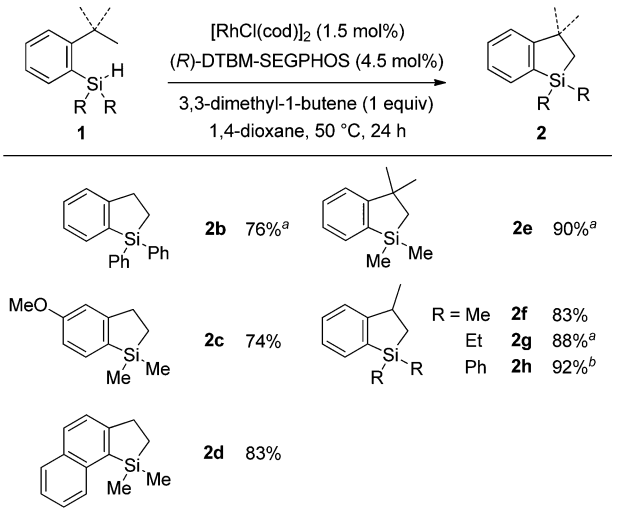
silylation of **1a** with norbornene (entry 4). Other hydrogen acceptors, including 1,5-cyclooctadiene and 1,4-cyclohexadiene, were totally ineffective with most of **1a** recovered (entries 5 and 6). The expected 2,3-dihydrobenzo[*b*]silole **2a** was not obtained when the reaction was examined without adding any hydrogen acceptor (entry 7).

Next, several 2-alkylphenylsilanes were subjected to the current optimized reaction conditions (Table 3). Diphenylsilane **1b** was converted to the corresponding 2,3-dihydrobenzo[*b*]silole **2b** in 76% yield with a slightly higher temperature. Reactions with 2-ethylarylsilanes **1c** and **1d** having anisyl or naphthyl groups gave **2c** and **2d** in good yields even at 50 °C. C(sp^3)−H bonds of 2-*tert*-butylphenyldimethylsilane (**1e**) and 2-isopropylphenyldimethylsilane **1f** were also silylated effectively, affording the expected silacycles **2e** and **2f** in 90% and 83% yields, respectively. The effect of the substituents on the silicon was also examined to find that diethyl and diphenylsilanes **1g** and **1h** could also be used as silicon sources.[13]

Table 3. Rhodium-Catalyzed Dehydrogenative Silylation of 1 Leading to 2,3-Dihydro-1*H*-benzo[*b*]siloles 2

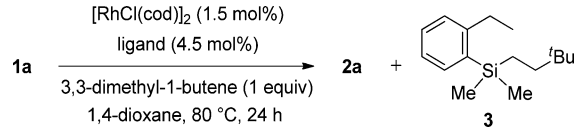


[a] At 80 °C. [b] At 65 °C.

To obtain insight into the ligand effects, the reaction of **1a** was reexamined in the presence of several phosphine ligands and 3,3-dimethyl-1-butene at 80 °C. Representative results are shown in Table 4. All of the phosphine ligands except (*R*)-DTBM-SEGPHOS afforded a mixture of the desired 2,3-dihydrobenzo[*b*]silole **2a** and the hydrosilylated product **3** (entries 1−4). In fact, the combination of rhodium and phosphine ligands has been previously reported as an effective catalyst for the hydrosilylation of olefins.[14] In sharp contrast, formation of hydrosilylated product **3** was not observed, furnishing only **2a** in 83% yield, when (*R*)-DTBM-SEGPHOS was used with 3,3-dimethyl-1-butene (entry 5). This result clearly indicates that (*R*)-DTBM-SEGPHOS can selectively accelerate dehydrogenative silylation of C(sp^3)−H bonds even in the presence of olefins without producing hydrosilylated adducts.

Based on these observations, Scheme 1 presents a plausible mechanism for the current dehydrogenative silylation of unreactive C(sp^3)−H bonds. First, a rhodium hydride species is generated via the oxidative addition of hydrosilane **1** to the rhodium precatalyst followed by the reductive elimination of chlorosilane.[15] This rhodium hydride species is subsequently added to the Si−H bond of **1**, and the resulting intermediate **A** then reacts with 3,3-dimethyl-1-butene to form intermediate **B**. Reductive elimination of H and 3,3-dimethylbutyl groups on the rhodium center affords intermediate **C**, whereas that of silyl and 3,3-dimethylbutyl groups produces hydrosilylated product **3**. Because sterically bulky silyl and 3,3-dimethylbutyl groups tend to keep their distance from each other, the reductive elimination to form **C** might be energetically more favorable. In the absence of a hydrogen acceptor, 3,3-dimethyl-1-butene, intermediate **A** is directly converted to intermediate **C** via the reductive elimination of H_2. Generally, this step is thermodynamically unfavorable and, therefore, requires additional heating to 180 °C as shown in Table 1 and our previous report.[9d] Rhodium silyl species **C** can potentially react with 3,3-dimethyl-1-butene via silylrhodation followed by the sigma-bond metathesis with **1** leading to **3**. However, the electron-rich rhodium center with a strongly electron-donating (*R*)-DTBM-SEGPHOS ligand should favor the oxidative addition of C(sp^3)−H bonds to the rhodium center over the silylrhodation, which is usually promoted by the electron-deficient metal complex.[16] This is consistent with the results shown in Table 4. Moreover, the intramolecular oxidative addition of C(sp^3)−H bonds to the rhodium center can be also facilitated by the steric effect of the ligand due to the bulky (*R*)-DTBM-SEGPHOS overhanging outside. The subsequent reductive elimination

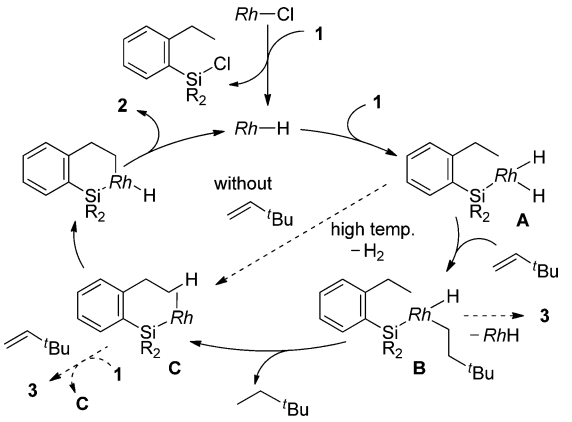
Table 4. Competition between Intramolecular Dehydrogenative Silylation and Intermolecular Hydrosilylation



entry	ligand	yield of **2a**[a] (%)	yield of **3**[a] (%)
1[b]	PPh_3	42	15
2	dppp	39	6
3	dppbz	31	52 (50)
4	*rac*-BINAP	22	18
5	(*R*)-DTBM-SEGPHOS	83	0

[a] Determined by ^{1}H NMR. Isolated yield is shown in parentheses. [b] Ligand 9.0 mol %.

Scheme 1. Proposed Reaction Mechanism (Phosphine Ligand Omitted for Clarity)



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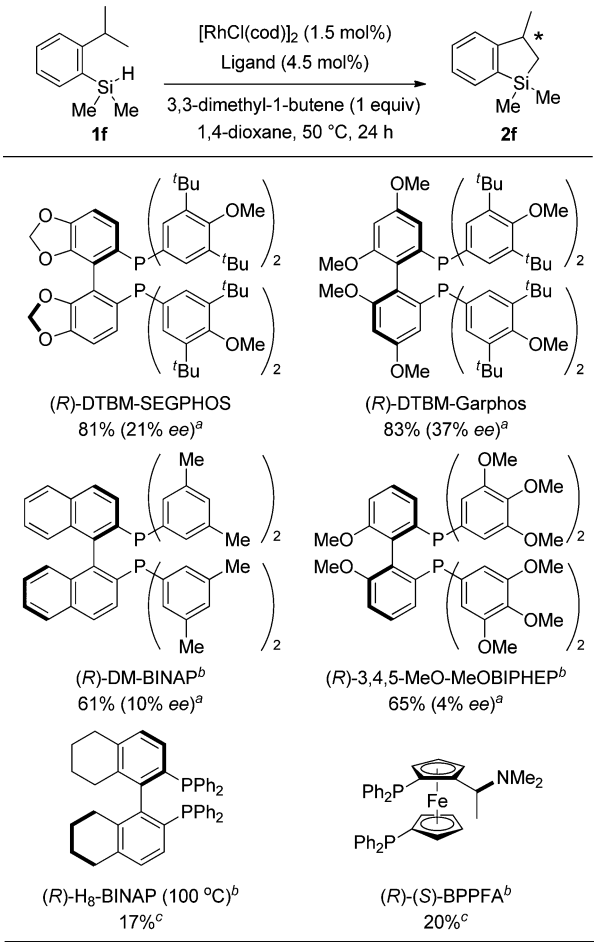
provides 2,3-dihydrobenzo[*b*]silole **2** along with the regeneration of the rhodium hydride species.

We further examined this unprecedented rhodium-catalyzed enantioselective desymmetrization of C(sp^3)−H bonds via dehydrogenative silylation (Table 5).[17,18] Treatment of 2-isopropylphenylsilane **1f** with (*R*)-DTBM-SEGPHOS afforded the corresponding 2,3-dihydrobenzo[*b*]silole **2f** in 81% yield and 21% ee. Because enantiomers of **2f** were not separated by HPLC methods using a chiral stationary phase, the ee was determined by the HPLC analysis of diol **4**, which could be readily converted from **2f** by Tamao−Fleming oxidation (Scheme 2).[5] To increase the ee, the effect of other chiral diphosphine ligands was tested. Among the phosphines examined, high yield, as well as better enantioselectivity, was observed in the reaction catalyzed by the rhodium complex with (*R*)-DTBM-Garphos. These studies also confirm that ligands having electron-rich biaryl backbones were much more reactive, as revealed by a comparison of the reactions with (*R*)-DTBM-SEGPHOS and (*R*)-DTBM-Garphos to those with (*R*)-3,4,5-MeO-MeOBIPHEP. Although the enantioselective silylative cyclization of diethyl and diphenylsilanes **1g** and **1h** were also examined, ee's were less than 10% (data not shown).

With (*R*)-DTBM-SEGPHOS as a ligand, dihydrosilane **5** provided 1,1′-spirosilabiindane **6** in 73% yield with 27% ee (Table 6, entry 1). This is a rare example of the catalytic construction of tetraorganosilicon stereocenters.[19] The reaction proceeded via the sequential 2-fold dehydrogenative silylation of C(sp^3)−H bonds. The chirality of the spirosilabiindane is thought to be determined at the first dehydrogenative cyclization. (*R*)-DTBM-Garphos, which was the best ligand in the enantioselective dehydrogenative silylation of **1f**, produced both lower yield and ee, although the starting dihydrosilane **5** was consumed completely (entry 2). Further screening of the catalyst revealed that changing the ligand to (*R*)-H_8−BINAP increased the ee up to 39%, albeit with only moderate yield of **6** (entry 3). Fortunately, the yield was improved to 75% without deterioration of the ee when the catalyst loading was increased (entry 4). As mentioned above, strongly electron-donating (*R*)-DTBM-SEGPHOS was the most effective for the silylative cyclization of 2-alkylphenylsilanes **1**. This is probably because oxidative addition of C(sp^3)−H bonds can be selectively promoted by the electron-rich phosphine ligand compared with the competitive hydrosilylation with 3,3-dimethyl-1-butene. In the reaction of **5**, however, (*R*)-H_8−BINAP also worked as an efficient promoter (entry 1 vs 3). The difference might be explained by considering the fact that the bulky 2-*tert*-butylphenyl group on the silicon atom prevented intermolecular hydrosilylation and facilitated intramolecular C(sp^3)−H bond silylation selectively. In fact, no hydrosilylated product was observed under any of the conditions described in Table 6.

In contrast to the well-studied bond formation reactions between second- or third-row elements and hydrogens, much less attention has been paid to the dehydrogenative functionalization of C−H bonds involving bonds between the fourth-row elements and hydrogens.[20] The present successful result on the catalytic dehydrogenative silylation of C(sp^3)−H bonds further stimulated us to examine dehydrogenative

Table 5. Rhodium-Catalyzed Enantioselective C(sp^3)−H Bond Silylation with Chiral Diphosphines



[a]Determined on a CHIRALPAK OD column with hexane/2-propanol = 9/1 as the eluent. [b]At 100 °C. [c]Determined by ^{1}H NMR.

Scheme 2. Transformation of the 2,3-Dihydrobenzo[*b*]silole 2f

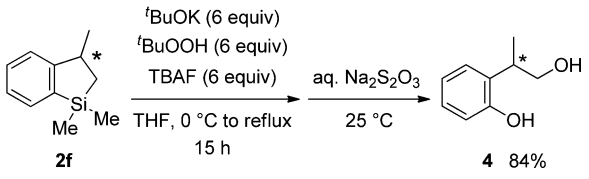
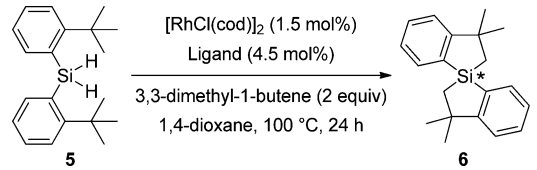


Table 6. Rhodium-Catalyzed Sequential 2-Fold Dehydrogenative Silylation of C(sp^3)−H Bonds of 5 Leading to 1,1′-Spirosilabiindane 6



entry	ligand	yield of **6** (%)	ee of **6**[a] (%)
1	(*R*)-DTBM-SEGPHOS	73	27
2	(*R*)-DTBM-Garphos	20	25
3	(*R*)-H_8−BINAP	54	39
4[b]	(*R*)-H_8−BINAP	75	40

[a]Determined on a CHIRALPAK OD column with hexane/2-propanol = 9/1 as the eluent. [b][RhCl(cod)]$_2$ (3 mol %) and (*R*)-H_8−BINAP (9 mol %).

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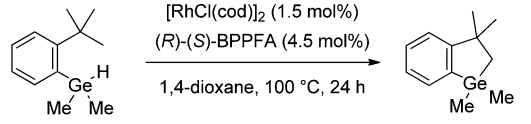
germylation of unactivated C(sp^3)−H bonds. When (*R*)-DTBM-SEGPHOS was used as a ligand together with 3,3-dimethyl-1-butene at 100 °C, the yield of the expected 2,3-dihydrobenzo[*b*]germole **8** was low (15%) with the decomposition of the precursor 2-germyl-*tert*-butylbenzene **7**. After further screening of the phosphine ligands, (*R*)-(*S*)-BPPFA was found to be effective to afford **8** in 65% yield (Scheme 3).[21] It

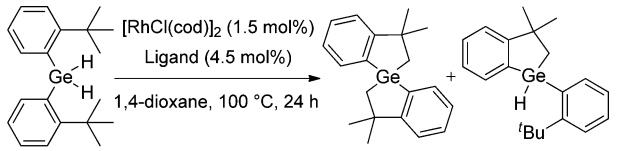
Scheme 3. Rhodium-Catalyzed Synthesis of 2,3-Dihydrobenzo[*b*]germole 8 via the Dehydrogenative Germylation of the C(sp^3)−H Bond



7 **8** 65%

should be noteworthy that the reaction does not require a hydrogen acceptor, 3,3-dimethyl-1-butene.[22] This result is in good agreement with our previous report on the dehydrogenative germylation of C(sp^2)−H bonds.[20b] Under the same reaction conditions, dihydrogermane **9** afforded 1,1′-spirogermabiindane **10** in 68% yield via the sequential 2-fold dehydrogenative germylation of C(sp^3)−H bonds (Table 7).

Table 7. Rhodium-Catalyzed Dehydrogenative Germylation of C(sp^3)−H Bonds of Dihydrogermane 9



9 **10** **11**

entry	ligand	yield of **10** (%)	yield of **11** (%)
1	(*R*)-DTBM-SEGPHOS	0	88
2	(*R*)-(S)-BPPFA	68	11

In contrast, when (*R*)-DTBM-SEGPHOS was used in place of (*R*)-(*S*)-BPPFA, dehydrogenative germylation occurred only one time to furnish selectively 2,3-dihydrobenzo[*b*]germole **11** in 88% yield without forming 1,1′-spirogermabiindane **10**.[23]

CONCLUSION

The work described herein is the acceleration effect of phosphine ligands for the dehydrogenative silylation of C(sp^3)−H bonds. Proper choice of diphosphine ligands and hydrogen acceptors is highly important. Among the phosphines examined, bulky and electron-donating (*R*)-DTBM-SEGPHOS was found to be the most effective to facilitate the dehydrogenative silylation of C(sp^3)−H bonds while suppressing the competitive hydrosilylation of a hydrogen acceptor, 3,3-dimethy-1-butene. By employing bulky and electron-rich C_2-symmetric diphosphine ligands, asymmetric desymmetrizations of 2-(isopropyl)silylbenzene or dihydrosilane via the silylative cyclization were achieved. Although the ee was low, this is the rare example of the asymmetric dehydrogenative functionalization of C(sp^3)−H bonds. Furthermore, the use of (*R*)-(*S*)-BPPFA enabled the unprecedented catalytic germylation of C(sp^3)−H bonds with dehydrogenation. Expansion of these observations to enantioselective C(sp^3)−H and C(sp^2)−H bond functionalization is underway in our laboratory.

EXPERIMENTAL SECTION

General Methods. All reactions were carried out in dry solvent under an argon atmosphere. 1,4-Dioxane was purchased from a chemical supplier, dried by the usual methods, distilled, and degassed with an argon gas for 20 min before use. [RhCl(cod)]$_2$, (*R*)-DTBM-SEGPHOS, (*R*)-DTBM-Garphos, (*R*)-H$_8$−BINAP, and (*R*)-(*S*)-BPPFA were purchased from chemical suppliers. Other chemicals obtained from commercial suppliers were used without further purification. ^{1}H and ^{13}C NMR spectra were recorded on a 400 MHz spectrometer (100 MHz for ^{13}C NMR) at 25 °C. Proton chemical shifts are reported with a residual solvent peak ($CDCl_3$ at δ 7.26 ppm) as an internal standard. Carbon chemical shifts are reported relative to $CDCl_3$ at 77.00 ppm. The following abbreviations are used: br s, broad singlet; s, singlet; d, doublet; t, triplet; q, quartet; sept, septet; m, multiplet. The mass analyzer type used for high-resolution mass spectrometry (HRMS) was orbitrap. Melting points were determined with a micromelting point apparatus without corrections. The analytical data for (2-alkylaryl)silanes **1a−e,h** and 2,3-dihydro-1*H*-benzo[*b*]siloles **2a−e,h** have been reported previously by our group.[9d]

Procedure for the Preparation of (2-Alkylphenyl)silanes. To a mixture of magnesium turnings (243 mg, 10 mmol) and chlorosilane (10 mmol) in THF (10 mL) was added 2-alkylbromobenzene (8.0 mmol) at 25 °C. The mixture was refluxed for 1 h, quenched with saturated NH_4Cl solution, and extracted with Et_2O three times (20 mL × 3). The combined organic layers were dried over $MgSO_4$, and the organic solvent was removed under reduced pressure. The residue was purified by flash column chromatography on silica gel with hexane as the eluent to give the corresponding (2-alkylphenyl)silanes.

*2-(Dimethylsilyl)isopropylbenzene (**1f**).* Colorless oil (87% yield, 1.24 g, 7.0 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.39 (d, J = 4.0 Hz, 6H), 1.29 (d, J = 6.8 Hz, 6H), 3.19 (sept, J = 6.8 Hz, 1H), 4.58 (sept, J = 4.0 Hz, 1H), 7.20 (t, J = 7.6 Hz, 1H), 7.33 (d, J = 7.6 Hz, 1H), 7.39 (t, J = 7.6 Hz, 1H), 7.49 (d, J = 7.6 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ −2.7, 24.4, 33.6, 124.7, 125.3, 129.8, 134.6, 135.0, 154.9. IR (neat/cm^{-1}): 3057, 3007, 2962, 2927, 2868, 2119, 1589, 1473, 1458, 1382, 1363, 1249, 1120, 1070, 1029, 883, 837, 773, 763, 748, 731, 711, 644. HRMS (FAB$^+$): calcd for $C_{11}H_{18}Si$ ([M]$^+$) 178.1178, found 178.1177.

*2-(Diethylsilyl)isopropylbenzene (**1g**).* Colorless oil (84% yield, 1.39 g, 6.7 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.83−0.89 (m, 4H), 1.00 (t, J = 7.4 Hz, 6H), 1.25 (d, J = 7.2 Hz, 6H), 3.13 (sept, J = 7.2 Hz, 1H), 4.34 (quint, J = 3.2 Hz, 1H), 7.16 (t, J = 6.2 Hz, 1H), 7.29−7.38 (m, 2H), 7.44 (d, J = 7.6 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 4.2, 8.4, 24.4, 33.7, 124.7, 125.1, 129.7, 133.2, 135.4, 155.2. The analytical data match those reported in the literature.[23]

*2-(Diphenylsilyl)isopropylbenzene (**1h**).* Colorless oil (80% yield, 1.94 g, 6.4 mmol); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.09 (d, J = 6.8 Hz, 6H), 3.13 (sept, J = 6.8 Hz, 1H), 5.62 (s, 1H), 7.14 (t, J = 6.8 Hz, 1H), 7.31−7.43 (m, 9H), 7.54 (d, J = 6.8 Hz, 4H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 24.1, 34.2, 125.1, 125.3, 127.9, 129.6, 130.6, 130.9, 133.8, 135.8, 137.0, 155.8. The analytical data match those reported in the literature.[24]

*Di(2-tert-butylphenyl)silane (**5**).* Colorless oil (51% yield, 1.21 g, 4.1 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.48 (s, 18H), 5.52 (s, 2H), 7.12 (dt, J = 1.2, 7.6 Hz, 2H), 7.37 (dt, J = 1.2, 7.6 Hz, 2H), 7.42 (dd, J = 1.2, 7.6 Hz, 2H), 7.54 (dd, J = 1.2, 8.0 Hz, 2H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 32.1, 37.5, 124.9, 125.8, 129.7, 130.8, 139.9, 157.2. IR (neat/cm^{-1}): 2986, 2965, 2904, 2869, 2176, 2138, 1586, 1472, 1430, 1363, 1247, 1127, 1116, 1057, 967, 880, 869, 764, 739, 613. HRMS (FAB$^+$): calcd for $C_{20}H_{28}Si$ ([M]$^+$) 296.1960, found 296.1952.

*Preparation of 2-(Dimethylgermyl)-tert-butylbenzene **7**.* To a solution of 2-*tert*-butylbromobenzene (852 mg, 4.0 mmol) in Et_2O (5.0 mL) was added ^{n}BuLi (3.0 mL, 4.8 mmol, 1.6 M in hexane) dropwise at −78 °C. After the mixture was stirred for 10 min, dichlorodimethylgermane (833 mg, 4.8 mmol) was added, and the mixture was gradually warmed to 25 °C. After being stirred overnight, the resultant mixture was added to a suspension of $LiAlH_4$ (304 mg, 8.0 mmol) in Et_2O (20 mL) at 25 °C and stirred for further 6 h. The

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mixture was quenched with H_2O (3.0 mL), aq NaOH (15 wt %, 3.0 mL), and H_2O (1.0 mL). The resultant suspension was filtered through Celite, and the solvent was removed under reduced pressure. The residue was purified by flash column chromatography on silica gel with hexane as the eluent to afford the 2-(dimethylgermyl)-*tert*-butylbenzene **7** (94% yield, 891 mg, 3.8 mmol) as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.50 (d, J = 3.2 Hz, 6H), 1.44 (s, 9H), 3.19 (sept, J = 3.2 Hz, 1H), 7.19 (dt, J = 0.8, 7.2 Hz, 1H), 7.28 (dt, J = 1.2, 8.0 Hz, 1H), 7.45 (dd, J = 1.2, 8.0 Hz, 1H), 7.49 (d, J = 7.2 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ −1.6, 32.0, 37.1, 125.1, 125.2, 128.2, 135.4, 139.0, 155.5. IR (neat/cm^{-1}): 2966, 2912, 2060, 1469, 1465, 1437, 1424, 1395, 1363, 1249, 1237, 1112, 847, 833, 766, 732, 712, 597. HRMS (FAB$^+$): calcd for $C_{12}H_{20}Ge$ ([M]$^+$) 238.0777, found 238.0762.

*Bis(2-tert-butylphenyl)germane (**9**).* Colorless oil (56% yield, 766 mg, 2.2 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.46 (s, 18H), 5.77 (s, 2H), 7.12 (dt, J = 0.8, 7.2 Hz, 2H), 7.32−7.38 (m, 4H), 7.55 (dt, J = 1.2, 7.8 Hz, 2H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 32.0, 37.3, 125.2, 126.0, 129.0, 133.6, 138.8, 156.1. IR (neat/cm^{-1}): 2989, 2964, 2358, 2084, 2047, 1471, 1363, 889, 792, 762, 732. HRMS (FAB$^+$): calcd for $C_{20}H_{28}Ge$ ([M]$^+$) 342.1403, found 342.1420.

General Procedure for Rhodium-Catalyzed Dehydrogenative Silylation and Germylation of Unactivated C(sp^3)−H Bonds. A flame-dried sealed tube was charged with $[RhCl(cod)]_2$ (1.8 mg, 3.8 μmol), phosphines (11 μmol), and 1,4-dioxane (0.25 mL), and the resulting mixture was stirred at 25 °C for 30 min. 2-Alkylphenylsilanes or 2-alkylphenylgermane (0.25 mmol) and 3,3-dimethyl-1-butene (21.0 mg, 0.25 mmol) were added to the mixture, which was then stirred at 50 or 100 °C for 24 h. The solvent was removed in vacuo and the residue was subjected to flash column chromatography on silica gel with hexane as an eluent to give the corresponding 2,3-dihydro-1*H*-benzo[*b*]siloles or 2,3-dihydro-1*H*-benzo[*b*]germole.

*1,1,3-Trimethyl-2,3-dihydro-1H-benzo[b]silole (**2f**).* Colorless oil (83% yield, 36.5 mg, 0.21 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.26 (s, 3H), 0.34 (s, 3H), 0.67 (dd, J = 6.0, 14.8 Hz, 1H), 1.28 (dd, J = 6.8, 14.8 Hz, 1H), 1.34 (d, J = 6.8 Hz, 3H), 3.30−3.32 (m, 1H), 7.21 (t, J = 6.8 Hz, 1H), 7.28 (d, J = 6.8 Hz, 1H), 7.34 (t, J = 6.8 Hz, 1H), 7.51 (d, J = 6.8 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ −1.7, −0.6, 21.6, 25.2, 38.4, 124.6, 125.7, 129.4, 131.8, 139.7, 157.8. IR (neat/cm^{-1}): 3055, 2993, 2956, 2897, 1591, 1560, 1452, 1438, 1406, 1367, 1296, 1247, 1195, 1174, 1128, 1078, 1056, 1022, 997, 920, 844, 802, 769, 756, 723, 694, 644. HRMS (FAB$^+$): calcd for $C_{11}H_{16}Si$ ([M]$^+$) 176.1021, found 176.1029. The ee of **2f** was determined by HPLC analysis after the derivatization leading to diol **4** by Tamao oxidation (see below for details).

*1,1-Diethyl-3-methyl-2,3-dihydro-1H-benzo[b]silole (**2g**).* Colorless oil (88% yield, 44.9 mg, 0.22 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.61 (dd, J = 6.0, 14.8 Hz, 1H), 0.74−0.84 (m, 4H), 0.93−1.04 (m, 6H), 1.29 (dd, J = 8.0, 14.8 Hz, 1H), 1.35 (d, J = 6.8 Hz, 3H), 3.29 (sext, J = 6.8 Hz, 1H), 7.19 (t, J = 7.2 Hz, 1H), 7.28−7.36 (m, 2H), 7.51 (d, J = 6.8 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 5.0, 5.6, 7.6, 7.7, 17.6, 25.2, 38.3, 124.6, 125.4, 129.3, 132.4, 137.8, 158.4. IR (neat/cm^{-1}): 3055, 2995, 2954, 2910, 2873, 1591, 1560, 1456, 1438, 1413, 1371, 1298, 1255, 1232, 1126, 1085, 1060, 1006, 956, 756, 682, 665, 624. HRMS (FAB$^+$): calcd for $C_{13}H_{20}Si$ ([M]$^+$) 204.1334, found. 204.1344.

*3-Methyl-1,1-diphenyl-2,3-dihydro-1H-benzo[b]silole (**2h**).* Colorless oil (92% yield, 69.1 mg, 0.23 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.17 (dd, J = 6.0, 14.8 Hz, 1H), 1.38 (d, J = 6.8 Hz, 3H), 1.79 (dd, J = 7.6, 14.8 Hz, 1H), 3.46 (sext, J = 6.8 Hz, 1H), 7.26−7.28 (m, 1H), 7.31−7.40 (m, 8H), 7.53−7.55 (m, 2H), 7.60−7.61 (m, 2H), 7.66 (d, J = 7.6 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 20.5, 24.9, 38.4, 124.8, 126.1, 127.8, 127.9, 129.5, 130.0, 133.1, 135.1, 135.2, 158.9. The analytical data match those reported in the literature.[12b]

*2-(Dimethyl(3,3-dimethylbutyl)silyl)ethylbenzene (**3**).* Colorless oil (50% yield with dppbz as a ligand (see Table 4, entry 3), 31.0 mg, 0.13 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.31 (s, 6H), 0.72−0.77 (m, 2H), 0.85 (s, 9H), 1.15−1.19 (m, 2H), 1.25 (t, J = 7.4 Hz, 3H), 2.75 (q, J = 7.4 Hz, 2H), 7.17 (t, J = 7.6 Hz, 1H), 7.24 (d, J = 7.6 Hz, 1H), 7.33 (t, J = 7.6 Hz, 1H), 7.45 (d, J = 7.6 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ −1.5, 10.6, 16.4, 28.8, 28.9, 31.1, 37.9, 124.8, 127.9, 129.2, 134.7, 136.9, 150.1. IR (neat/cm^{-1}): 3057, 2954, 2866, 1589, 1541, 1508, 1390, 1363, 1249, 1219, 1159, 1128, 1083, 1060, 1041, 1006, 929, 885, 837, 819, 775, 754, 731, 682, 632. HRMS (FAB$^+$): calcd for $C_{16}H_{28}Si$ ([M]$^+$) 248.1960, found 248.1967.

*3,3-Dimethyl-1-sila-1,1-spirobiindane (**6**).* Colorless oil (75% yield, 54.8 mg, 0.19 mmol). The ee was determined to 39% on a Daicel CHIRALPAK OD column with hexane as the eluent (flow rate = 0.50 mL/min). Retention time for the major enantiomer was 16 min, and that for the minor enantiomer was 13 min. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.25 (d, J = 15.2 Hz, 2H), 1.34 (d, J = 15.2 Hz, 2H), 1.41 (s, 6H), 1.51 (s, 6H), 7.18−7.22 (m, 2H), 7.41−7.44 (m, 6H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 29.2, 33.65, 33.69, 43.3, 123.3, 126.0, 130.3, 133.0, 135.5, 163.0. IR (neat/cm^{-1}): 3045, 3005, 2996, 2952, 2881, 2860, 1966, 1927, 1589, 1559, 1462, 1439, 1402, 1379, 1360, 1285, 1257, 1188, 1138, 1098, 1064, 1030, 946, 869, 856, 767, 734, 729, 708. HRMS (FAB$^+$): calcd for $C_{20}H_{24}Si$ ([M]$^+$) 292.1647, found 292.1626.

*1,1,3,3-Tetramethyl-2,3-dihydro-1H-benzo[b]germole (**8**).* Colorless oil (65% yield, 38.5 mg, 0.16 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.47 (s, 6H), 1.17 (s, 2H), 1.34 (s, 6H), 7.19−7.22 (m, 1H), 7.31−7.33 (m, 2H), 7.51 (d, J = 7.6 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ −0.98, 30.6, 33.6, 44.4, 123.5, 125.8, 128.9, 132.1, 141.1, 159.4. IR (neat/cm^{-1}): 3065, 3053, 2956, 2907, 2862, 1587, 1464, 1439, 1411, 1379, 1360, 1283, 1255, 1235, 1187, 1123, 1056, 1030, 860, 833, 797, 766, 728, 672, 667, 601, 582, 552. HRMS (FAB$^+$): calcd for $C_{12}H_{19}Ge$ ([M + H]$^+$) 237.0699, found 237.0694.

*3,3-Dimethyl-1-germa-1,1-spirobiindane (**10**).* Colorless solid (68% yield with (*R*)-(*S*)-BPPFA (Table 7, entry 2), 67.8 mg, 0.17 mmol); mp 83.4−83.7 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.41 (s, 12H), 1.42 (d, J = 12.4 Hz, 2H), 1.51 (d, J = 12.4 Hz, 2H), 7.20 (dt, J = 1.6, 7.0 Hz, 2H), 7.38 (dt, J = 1.2, 8.0 Hz, 2H), 7.41 (d, J = 8.0 Hz, 2H), 7.45 (d, J = 8.0 Hz, 2H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 30.0, 33.3, 33.7, 43.8, 123.6, 126.0, 129.5, 132.8, 137.6, 160.3. IR (KBr/cm^{-1}): 3054, 2960, 2905, 1584, 1456, 1436, 1380, 1359, 1261, 1251, 1157, 1121, 1050, 1030, 771, 766, 745, 730, 670. HRMS (FAB$^+$): calcd for $C_{20}H_{25}Ge$ ([M + H]$^+$) 339.1168, found 339.1158.

*3,3-Dimethyl-1-(2-tert-butylphenyl)-2,3-dihydro-1H-benzo[b]-germole (**11**).* Colorless oil (88% yield with (*R*)-DTBM-SEGPHOS (Table 7, entry 1), 74.8 mg, 0.22 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.22 (s, 6H), 1.35 (d, J = 13.2 Hz, 1H), 1.36 (s, 9H), 1.52 (d, J = 13.2 Hz, 1H), 5.74 (d, J = 4.4 Hz, 1H), 6.92 (t, J = 7.2 Hz, 1H), 7.10−7.18 (m, 3H), 7.26 (d, J = 3.6 Hz, 1H), 7.38 (d, J = 8.4 Hz, 1H), 7.45 (d, J = 7.2 Hz, 1H). ^{13}C{^{1}H } NMR (100 MHz, $CDCl_3$): δ 31.3, 32.3, 33.2, 33.5, 37.2, 44.3, 124.0, 125.2, 125.8, 126.2, 128.9, 129.4, 133.7, 134.6, 136.7, 137.0, 156.1, 160.6. IR (neat/cm^{-1}): 3052, 2956, 2864, 2054, 1586, 1464, 1439, 1395, 1380, 1362, 1282, 1249, 1189, 1171, 1125, 1112, 1052, 1031, 792, 764, 737, 724, 686, 668, 637. HRMS (FAB$^+$): calcd for $C_{20}H_{26}Ge$ ([M]$^+$) 340.1246, found 340.1251.

Derivatization of 2f for the Determination of the ee. To a solution of *t*-BuOK (135 mg, 1.2 mmol) in THF (1.4 mL) was added *tert*-butyl hydroperoxide (0.22 mL, 5.0−6.0 M in decane) at 0 °C, and the mixture was stirred for 10 min. A solution of **2f** (35.2 mg, 0.20 mmol) in THF (1.0 mL) and TBAF (1.2 mL, 1.0 M in THF) was added, and the mixture was stirred at 70 °C for 15 h. The resultant mixture was cooled to 25 °C, and $Na_2S_2O_3{\cdot}5H_2O$ (ca. 650 mg) in water (6.0 mL) was added. After being stirred for 30 min, the reaction mixture was quenched with saturated NH_4Cl solution and extracted with Et_2O three times (15 mL × 3). The combined organic layer was washed with 5 wt % of citric acid and dried over $MgSO_4$. The organic solvent was removed under reduced pressure, and then the residue was purified by flash column chromatography on silica gel with hexane as the eluent to give 2-(2-hydroxy-1-methylethyl)phenol **4** (84% yield, 25.6 mg, 0.17 mmol) as a colorless oil. The ee was determined to 37% on a Daicel CHIRALPAK OD column with hexane/2-propanol (v/v = 9/1) as the eluent (flow rate = 0.5 mL/min). The retention time for the major enantiomer was 21 min and that for the minor enantiomer was 23 min. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.32 (d, J = 7.2 Hz, 3H),

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3.22−3.28 (m, 1H), 3.74 (dd, J = 7.6, 9.6 Hz, 1H), 3.95 (dd, J = 3.6, 9.6 Hz, 1H), 6.88−6.91 (m, 2H), 7.11−7.16 (m, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 15.6, 36.8, 69.4, 117.1, 120.7, 127.7, 127.8, 130.5, 154.8. The analytical data match those reported in the literature.[12b]

■ ASSOCIATED CONTENT

Supporting Information

^1H and ^{13}C NMR spectra for new compounds. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b00920.

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Notes

The authors declare no competing financial interest.

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Kakiuchi, F.; Murai, S. *Organometallics* **1999**, *18*, 3764−3767. We have recently reported the rhodium-catalyzed dehydrogenative germylation of the C(sp^2)−H bonds leading to 9-germafluorenes. See: (b) Murai, M.; Matsumoto, K.; Okada, R.; Takai, K. *Org. Lett.* **2014**, *16*, 6492−6495.

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(23) Effect of other ligands at 100 °C: (*R*)-DTBM-Garphos, 0% of **10** and 70% of **11**; (*R*)-H_8−BINAP, 20% of **10** and 30% of **11**; dppp, 51% of **10** and 33% of **11**; dppf, 5% of **10** and 80% of **11**; (*R*)-SEGPHOS, 6% of **10** and 78% of **11**. The ee's of **10** and **11** were less than 10% with these ligands. For example, the ee of **11** was 3% (Table 7, entry 1) and **10** was 5% (entry 2), respectively.

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