Asymmetric Synthesis Catalyzed by Chiral Ferrocenylphosphine–Transition-Metal Complexes. 3.[1] Preparation of Optically Active Allylsilanes by Palladium-Catalyzed Asymmetric Grignard Cross-Coupling[2,3]

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Asymmetric cross-coupling of the [α-(trimethylsilyl)benzyl]- or [1-(trialkylsilyl)ethyl]-Grignard reagent with alkenyl bromides in the presence of a chiral ferrocenylphosphine–palladium complex, dichloro[(*R*)-*N*,*N*-dimethyl-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine]palladium(II) ($PdCl_2$[(*R*,*S*)-PPFA]), as a catalyst, gave optically active allylsilanes which contain an asymmetric carbon atom directly bonded to the silicon atom, e.g., (*R*)-3-phenyl-3-(trimethylsilyl)propene (**3a**) (95% ee), (*R*,*E*)-1-phenyl-1-(trimethylsilyl)-2-butene (**3b**) (85% ee), (*R*,*Z*)-**3b** (24% ee), (*R*,*E*)-1,3-diphenyl-3-(trimethylsilyl)propene (**3c**) (95% ee), (*S*,*E*)-1-phenyl-3-(trimethylsilyl)-1-butene (**14c**) (71% ee), (*S*,*Z*)-**14c** (59% ee), (*S*,*E*)-1-phenyl-3-(triethylsilyl)-1-butene (**16c**) (93% ee), (*S*,*E*)-3-(triethylsilyl)-2-pentene (**16b**) (85% ee), (*S*,*E*,*E*)-2-(dimethylphenylsilyl)-3,5-heptadiene (**15d**) (45% ee), and 1-[1-(trimethylsilyl)ethyl]cyclopentene (**21**) (37% ee). The configuration and enantiomeric purity of the allylsilanes were determined with the aid of stereoselective oxidative cleavage of the carbon–silicon bond in optically active alkylsilanes.

It is well-documented that allylsilanes are highly useful intermediates in organic synthesis.[4,5] They react with a wide range of electrophiles in a regiospecific manner, the electrophile attacking the γ-carbon to give products of substitution with allylic rearrangement (S_E' reaction). Use of optically active allylsilanes, which contain an asymmetric carbon atom directly bonded to the silicon atom, for the electrophilic substitution reaction would possibly produce various kinds of optically active compounds by an asymmetric induction and would provide significant information regarding the mechanism of the S_E' reaction. Previously, we have shown that a chiral ferrocenylphosphine, (*R*)-*N*,*N*-dimethyl-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine ((*R*,*S*)-PPFA), is an effective ligand for nickel- or palladium-catalyzed asymmetric cross-coupling of (secondary alkyl)-Grignard reagents with alkenyl bromides to give optically active olefins.[6,7] By using [α-silylalkyl]-Grignard reagents in the asymmetric cross-coupling, we have succeeded, for the first time, in a simple and efficient synthesis of optically active allylsilanes with high optical purity. Recently, the allylsilanes have also been prepared by the catalytic asymmetric hydrosilylation of 1,3-dienes[8] or by the enol–ether Claisen rearrangement of a vinylsilane,[9] but the preparation by cross-coupling seems to be the most convenient since it has the advantages both of employing only a catalytic amount of a chiral auxiliary and of giving a variety of allylsilanes generally with high stereoselectivity. We describe here the preparation of the optically active allylsilanes by asymmetric cross-coupling and the determination of configuration and enantiomeric purity of the allylsilanes.

Table I. Cross-Coupling of [α-(Trimethylsilyl)benzyl]magnesium Bromide (1) with Vinyl Bromide (2a) Catalyzed by Several Nickel and Palladium Complexes[a]

entry	catalyst	yield of **3a** (%)	$[\alpha]^{20}_D$ (deg) of **3a** (*c* in benzene)	% ee of **3a** (confign)
1	$PdCl_2$[(*R*,*S*)-PPFA]	80	−36.2 (5.0)	56 (*R*)
2	$PdCl_2$[(*R*,*S*)-BPPFA]	33	−13.4 (4.6)	21 (*R*)
3	$PdCl_2$[(*S*)-Valphos]	98	+4.8 (5.1)	7 (*S*)
4	$NiCl_2$[(*S*)-prophos]	25	+2.4 (4.8)	4 (*S*)
5	$NiCl_2$[(−)-DIOP]	65	−3.3 (5.1)	5 (*R*)
6	(*R*,*S*)-PPFA/$NiCl_2$[c]	10		
7	(*S*)-Valphos/$NiCl_2$[c]	13		
8[d]	$PdCl_2$[(*R*,*S*)-PPFA]	27	−0.7 (5.0)	1 (*R*)

[a] Catalyst/**2a** = 0.005. **1**/**2a** = 2. Concentration of **1** in ether was 0.7–1.0 M. Reaction was carried out at 50 °C for 4 days. [b] Yields based on **2a** were determined by GLC. [c] The catalyst was prepared in situ by mixing nickel chloride with 1 equiv of a ligand. [d] Reaction of the zinc reagent prepared in situ by mixing **1** with 1 equiv of zinc bromide in THF.

Results and Discussion

For the cross-coupling of [α-(trimethylsilyl)benzyl]-magnesium bromide (**1**) with vinyl bromide (**2a**) (eq 1),[10]

$$\underset{\textbf{1}}{Me_3SiCH(Ph)MgBr} + \underset{\textbf{2a}}{CH_2{=}CHBr} \xrightarrow{[M\text{-}L^*]} \underset{\textbf{3a}}{Me_3Si\overset{*}{C}H(Ph)CH{=}CH_2} \quad (1)$$

we have examined several nickel and palladium catalysts containing optically active phosphine ligands. Results

(1) For part 2 in this series, see ref 6.
(2) Part of this paper appeared previously: (a) Hayashi, T.; Konishi, M.; Ito, H.; Kumada, M. *J. Am. Chem. Soc.* **1982**, *104*, 4962. (b) Hayashi, T.; Okamoto, Y.; Kumada, M. *Tetrahedron Lett.* **1983**, *24*, 807.
(3) This paper corresponds to part 10 of the series Optically Active Allylsilanes. For part 9, see ref 8b.
(4) For review: (a) Chan, T. H.; Fleming, I. *Synthesis* **1979**, 761. (b) Sakurai, H. *Pure Appl. Chem.* **1982**, *54*, 1. (c) Colvin, E. W. *Silicon in Organic Synthesis*; Butterworth: London, 1981; pp 97–124. (d) Weber, W. P. *Silicon Reagents for Organic Synthesis*; Springer-Verlag: New York, 1983; pp 173–205.
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(10) Cross-coupling of **1** with vinyl chloride catalyzed by dichlorobis(triphenylphosphine)nickel(II) has been reported: ref 5a.

0022-3263/86/1951-3772$01.50/0

Table II. Asymmetric Cross-Coupling of [α-(Trimethylsilyl)benzyl]magnesium Bromide (1) with Alkenyl Bromides 2 Catalyzed by $PdCl_2$[(*R*,*S*)-PPFA][a]

entry	alkenyl bromide 2[b]	temp (°C)	time (days)	product (yield, %)[c]	$[\alpha]^{20}_D$ (deg) of **3** (c in benzene)	% ee[d] (confign)	$[\alpha]^{20}_D$ (deg) of **4** (c in benzene)
9	**2a**	30	4	**3a** (79)	−42.9 (5.0)	66 (*R*)	
10	**2a**	19	4	**3a** (63)	−55.2 (5.0)	85 (*R*)	
11[e]	**2a**	19	4	**3a** (52)	−50.1 (5.0)	77 (*R*)	
12	**2a**	0	4	**3a** (42)	−61.8 (5.0)	95 (*R*)	−1.35 (2.6)
13	(*E*)-**2b**	0	5	(*E*)-**3b** (77)	−36.3 (5.1)	85 (*R*)	+8.10 (3.8)
14	(*Z*)-**2b**	0	5	(*Z*)-**3b** (38)	−21.3 (4.5)	24 (*R*)	+2.30 (6.4)
15	(*E*)-**2c**	0	2	(*E*)-**3c** (93)	−43.9 (1.0)	95 (*R*)	−2.3 (5.6)
16	(*Z*)-**2c**	15	2	(*Z*)-**3c** (95)	−44.3 (1.0)	13 (*R*)	−0.3 (1.5)
17	**8**	rt[g]	1	**9** (62)	+9.84 (6.1)[f]	18 (*S*)	−0.42 (2.9)

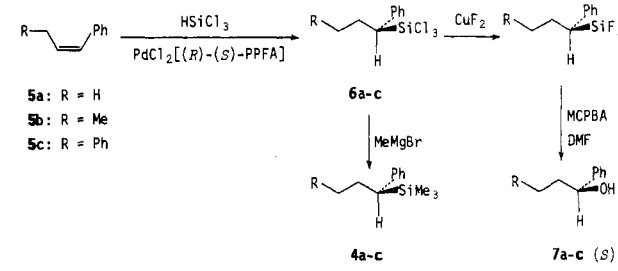
[a] Reaction of 40 mmol of the bromide **2** with 80–120 mmol of **1** in 40–60 mL of ether in the presence of 0.20 mmol of the palladium catalyst unless otherwise noted. [b] For the structures, refer to eq 2 and 3. [c] Isolated yields based on the bromide. [d] Calculated on the basis of the rotation data of **4**. [e] Reaction of 60 mmol of **2a** with 40 mmol of **1**. The yield is based on **1**. [f] $[\alpha]^{20}_D$ of 1,3-diphenyl-3-(trimethylsilyl)propyne (**9**). [g] rt = room temperature.

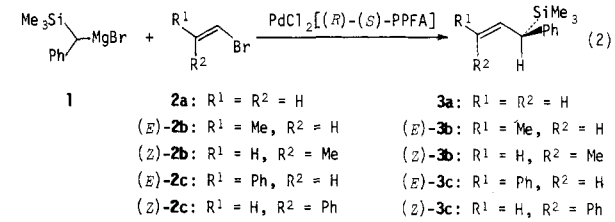
obtained for the reaction at 50 °C are summarized in Table I.

A ferrocenylphosphine–palladium complex, dichloro[(*R*)-*N*,*N*-dimethyl-1-[(*S*)-2-(diphenylphosphino)ferrocenyl]ethylamine]palladium(II) ($PdCl_2$[(*R*,*S*)-PPFA]),[6,11] was found to be the most effective catalyst giving the coupling product 3-phenyl-3-(trimethylsilyl)propene (**3a**) with the highest optical purity in a high yield (entry 1). The high efficiency of $PdCl_2$[(*R*,*S*)-PPFA] has already been demonstrated[6,11] in the asymmetric cross-coupling of secondary alkyl-Grignard and alkylzinc reagents represented by (1-phenylethyl)magnesium chloride with vinyl bromide. The bisphosphine analogue, dichloro[(*R*)-*N*,*N*-dimethyl-1-[(*S*)-1′,2-bis(diphenylphosphino)ferrocenyl]ethylamine]palladium(II) ($PdCl_2$[(*R*,*S*)-BPPFA])[6] was less effective for the present reaction (entry 2). Dichloro[(*S*)-2-(dimethylamino)-3-methyl-1-(diphenylphosphino)butane]palladium(II) ($PdCl_2$[(*S*)-Valphos])[12] was catalytically very active but much lower in stereoselectivity than the palladium–PPFA catalyst (entry 3). Nickel complexes, dichloro[(*S*)-1,2-bis(diphenylphosphino)propane]nickel(II) ($NiCl_2$[(*S*)-prophos])[13,14] and dichloro[(−)-2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane]nickel(II) ($NiCl_2$[(−)-DIOP]),[15,16] showed lower catalytic activity and stereoselectivity (entries 4 and 5). Nickel catalysts prepared in situ by mixing nickel chloride with (*R*,*S*)-PPFA[17] and (*S*)-Valphos,[12] both of which had been successfully used for the cross-coupling of (1-phenylethyl)magnesium chloride,[6,12] were almost inactive for reaction of **1** (entries 6 and 7). Reaction of the organozinc reagent prepared from **1** and zinc bromide gave racemic **3a** in a low yield (entry 8), though a few instances have been recorded of the improvement of stereoselectivity in the asymmetric cross-coupling by use of organozinc reagents instead of Grignard reagents.[11]

The results obtained for the cross-coupling of the Grignard reagent **1** with vinyl bromide (**2a**) and 2-substituted alkenyl bromides **2b,c** in the presence of $PdCl_2$[(*R*,*S*)-PPFA] (eq 2) are summarized in Table II. The stereoselectivity in the reaction of vinyl bromide (**2a**) was strongly dependent on the reaction temperature (entries 9–12), the lower temperature giving the higher selectivity. Thus, the reaction at 50 °C, 30 °C, 19 °C, and 0 °C gave **3a** of 56%, 66%, 85%, and 95% ee, respectively. As shown in entries 10 and 11, the initial ratio of the Grignard reagent **1** to the bromide **2a** did not lagely affect the optical purity of the product **3a**, which is due to the fast inversion of **1** compared with the coupling reaction and what has been usually observed in the asymmetric cross-coupling.[6,18] The palladium catalyst $PdCl_2$[(*R*,*S*)-PPFA] was also effective for the reaction of **1** with (*E*)- and (*Z*)-1-bromopropene (**2b**) and (*E*)- and (*Z*)-β-bromostyrene (**2c**) to afford the corresponding coupling products **3b** and **3c** in an optically active form without *E*–*Z* isomerization of the olefinic double bond (entries 13–16). The *R* isomer was preferentially produced in every case. Bromides of *E*

Scheme I





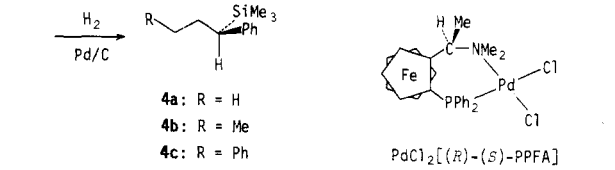


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Table III. Asymmetric Cross-Coupling of [1-(Trialkylsilyl)ethyl]magnesium Chlorides 10–13 with Alkenyl Bromides 2 Catalyzed by $PdCl_2$[(*R*,*S*)-PPFA][a]

entry	Grignard reagent (R_3Si in $R_3SiCH(Me)MgCl$)	alkenyl bromide[b]	temp (°C)	time (h)	product (yield, %)[c]	$[\alpha]^{20}_D$ (deg) (*c* in benzene)	% ee[d] (config)
18	**10** (Me_3Si)	(*E*)-**2c**	0	8	(*E*)-**14c** (78)	−15.9 (2.8)	71 (*S*)
19	**10** (Me_3Si)	(*E*)-**2c**	−10	20	(*E*)-**14c** (65)	−15.2 (5.7)	68 (*S*)
20	**10** (Me_3Si)	(*E*)-**2c**	−30	20	(*E*)-**14c** (60)	−14.7 (4.9)	65 (*S*)
21	**10** (Me_3Si)	(*Z*)-**2c**	−10	20	(*Z*)-**14c** (76)	+88.1 (3.3)	59 (*S*)
22	**11** ($PhMe_2Si$)	(*E*)-**2c**	−10	20	(*E*)-**15c** (92)	−6.88 (4.1)	68 (*S*)
23	**11** ($PhMe_2Si$)	(*E*)-**2c**	20	6	(*E*)-**15c** (78)	−6.79 (3.5)	67 (*S*)
24	**12** (Et_3Si)	(*E*)-**2c**	−10	20	(*E*)-**16c** (88)	−38.5 (2.8)	93 (*S*)
25[e]	**12** (Et_3Si)	(*E*)-**2c**	−10	4	(*E*)-**16c** (93)	−5.9 (9.9)	14 (*S*)
26	**12** (Et_3Si)	(*Z*)-**2c**	−10	20	(*Z*)-**16c** (30)	+11.7 (1.1)	14 (*S*)
27	**13** (Ph_3Si)	(*E*)-**2c**	−10	20	(*E*)-**17c** (20)	+8.43 (0.9)	36 (*S*)
28	**10** (Me_3Si)	(*E*)-**2b**	−10	20	(*E*)-**14b** (78)	−15.7 (1.4)	55 (*S*)
29	**12** (Et_3Si)	(*E*)-**2b**	−20	90	(*E*)-**16b** (36)	−26.6 (1.1)	85 (*S*)
30	**10** (Me_3Si)	**2a**	−20	40	**14a** (22)	−14.9 (5.0)	
31	**11** ($PhMe_2Si$)	**2a**	0	20	**15a** (57)	−23.5 (4.4)	>49 (*S*)
32[f]	**12** (Et_3Si)	**2a**	−10	40	**16a** (77)	−27.2 (3.5)	>46 (*S*)
33[f]	**10** (Me_3Si)	**2d**[g]	−20	40	(*E*,*E*)-**14d** (69)[h]	−16 (5.0)	35 (*S*)
					(*Z*,*E*)-**14d**	+13 (5.1)	8 (*S*)
34	**11** ($PhMe_2Si$)	(*E*,*E*)-**2d**	0	40	(*E*,*E*)-**15d** (51)		45 (*S*)
35[f]	**10** (Me_3Si)	**19**	−5	20	**21** (60)	−6.2 (0.5)	34
36[f]	**10** (Me_3Si)	**20**	0	20	**21** (70)	−6.9 (1.0)	37

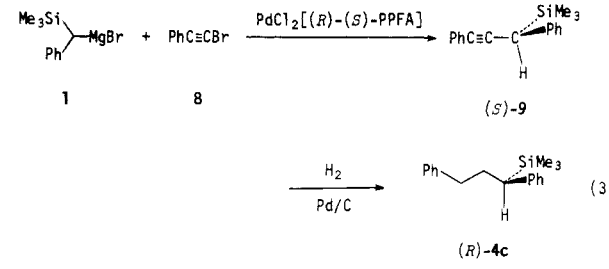
[a] Reaction of 40 mmol of the bromide with 120 mmol of the Grignard reagent in 60–90 mL of ether in the presence of 0.20 mmol of the palladium catalyst unless otherwise noted. [b] For the structures, refer to eq 2, 4, and 5. [c] Isolated yields based on the bromide. [d] Determination of the absolute configuration and enantiomeric purity is shown in Schemes III–VII and in the Experimental Section. [e] The ratio of **12** to **2c** is 0.86 to 1. [f] The ratio of Grignard reagent to bromide is 2 to 1. [g] A mixture of (1*Z*,3*E*)-1-bromo-1,3-pentadiene (**2d**) and the *E*,*E* isomer in a ratio of 45 to 55. [h] Yield of the mixture of *E*,*E* and *Z*,*E* isomers in a ratio of 1 to 1.

configuration, (*E*)-**2b** and (*E*)-**2c**, led to the (*E*)-allylsilanes (*E*)-**3b** and (*E*)-**3c** with high optical purity (85% and 95% ee, respectively), while *Z* bromides to (*Z*)-allylsilanes with lower optical purity.

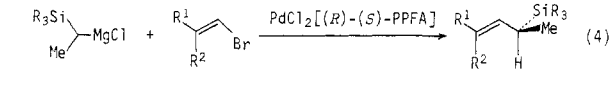
It is rather surprising that the difference in stereoselectivity is quite large between the reaction of the *E* bromides and that of the *Z* bromides, since the stereochemistry of the coupling product is thought to be mainly determined at the transmetalation step in the catalytic cycle,[6,12] where the alkenyl group is unlikely to have a large effect on the stereocontrol of the Grignard reagent.

The configuration and enantiomeric purity of the allylsilanes **3a–c** were determined by converting them into alkyltrimethylsilanes **4** by hydrogenation in the presence of Pd/C. The stereochemistry of **4** was established by the method shown in Scheme I, where optically active alkyltrichlorosilanes **6** were converted into **4** and known secondary alkyl alcohols **7**. Since the oxidative cleavage of the carbon–silicon bond in trifluorosilylalkanes with *m*-chloroperoxybenzoic acid (MCPBA) forming the carbon–oxygen bond has been known to proceed with retention of configuration,[19] the alkyltrimethylsilanes **4a–c** derived from **6a–c** should have the same configuration and enantiomeric purity as the alcohols **7a–c** have. The alkyltrimethylsilanes **4a**, **4b**, and **4c** which have specific rotations $[\alpha]^{20}_D$ +0.68°, −4.87°, and +0.85° (benzene), respectively, proved to be all *S* isomers of 48%, 51%, and 36% ee, respectively. Thus, the maximum rotations of (*S*)-**4a**, (*S*)-**4b**, and (*S*)-**4c** were calculated to be $[\alpha]^{20}_D$ +1.42°, −9.55°, and +2.36° (benzene), respectively. Optical rotation data of **4** obtained by hydrogenation of **3** are summarized in Table II. It should be noted that the preparation of the optically active trichlorosilanes **6** was achieved by catalytic asymmetric hydrosilylation[20] of styrene derivatives **5** with trichlorosilane in the presence of $PdCl_2$[(*R*,*S*)-PPFA], identical catalyst with that used in the present cross-coupling.

Asymmetric cross-coupling of the Grignard reagent **1** with phenylbromoacetylene (**8**) gave 62% yield of optically active propargylsilane, 1,3-diphenyl-3-(trimethylsilyl)-propyne (**9**) (entry 17). Hydrogenation of **9** gave (*R*)-**4c** with $[\alpha]^{20}_D$ −0.42° (benzene), indicating that the propargylsilane **9** is an *S* isomer of 18% ee (eq 3).



Asymmetric cross-coupling of [1-(trialkylsilyl)ethyl]-magnesium chlorides **10–13** which can produce optically active allylsilanes containing a methyl group at the chiral carbon atom was also examined in the presence of the $PdCl_2$[(*R*,*S*)-PPFA] catalyst (eq 4). The results are summarized in Table III. The stereoselectivity of the reaction was dependent strongly on the substituents on the silicon atom of the Grignard reagent. In the reaction of (*E*)-bromostyrene (**2c**), the highest selectivity was observed with [1-(triethylsilyl)ethyl]magnesium chloride (**12**). The enantiomeric purities of (*S*,*E*)-1-phenyl-3-silyl-1-butenes (**14c–17c**) obtained with the Grignard reagent substituted with trimethylsilyl (**10**), dimethylphenylsilyl (**11**), tri-



10: R_3Si = Me_3Si **2a**
11: R_3Si = $PhMe_2Si$ **2b**
12: R_3Si = Et_3Si **2c**
13: R_3Si = Ph_3Si **2d**: R^1, R^2 = H, (*E*)-MeCH=CH

14: R_3Si = Me_3Si
15: R_3Si = $PhMe_2Si$
16: R_3Si = Et_3Si
17: R_3Si = Ph_3Si

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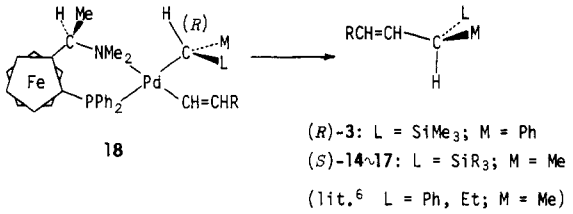
Scheme II



18

(*R*)-**3**: L = $SiMe_3$; M = Ph
(*S*)-**14**~**17**: L = SiR_3; M = Me
(lit.[6] L = Ph, Et; M = Me)

ethylsilyl (**12**), and triphenylsilyl (**13**) were 71% ee (entry 18), 68% ee (entry 22), 93% ee (entry 24), and 36% ee (entry 27), respectively. The high selectivity of the (triethylsilyl-substituted)-Grignard reagent **12** was also observed in the coupling reaction with (*E*)-bromopropene (**2b**), which gave (*S*,*E*)-4-(triethylsilyl)-2-pentene (**16b**) of 85% ee (entry 29). In the reaction with (*Z*)-bromostyrene (**2c**), on the contrary, the Grignard reagent **12** gave the coupling product, (*Z*)-allylsilane, of much lower optical purity than the [1-(trimethylsilyl)ethyl]-Grignard reagent **10** (entries 21 and 26).

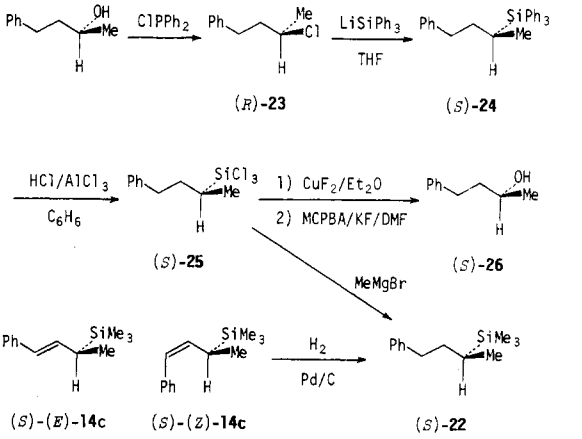
The stereoselectivity in the reaction of the [1-(trialkylsilyl)ethyl]-Grignard reagents was not affected by the reaction temperature but was strongly affected by the initial ratio of the Grignard reagent to the bromide. Thus, the reaction of **10** with (*E*)-**2c** at 0 °C, −10 °C, and −30 °C gave the product (*S*,*E*)-**14c** of about 70% ee independently of the reaction temperature (entries 18, 19, and 20). The independence was also observed in the reaction of **11** with (*E*)-**2c** (entries 22 and 23). The high enantiomeric purity (93%) of (*E*)-**16c** obtained in the reaction under usual conditions (the initial ratio of **12**/**2c** = 2/1) decreased to 14% when an excess of the halide **2c** was used (entries 24 and 25). The decrease indicates that the inversion of the [1-(trialkylsilyl)ethyl]-Grignard reagent is relatively slow as compared with the coupling reaction, and the slow inversion makes a contrast with the inversion of [α-(trimethylsilyl)benzyl]- and other (secondary alkyl)-Grignard reagents which has been shown to be faster than their cross-coupling in the presence of a palladium or nickel catalyst.[6,12]

The asymmetric cross-coupling of [1-(trimethylsilyl)-ethyl]magnesium chloride (**10**) with 1-bromo-1,3-pentadiene (**2d**), which was a mixture of *E*,*E* and *Z*,*E* isomers in a ratio of 55 to 45, gave optically active dienylsilanes 2-(trimethylsilyl)-3,5-heptadienes (**14d**) consisting of *E*,*E* and *Z*,*E* isomers in a ratio of 50 to 50 (entry 33). The *E*,*E* and *Z*,*E* isomers, isolated by preparative GLC, were found to be *S* isomers of 35% ee and 8% ee, respectively. The optical purity of the (*E*,*E*)-dienylsilane was enhanced to 45% by use of the [1-(dimethylphenylsilyl)ethyl]-Grignard reagent **11** (entry 34).

It is noteworthy that all the allylsilanes produced in the reaction of the [1-(trialkylsilyl)ethyl]-Grignard reagents **10**–**13** catalyzed by $PdCl_2$[(*R*,*S*)-PPFA] have an *S* configuration and those produced in the reaction of the [α-(trimethylsilyl)benzyl]-Grignard reagent have an *R* configuration. The preference of these configurations is rationalized by the mechanism shown in Scheme II where the reaction proceeds by way of the diorganopalladium intermediate **18** containing an alkyl group of *R* configuration.[21] The intermediate **18** is imagined to be more favorable than its diastereomeric isomer with an *S* alkyl group which would suffer from steric repulsion between the ferrocene moiety and the trialkylsilyl group. The silyl

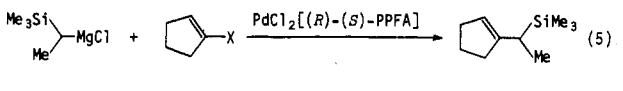
(21) Reductive elimination on a palladium complex has been reported to proceed with retention of configuration at carbon: Milstein, D.; Stille, J. K. *J. Am. Chem. Soc.* **1979**, *101*, 4981.

Scheme III



group must be larger than the phenyl or methyl group. The illustration is consistent with the stereoselectivity we have observed in the reaction of the (1-phenylethyl)- or 2-butyl-Grignard reagent.[22]

In the reaction forming allylsilane containing cyclic olefin **21**, cyclopentenyl phosphate **20** was found to undergo the cross-coupling with essentially the same reactivity and stereoselectivity as cyclopentenyl bromide **19** (eq 5) (entries 35 and 36). The method via alkenyl



10 **19**: X = Br; **20**: X = OP(O)(OPh)$_2$ **21**

phosphates[23] must be useful for the preparation of various types of optically active allylsilanes since alkenyl phosphates can be prepared regio- and stereoselectively and can overcome the otherwise difficult accessibility of alkenyl substrates.

Scheme III shows a sequence of reactions carried out to determine the configuration and enantiomeric purity of 1-phenyl-3-(trimethylsilyl)butane (**22**) which is the alkylsilane obtained by hydrogenation of the allylsilanes (*E*)- and (*Z*)-**14c**. The key compound, optically active 1-phenyl-3-(trichlorosilyl)butane (**25**), was prepared by stereospecific (100% inversion) nucleophilic substitution of (*R*)-4-phenyl-2-chlorobutane (**23**) with (triphenylsilyl)-lithium in THF[24] followed by chlorodephenylation of the resulting alkyltriphenylsilane (**24**) with dry hydrogen chloride in the presence of aluminum chloride in benzene. In a similar manner to the transformations shown in Scheme I, the alkyltrichlorosilane (*S*)-**25** was oxidized to known secondary alkyl alcohol (*S*)-**26** with retention of configuration[19] to confirm the enantiomeric purity and was methylated to the trimethylsilane (*S*)-**22**. Thus, the maximum rotation of (*S*)-**22** was determined to be $[\alpha]^{20}_D$ −35.6° (benzene), and those of (*S*,*E*)-**14c** and (*S*,*Z*)-**14c**, both of which were correlated with (*S*)-**22** by hydrogenation, were deduced to be $[\alpha]^{20}_D$ −22.5° and +149° (benzene), respectively.

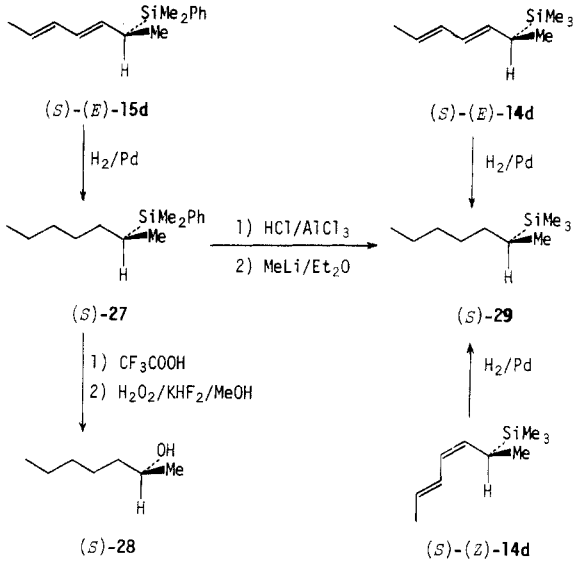
Similarly, the configuration and enantiomeric purity of the dienylsilanes, (*E*)-**14d**, (*Z*)-**14d**, and (*E*)-**15d**, was de-

(22) Reaction of 1-phenylethyl- and 2-butyl-Grignard reagents with vinyl bromide in the presence of a catalyst containing (*R*,*S*)-PPFA gave (*S*)-3-phenyl-1-butene and (*R*)-3-methyl-1-pentane, respectively: ref 6.

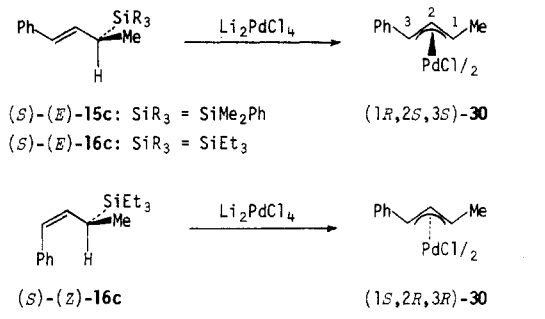
(23) Nickel- or palladium-catalyzed cross-coupling of alkenyl phosphates with Grignard reagents has been reported: Hayashi, T.; Fujiwa, T.; Okamoto, Y.; Katsuro, Y.; Kumada, M. *Synthesis* **1981**, 1001. See also: Hayashi, T.; Katsuro, Y.; Okamoto, Y.; Kumada, M. *Tetrahedron Lett.* **1981**, *22*, 4449.

(24) Hayashi, T.; Okamoto, Y.; Kumada, M. *J. Chem. Soc., Chem. Commun.* **1982**, 1072.

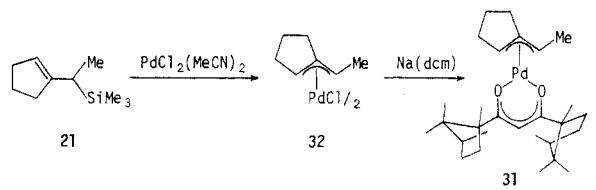
Scheme IV



Scheme V



Scheme VI



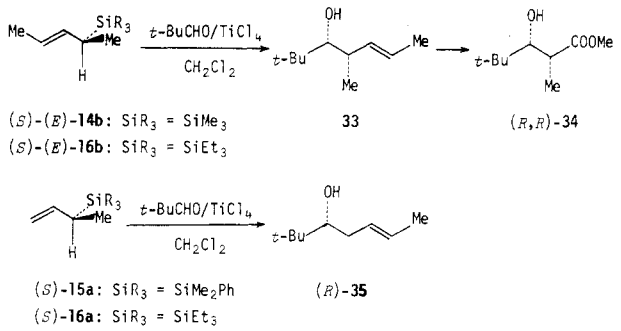
termined by correlation with 2-heptanol (**28**) (Scheme IV).

Reactions of allylsilanes, (*E*)-**15c** ($[\alpha]^{20}_D$ −6.88°), (*E*)-**16c** ($[\alpha]^{20}_D$ −38.5°), and (*Z*)-**16c** ($[\alpha]^{20}_D$ +11.7°), with lithium chloropalladate or dichlorobis(acetonitrile)palladium in methanol gave known optically active (π-allyl)palladium complex, bis(μ-chloro)bis(1-methyl-3-phenyl-π-allyl)dipalladium(II)[25] (**30**), with the rotations of $[\alpha]^{20}_D$ +481°, +654°, and −99° (chloroform), respectively (Scheme V). The maximum rotation of (1*R*,2*S*,3*S*)-**30** is $[\alpha]^{20}_D$ +703° and the palladation of allylsilanes has been established to proceed with anti stereochemistry by using optically active allylsilanes with unambiguous stereochemistry.[25] It follows that the allylsilanes (*E*)-**15c**, (*E*)-**16c**, and (*Z*)-**16c** are all *S* isomers and of 68%, 93%, and 14% ee, respectively.

The enantiomeric purity of **21** was determined by ^{1}H NMR of diastereomeric (π-allyl)(acetylacetonato)palladium(II) complex **31**, which was obtained by the reaction of (π-allyl)palladium **32** with the sodium enolate of di-(+)-campholylmethane (dcmH)[26] (Scheme VI).

The allylsilanes (*E*)-**14b** and (*E*)-**16b** which have the methyl group at the γ position were converted to erythro

Scheme VII



β-hydroxy ester **34** by way of homoallyl alcohol **33**, which was obtained by the reaction with trimethylacetaldehyde in the presence of titanium chloride (Scheme VII). The established stereochemical pathway (anti) of the S_E' reaction permitted the determination of configuration and enantiomeric purity of the starting allylsilanes.[2a,27] Thus, the allylsilanes which gave (2*R*,3*R*)-**34** were determined to have an *S* configuration. The allylsilanes **15a** and **16a** are assumed to have an *S* configuration and enantiomeric purity of at least 49% ee and 46% ee, respectively, by the stereochemical results observed in the enantioselective reaction with trimethylacetaldehyde[28] which gave (*R*)-homoallyl alcohol **35** of 49% ee and 46% ee, respectively.

Conclusions

We have shown here that optically active allylsilanes can be prepared by asymmetric cross-coupling of [α-(silyl)alkyl]-Grignard reagents with alkenyl bromides in the presence of a chiral ferrocenylphosphine–palladium catalyst. The allylsilanes contain a chiral carbon atom substituted with a silyl group and could hardly be obtained by other methods. The stereoselectivity attained here in the reaction to produce (*R*)-**3a** (95% ee), (*R*,*E*)-**3c** (95% ee), and (*S*,*E*)-**16c** (93% ee) is among the highest of asymmetric reactions by means of chiral catalysis, especially for carbon–carbon bond-forming reactions.[18,29]

The optically active allylsilanes obtained here have been used for the reaction with various electrophiles (*t*-BuCl/$TiCl_4$,[2a] MeCOCl/$AlCl_3$,[2a] CF_3COOD,[30] MCPBA[31]) to demonstrate that the S_E' reaction of allylsilanes proceeds with anti stereochemistry. Reaction with aldehydes in the presence of titanium chloride gave optically active homoallylic alcohols with over 90% enantio- and erythroselectivities,[27,32] and reaction with palladium(II) led to optically active (π-allyl)palladium complexes[25] which have been shown useful for the stereochemical studies in the reaction with nucleophiles.[33] It is expected that the al-

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(26) McCreary, M. D.; Lewis, D. W.; Wernik, D. L.; Whitesides, G. M. *J. Am. Chem. Soc.* **1974**, *96*, 1038.

(27) Hayashi, T.; Konishi, M.; Kumada, M. *J. Am. Chem. Soc.* **1982**, *104*, 4963.

(28) The stereochemical relationship between the allylsilane **3a** and homoallyl alcohols obtained in the reaction with aldehydes has been reported: ref 32.

(29) For reviews concerning asymmetric synthesis by chiral transition metal catalysts: (a) Kagan, H,. B.; Fiaud, J. C. *Top. Stereochem.* **1978**, *10*, 175. (b) Bosnich, B.; Fryzuk, M. D. *Top. Stereochem.* **1981**, *12*, 119. (c) Kagan, H. B. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: 1982; Vol. 8, p 463.

(30) Hayashi, T.; Ito, H.; Kumada, M. *Tetrahedron Lett.* **1982**, *23*, 4605.

(31) Hayashi, T.; Okamoto, Y.; Kabeta, K.; Hagihara, T.; Kumada, M. *J. Org. Chem.* **1984**, *49*, 4224.

(32) Hayashi, T.; Konishi, M.; Kumada, M. *J. Org. Chem.* **1983**, *48*, 281.

(33) (a) Hayashi, T.; Hagihara, T.; Konishi, M.; Kumada, M. *J. Am. Chem. Soc.* **1983**, *105*, 7767. (b) Hayashi, T.; Konishi, M.; Kumada, M. *J. Chem. Soc., Chem. Commun.* **1984**, 107.

lylsilanes will be more extensively applied to the synthesis of optically active compounds.

Experimental Section

General. Optical rotations were measured with a Perkin-Elmer 241 polarimeter. Infrared spectra were taken with a Hitachi EPI-G3 grating infrared spectrometer. ^{1}H NMR spectra were measured with a JEOL JNM-MH-100 (100 MHz), JEOL JNM-GX-400 (400 MHz), or Varian XL-200 (200 MHz) spectrometer. Enantiomeric purities by ^{1}H NMR analysis were determined by using a chiral shift reagent tris(*d,d*-dicampholylmethanato)europium(III) [Eu(dcm)$_3$][26,34] or tris[3-(trifluoroacetyl)-*d*-camphorato]europium(III) [Eu(facam)$_3$][34] and measuring peak areas by cutting and weighing. GLC analyses were performed on a Shimadzu GC-4C gas chromatograph, equipped with a 3-m column packed with Silicone DC 550 (30% on Celite) or Silicone DC QF-1 (20% on Chromosorb W AW). A Varian Aerograph Model 920, equipped with a 20-ft column packed with Silicone DC 550 (30% on Celite) or PEG 20M (30% on Celite), was used for isolation and purification of the products. Preparative medium-pressure liquid chromatography (MPLC) was done on a system consisting of an FMI RPSY laboratory pump and a silica gel 60 prepacked Lobar (Merck) column.

Materials. NiCl$_2$[(−)-DIOP] was prepared by a known method.[16] The preparation of (*R,S*)-PPFA,[17] (*S*)-Valphos,[12] NiCl$_2$[(*S*)-prophos],[13] PdCl$_2$[(*R,S*)-PPFA],[6] and PdCl$_2$[(*R,S*)-BPPFA][6] has been reported. (*Z*)-1-Bromopropene,[35] (*E*)-β-bromostyrene,[36] (*Z*)-β-bromostyrene,[37] phenylbromoacetylene,[38] and α-(trimethylsilyl)benzyl bromide[39] were prepared according to the literature procedure. (*Z*)-1-Phenyl-1-butene (bp 87–89 °C/23 mmHg) and (*Z*)-1,3-diphenylpropene (bp 94–96 °C/0.2 mmHg) were prepared by cross-coupling of (*Z*)-β-bromostyrene with an appropriate Grignard reagent.[40] The 1-(trialkylsilyl)ethyl chlorides ((R$_3$Si)CHMeCl, R$_3$Si = Me$_3$Si,[41] PhMe$_2$Si,[42] Et$_3$Si,[43] and Ph$_3$Si[44]) were prepared by the alkylation of (1-chloroethyl)trichlorosilane. The Grignard reagents **1**, **10**, **11**, **12**, and **13** were prepared in a standard manner by adding slowly a solution of an organic halide in ether to magnesium ribbons which had been dried in a rapid stream of dry nitrogen by flaming. Vinyl bromide, trichlorosilane, (1-chloroethyl)trichlorosilane, and 1-phenylpropene (mixture of *E* and *Z* isomers) were commercially available and used without further purification.

Preparation of (*E*)-1-Bromopropene (2b). Commercially available 1-bromopropene (50 g, 0.41 mmol), which was a mixture of *E* and *Z* isomers in a ratio of 3:7, was added to sodium hydroxide (12 g, 0.30 mmol) in 400 mL of butanol. The solution was heated under reflux until no (*Z*)-1-bromopropene was detected by GLC. Distillation from the reaction mixture through a column (25 cm) packed with glass helices gave 9.5 g (63%) of (*E*)-1-bromopropene (98% pure by GLC): bp 65 °C/760 mmHg (lit.[45] bp 64.2–64.4 °C/748 mmHg). Isomerically pure (*E*)- and (*Z*)-1-bromopropene were stored in the dark.

Preparation of 1-Bromo-1,3-pentadiene (2d). A 55:45 mixture of (*E,E*)- and (*Z,E*)-**2d** was obtained (bp 49–51 °C/45 mmHg) by dibromomethylation of crotonaldehyde followed by reductive elimination with zinc–acetic acid according to the procedures reported by Williams.[46] A mixture of 3.36 g (22.9 mmol) of the bromide **2d** and 0.71 g (17.8 mmol) of sodium hydroxide in 20 mL of ethanol was refluxed with stirring until the *Z* isomer was not detected by GLC. It required 6 h. Ether (110 mL) was added and the mixture was washed three times with 50 mL of water, dried over anhydrous magnesium sulfate, and stripped of solvent. The residue was distilled to give 1.19 g (8.1 mmol) of (*E,E*)-**2d**: ^{1}H NMR (CCl$_4$) δ 1.74 (d, *J* = 6 Hz, 3 H), 5.66 (dq, *J* = 14 and 6 Hz, 1 H), 5.92 (dd, *J* = 14 and 10 Hz, 1 H), 6.09 (d, *J* = 14 Hz, 1 H).

Asymmetric Cross-Coupling of [α-(Trimethylsilyl)-benzyl]magnesium Bromide (1) with Alkenyl Bromides 2a, 2b, and 2c. General Procedure. All the reactions were carried out under a dry nitrogen atmosphere. To a mixture of organic halide **2** (40 mmol) and a palladium or nickel complex (0.20 mmol) was added [α-(trimethylsilyl)benzyl]magnesium bromide (**1**) (0.6–1.0 M ether solution, 80 mmol) at −78 °C. The mixture was stirred at a given temperature for 2–5 days (see Tables I and II) and then hydrolyzed with 10% hydrochloric acid at 0 °C. The organic layer and ether extracts from the aqueous layer were combined, washed with saturated sodium hydrogen carbonate solution and then water, and dried over anhydrous magnesium sulfate. The solvent was evaporated. The product was isolated by distillation. Further purification was carried out by preparative GLC for **3a** and (*E*)- and (*Z*)-**3b** and by preparative MPLC for (*E*)- and (*Z*)-**3c**. Isomeric purity of the product was analyzed by GLC and HPLC. Experimental results are summarized in Tables I and II.

3a: bp 55 °C/0.4 mmHg (lit.[47] bp 63 °C/0.5 mmHg); ^{1}H NMR (CCl$_4$) δ −0.05 (s, 9 H), 2.87 (d, *J* = 9 Hz, 1 H), 4.75–5.04 (m, 2 H), 6.09 (dt, *J* = 18 and 9 Hz, 1 H), 6.84–7.27 (m, 5 H). Anal. Calcd for C$_{12}$H$_{18}$Si: C, 75.72; H, 9.53. Found: C, 75.91: H, 9.57.

(*E*)-3b: bp 55–57 °C/0.4 mmHg; ^{1}H NMR (CCl$_4$) δ −0.08 (s, 9 H), 1.69 (d, *J* = 6 Hz, 3 H), 2.79 (d, *J* = 9 Hz, 1 H), 5.31 (dq, *J* = 16 and 6 Hz, 1 H), 5.73 (dd, *J* = 9 and 16 Hz, 1 H), 6.85–7.25 (m, 5 H). Anal. Calcd for C$_{13}$H$_{20}$Si: C, 76.40; H, 9.86. Found: C, 76.34; H, 9.92.

(*Z*)-3b: bp 66.5 °C/1 mmHg; ^{1}H NMR (CCl$_4$) δ −0.08 (s, 9 H), 1.64 (d, *J* = 7 Hz, 3 H), 3.20 (d, *J* = 12 Hz, 1 H), 5.50 (dq, *J* = 12 and 7 Hz, 1 H), 5.82 (t, *J* = 12 Hz, 1 H), 6.90–7.30 (m, 5 H). Anal. Calcd for C$_{13}$H$_{20}$Si: C, 76.40; H, 9.86. Found: C, 76.19; H, 9.84.

(*E*)-3c: bp 135–139 °C/0.9 mmHg; ^{1}H NMR (CCl$_4$) δ 0.02 (s, 9 H), 3.09 (d, *J* = 9 Hz, 1 H), 6.33 (d, *J* = 15 Hz, 1 H), 6.50 (dd, *J* = 15 and 9 Hz, 1 H), 6.97–7.38 (m, 10 H). Anal. Calcd for C$_{18}$H$_{22}$Si: C, 81.14; H, 8.32. Found: C, 80.95; H, 8.44.

(*Z*)-3c: bp 127–131 °C/0.9 mmHg; ^{1}H NMR (CCl$_4$) δ −0.08 (s, 9 H), 3.55 (d, *J* = 11 Hz, 1 H), 6.11 (t, *J* = 11 Hz, 1 H), 6.51 (d, *J* = 11 Hz, 1 H), 6.98–7.40 (m, 10 H). Anal. Calcd for C$_{18}$H$_{22}$Si: C, 81.14; H, 8.32. Found: C, 81.33; H, 8.56.

Hydrogenation of Allylsilanes 3. The following procedure for the hydrogenation of 3-phenyl-3-(trimethylsilyl)propene (**3a**) is typical. Optical rotation data are summarized in Table II. A solution of 338 mg (1.78 mmol) of **3a** ([α]$^{20}_D$ −61.8° (*c* 5.0, benzene)) and 40 mg of Pd/C (Pd 10%) in 3 mL of benzene was placed in a stainless micro autoclave and magnetically stirred with hydrogen at 50 atm for 24 h. The reaction mixture was distilled to give 691 mg (97%) of 1-phenyl-1-(trimethylsilyl)propane (**4a**): bp 98 °C/20 mmHg (lit.[48] bp 112 °C/35 mmHg); [α]$^{20}_D$ −1.35° (*c* 2.6, benzene); ^{1}H NMR (CCl$_4$) δ −0.14 (s, 9 H), 0.72–0.94 (m, 3 H), 1.60–1.98 (m, 3 H), 6.87–7.30 (m, 5 H).

In a similar manner, (*E*)- and (*Z*)-**3b** were hydrogenated in the presence of Pd/C catalyst. Distillation gave **4b** in 89% and 96% yield, respectively. **4b**: bp 115 °C/20 mmHg (lit.[48] bp 129 °C/30 mmHg); ^{1}H NMR (CCl$_4$) δ −0.09 (s, 9 H), 0.82 (t, *J* = 7 Hz, 3 H), 1.00–2.08 (m, 5 H), 6.84–7.25 (m, 5 H).

Similarly, hydrogenation of (*E*)- and (*Z*)-**3c** gave **4c** in 97% and 98% yield, respectively. Isolation of **4c** was carried out by short silica gel (benzene) column chromatography. **4c**: ^{1}H NMR (CCl$_4$) 0.03 (s, 9 H), 2.0–2.9 (m, 5 H), 7.05–7.45 (m, 10 H). Anal. Calcd for C$_{18}$H$_{24}$Si: C, 80.53; H, 9.01. Found: C, 80.29; H, 8.80.

Asymmetric Hydrosilylation of Styrene Derivatives 5. 1-Phenyl-1-(trichlorosilyl)propane (6a). A glass ampule was charged with 1-phenyl-1-propene (**5a**) (6.6 g, *E/Z* = 65/35), trichlorosilane (10 g, 74 mmol), and PdCl$_2$[(*R,S*)-PPFA] (8.0 mg, 0.013 mmol), degassed at −196 °C, and then sealed. The mixture

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was heated at 90 °C for 3 days, and fractional distillation (87–88 °C/3 mmHg) gave 4.15 g (84% based on (*Z*)-**5a**) of **6a** (97% pure by GLC analysis). The *E* olefin was recovered intact.

1-Phenyl-1-(trichlorosilyl)butane (6b). In a similar manner, a mixture of (*Z*)-1-phenyl-1-butene (**5b**) (0.97 g, 7.4 mmol), trichlorosilane (2.68 g, 19.8 mmol), and $PdCl_2$[(*R*,*S*)-PPFA] (2.0 mg, 0.003 mmol) was heated in a sealed glass ampule at 90 °C for 7 days. Distillation (100 °C/0.5 mmHg) gave 1.3 g (70%) of **6b**.

1,3-Diphenyl-1-(trichlorosilyl)propane (6c). A mixture of (*Z*)-1,3-diphenylpropene (**5c**) (6.28 g, 32 mmol), trichlorosilane (6.1 g, 45 mmol), and $PdCl_2$[(*R*,*S*)-PPFA] (4.0 mg, 0.006 mmol) was heated in a sealed glass ampule at 90 °C for 12 days to give 6.47 g (61%) of **6c**, bp 115–117 °C/0.2 mmHg.

Methylation of Trichlorosilanes 6. 1-Phenyl-1-(trimethylsilyl)propane (4a). To a solution of 0.70 g (2.77 mmol) of **6a** in 10 mL of THF was added methylmagnesium bromide in ether (20 mmol, 8 mL of 2.5 M solution) at 0 °C. The reaction mixture was refluxed for 4 h and then hydrolyzed with 10% hydrochloric acid. The organic layer and ether extracts from the aqueous layer were combined, washed with saturated sodium hydrogen carbonate solution and then with water, and dried over anhydrous magnesium sulfate. Evaporation of solvent followed by distillation (100–120 °C/20 mmHg, bath temperature) of the residue gave 0.375 g (80%) of **4a**, which was purified by preparative GLC, $[\alpha]^{20}_D$ +0.68° (*c* 2.8, benzene).

1-Phenyl-1-(trimethylsilyl)butane (4b). In a similar manner **6b** was methylated with methylmagnesium bromide. Bulb-to-bulb distillation (100–120 °C/20 mmHg, bath temperature) gave **4b** in 86% yield. Purification by preparative GLC gave **4b** of $[\alpha]^{20}_D$ −4.87° (*c* 6.1, benzene).

1,3-Diphenyl-1-(trimethylsilyl)propane (4c). In a similar manner **6c** was methylated with methylmagnesium bromide. Preparative MPLC (silica gel–hexane) gave **4c** in 94% yield. **4c**: $[\alpha]^{20}_D$ +0.85° (*c* 5.1, benzene).

Oxidation of Trichlorosilanes 6 into Alcohols 7. 1-Phenyl-1-propanol (7a). To a suspension of $CuF_2{\cdot}2H_2O$ (1.57 g, 11.4 mmol) in ether was added **6a** (1.93 g, 7.61 mmol) dropwise at 0 °C with stirring. After 24 h of stirring at room temperature, pentane was added to ensure precipitation of Cu(II) salts. Filtration of the mixture gave a colorless filtrate which was dried over anhydrous sodium sulfate and stripped of solvent. The residue was distilled (90–110 °C/20 mmHg, bath temperature) to give 235 mg (15%) of 1-phenyl-1-(trifluorosilyl)propane: ^{1}H NMR (CCl_4) δ 0.70–1.10 (m, 3 H), 1.70–2.15 (m, 2 H), 2.20–2.49 (m, 1 H), 6.90–7.40 (m, 5 H). To a solution of 220 mg (1.08 mmol) of the trifluorosilane thus obtained in 5mL of DMF was added MCPBA (purity 80%, 256 mg, 1.19 mmol) at 0 °C. The mixture was stirred at 0 °C for 15 min and at room temperature for 4 h. Then it was poured into water and extracted with ether. The ether extract was washed successively once with aqueous sodium thiosulfate, three times with aqueous sodium bicarbonate, and once with water and dried over anhydrous sodium sulfate. After evaporation of solvent in vacuo, preparative TLC on silica gel (chloroform) of the residue gave 83 mg (57%) of the alcohol **7a**: $[\alpha]^{28}_D$ −22.9° (*c* 3.7, chloroform) (50% ee (*S*)) (lit.[49] (*S*)-**7a** $[\alpha]_D$ (max) −46.1° (*c* 5, chloroform)). Exact enantiomeric purity of **7a** was determined to be 48% by ^{1}H NMR analysis in the presence of chiral shift reagent tris[*d*,*d*-dicampholylmethanato]europium(III) [Eu(dcm)$_3$]. The C*H*OH signal was completely separated and the signal of (*S*)-**7a** appeared at a higher field than that of its *R* enantiomer.

1-Phenyl-1-butanol (7b). In a similar manner, 1-phenyl-1-(trifluorosilyl)butane was prepared from **6b** (2.00 g, 7.48 mmol) and $CuF_2{\cdot}2H_2O$ (1.54 g, 11.2 mmol) in 3 mL of ether at room temperature for 21 h and isolated by bulb-to-bulb distillation (50–70 °C/1 mmHg, bath temperature): ^{1}H NMR (CCl_4) δ 0.93 (t, *J* = 7 Hz, 3 H), 1.14–1.65 (m, 2 H), 1.92 (q, *J* = 8 Hz, 2 H), 2.50 (t, *J* = 8 Hz, 1 H), 7.03–7.45 (m, 5 H). Oxidation of the trifluorosilane with MCPBA as above gave **7b** in 84% yield. Isolation of **7b** was carried out by preparative TLC on silica gel (benzene). **7b**: $[\alpha]^{27}_D$ −20.0° (*c* 6.2, benzene) (lit.[50] (*S*)-**7b** $[\alpha]^{27}_D$(max) −45.93° (*c* 6.1, benzene)). ^{1}H NMR analysis using Eu(dcm)$_3$ indicated that enantiomeric purity was 51%. The C*H*OH signal was completely separated and the signal of (*S*)-**7b** appeared at a higher field.

1,3-Diphenyl-1-propanol (7c). The trichlorosilane **6c** (1.66 g, 5.0 mmol) was treated with $CuF_2{\cdot}2H_2O$ (1.03 g, 7.5 mmol) in ether (2 mL) overnight at room temperature. Removal of the Cu(II) salts by adding pentane and filtration gave the crude trifluorosilane, which was used for the oxidation with MCPBA (1.18 g, 5.5 mmol) in DMF (25 mL) without further purification. Workup as above followed by preparative TLC on silica gel (chloroform) gave **7c** in 78% yield. **7c**: $[\alpha]^{20}_D$ −10.0° (*c* 1.0, chloroform) (lit.[51] (*R*)-**7c** $[\alpha]^{27}_{578}$ +28.8° (*c* 1, dichloromethane)). The enantiomeric purity was determined to be 36% by ^{1}H NMR analysis using Eu(dcm)$_3$. The C*H*OH signal was separated and the signal of (*S*)-**7c** appeared at a higher field than that of (*R*)-**7c**.

Asymmetric Cross-Coupling of [α-(Trimethylsilyl)benzyl]magnesium Bromide (1) with Phenylbromoacetylene (8). The palladium catalyst $PdCl_2$[(*R*,*S*)-PPFA] (6.7 mg, 0.011 mmol) was placed in a two-necked flask equipped with a magnetic stirring bar, a serum cap, and a three-way stopcock. The flask was filled with nitrogen after evacuation and was cooled to −70 °C. To it were added a solution of 4.2 mmol of [α-(trimethylsilyl)benzyl]magnesium bromide (**1**) in ether and 0.353 g (1.95 mmol) of phenylbromoacetylene (**8**). The mixture was stirred at room temperature for 20 h and hydrolyzed with 10% hydrochloric acid. After the usual workup, preparative MPLC on silica gel with hexane as the eluent gave 0.323 g (63%) of 1,3-diphenyl-3-(trimethylsilyl)propyne (**9**). This propargylsilane is slowly decomposed on exposure to air. **9**: ^{1}H NMR (CCl_4) δ 0.11 (s, 9 H), 3.25 (s, 1 H), 6.96–7.46 (m, 10 H); IR (neat) 2214 cm^{-1} (C≡C); high-resolution mass calcd for $C_{18}H_{20}Si$ 264.1334, found 264.1322.

Hydrogenation of **9** ($[\alpha]^{20}_D$ +9.84° (*c* 6.05, benzene)) gave 1.3-diphenyl-1-(trimethylsilyl)propane (**4c**) of $[\alpha]^{20}_D$ −0.42° (*c* 2.86, benzene).

Asymmetric Cross-Coupling of [1-(Trialkylsilyl)ethyl]magnesium Chlorides 10, 11, 12, and 13 with Alkenyl Bromides 2a, 2b, 2c, 2d, and 19. The cross-coupling was carried out in essentially the same manner as the reaction of [α-(trimethylsilyl)benzyl]magnesium bromide (**1**). Reaction conditions and results including specific rotations and enantiomeric purities of the products are summarized in Table III. ^{1}H NMR data and transformations of the allylsilanes to determine their stereochemistry are shown below.

(*E*)-1-Phenyl-3-(trimethylsilyl)-1-butene ((*E*)-14c): isolated by bulb-to-bulb distillation (70–80 °C/0.5 mmHg) followed by preparative GLC (DC 550); ^{1}H NMR (CCl_4) δ 0.00 (s, 9 H), 1.14 (d, *J* = 7 Hz, 3 H), 1.50–1.90 (m, 1 H), 6.03–6.21 (m, 2 H), 6.90–7.45 (m, 5 H). Anal. Calcd for $C_{13}H_{20}Si$: C, 76.40; H, 9.86. Found: C, 76.64; H, 9.93. Hydrogenation (50 atm H_2) of 0.460 g (2.25 mmol) of (*E*)-**14c**, whose specific rotation was $[\alpha]^{20}_D$ −15.1° (*c* 5.2, benzene), in the presence of 30 mg of 10% Pd/C in 2 mL of benzene gave 0.446 g (96%) of 1-phenyl-3-(trimethylsilyl)butane (**22**) with $[\alpha]^{20}_D$ −23.9° (*c* 2.0, benzene). Since the maximum rotation of (*S*)-**22** is $[\alpha]^{20}_D$ −35.6° (see below), the allylsilane (*E*)-**14c** used here is an *S* isomer of 67% ee, and the maximum rotation of (*S*,*E*)-**14c** is calculated to be $[\alpha]^{20}_D$ −22.5° (benzene).

(*Z*)-1-Phenyl-3-(trimethylsilyl)-1-butene ((*Z*)-14c): isolated by bulb-to-bulb distillation followed by preparative GLC (DC 550); ^{1}H NMR (CCl_4) δ 0.05 (s, 9 H), 1.19 (d, *J* = 7 Hz, 3 H), 2.39 (dq, *J* = 12 and 7 Hz, 1 H), 5.49 (t, *J* = 12 Hz, 1 H), 6.32 (d, *J* = 12 Hz, 1 H), 7.00–7.45 (m, 5 H). Anal. Calcd for $C_{13}H_{20}Si$: C, 76.40; H, 9.86. C, 76.66; H, 10.11. Hydrogenation of (*Z*)-**14c** ($[\alpha]^{20}_D$ +88.1° (*c* 3.3, benzene)) gave (*S*)-**22** of 59% ee ($[\alpha]^{20}_D$ −20.9° (*c* 2.0, benzene)), indicating that the maximum rotation of (*S*,*Z*)-**14c** is $[\alpha]^{20}_D$ +149° (benzene).

(*E*)-1-Phenyl-3-(triphenylsilyl)-1-butene ((*E*)-17c): isolated by preparative TLC on silica gel (hexane); ^{1}H NMR (CCl_4) δ 1.37 (d, *J* = 7 Hz, 3 H), 2.72 (quint, *J* = 7 Hz, 1 H), 6.10 (d, *J* = 16 Hz, 1 H), 6.33 (dd, *J* = 7 and 16 Hz, 1 H), 7.12 (br s, 5 H), 7.20–7.90 (m, 15 H). Anal. Calcd for $C_{28}H_{26}Si$: C, 85.02; H, 7.79. Found: C, 84.62; H, 7.53. Hydrogenation of (*E*)-**17c** ($[\alpha]^{20}_D$ +8.43° (*c* 0.9, benzene)) gave 1-phenyl-3-(triphenylsilyl)butane (**24**) of $[\alpha]^{20}_D$ +2.74° (*c* 2.3, benzene), indicating that the allylsilane (*E*)-**17c** is an *S* isomer of 36% ee.

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(*E*)-1-Phenyl-3-(triethylsilyl)-1-butene ((*E*)-16c): isolated by MPLC (hexane); ^{1}H NMR (CCl_4) δ 0.60 (q, J = 7 Hz, 6 H), 0.99 (t, J = 7 Hz, 9 H), 1.20 (d, J = 7 Hz, 3 H), 1.95 (quint, J = 7 Hz, 1 H), 5.92–6.48 (m, 2 H), 6.92–7.52 (m, 5 H). Anal. Calcd for $C_{16}H_{26}Si$: C, 77.97; H, 10.36. Found: C, 77.67; H, 10.66. To a solution of 1.11 mmol of lithium chloropalladate in methanol, which was prepared by refluxing a mixture of 197 mg (1.11 mmol) of palladium chloride and 95 mg (2.24 mmol) of lithium chloride in 2 mL of methanol, was added at 0 °C 239 mg (0.97 mmol) of the allylsilane (*E*)-**16c** ($[\alpha]^{20}_D$ –38.5° (*c* 2.8, benzene)). The mixture was stirred at 0 °C for 20 h. The yellow precipitates formed were collected on a glass filter, washed with cold methanol, and dried under reduced pressure to give 238 mg (90%) of (1*R*,2*S*,3*S*)-bis(μ-chloro)bis(1-methyl-3-phenyl-π-allyl)dipalladium[25] (**30**) (93% ee, $[\alpha]^{20}_D$ +654° (*c* 1.3, chloroform)). Since the chirality transfer from allylsilane to (π-allyl)palladium has been established to proceed with 100% anti stereochemistry,[25] the allylsilane (*E*)-**16c** is determined to be an *S* isomer of 93% ee.

(*Z*)-1-Phenyl-3-(triethylsilyl)-1-butene ((*Z*)-16c): isolated by MPLC (hexane); ^{1}H NMR (CCl_4) 0.52 (q, J = 7 Hz, 6 H), 0.89 (t, J = 7 Hz, 9 H), 1.15 (d, J = 7 Hz, 3 H), 2.46 (dq, J = 12 and 7 Hz, 1 H), 5.56 (t, J = 12 Hz, 1 H), 6.30 (d, J = 12 Hz, 1 H), 7.05–7.45 (m, 5 H). Anal. Calcd for $C_{16}H_{26}Si$: C, 77.97; H, 10.63. Found: C, 78.14; H, 10.90. In a similar manner to the reaction of (*E*)-**16c**, reaction of (*Z*)-**16c** ($[\alpha]^{20}_D$ +11.7° (*c* 1.1, benzene)) with lithium chloropalladate in methanol gave the (π-allyl)palladium (1*S*,2*R*,3*R*)-**30**[25] (14% ee, $[\alpha]^{20}_D$ –99° (*c* 1.0, chloroform)), indicating that (*Z*)-**16c** is an *S* isomer of 14% ee.

(*E*)-1-Phenyl-3-(dimethylphenylsilyl)-1-butene ((*E*)-15c): isolated by MPLC (hexane); ^{1}H NMR (CCl_4) δ 0.30 (s, 6 H), 1.14 (d, J = 8 Hz, 3 H), 1.84–2.14 (m, 1 H), 5.89–6.29 (m, 2 H), 6.90–7.55 (m, 10 H). Anal. Calcd for $C_{18}H_{22}Si$: C, 81.12; H, 8.32. Found: C, 80.93; H, 8.28. In a similar manner to the reaction of (*E*)-**16c**, (*E*)-**15c** ($[\alpha]^{20}_D$ –6.88° (*c* 4.1, benzene)) gave (1*R*,2*S*,3*S*)-**30** (68% ee, $[\alpha]^{20}_D$ +481° (*c* 1.4, chloroform)).

(*E*,*E*)-2-(Dimethylphenylsilyl)-3,5-heptadiene ((*E*,*E*)-15d): isolated by MPLC (hexane); ^{1}H NMR (CCl_4) δ 0.26 (s, 6 H), 1.04 (d, J = 7 Hz, 3 H), 1.72 (d, J = 6 Hz, 3 H), 1.64–1.96 (m, 1 H), 5.20–6.12 (m, 4 H), 7.20–7.52 (m, 5 H). In a stainless microautoclave were placed 0.512 g (2.22 mmol) of (*E*,*E*)-**15d**, 51 mg of 10% palladium–carbon, and 2 mL of benzene, and the mixture was stirred with hydrogen at 140 atm for 14 h. The reaction mixture was filtered through a pad of silica gel. Evaporation of solvent gave 0.492 g (94%) of 2-(dimethylphenylsilyl)heptane (**27**): $[\alpha]^{20}_D$ –4.49° (*c* 5.0, benzene); ^{1}H NMR (CCl_4) δ 0.23 (s, 6 H), 0.75–1.00 (m, 6 H), 1.00–1.60 (m, 9 H), 7.16–7.55 (m, 5 H).

The dimethylphenylsilyl group in **27** was oxidized to a hydroxy group according to Tamao's procedure.[52] Thus, 0.27 g (1.2 mmol) of phenylsilane **27** was treated with trifluoroacetic acid (0.45 mL, 5.8 mmol) and a mixture of KHF_2 (0.18 g, 2.3 mmol) and methanol (0.5 mL) to give fluoro- or methoxysilane, which was subsequently oxidized with 30% hydrogen peroxide (2.2 mL, 22 mmol) in the presence of potassium bicarbonate (0.58 g, 5.8 mmol) in methanol (6 mL) and THF (6 mL) to give 81 mg (60%) of (*S*)-2-heptanol (**28**): $[\alpha]^{25}_D$ +2.2° (*c* 3.7, ethanol) (lit.[53] for (*S*)-**28** $[\alpha]_D$ +7.8° (*c* 12.0, ethanol)). The enantiomeric purity of **28** determined by ^{1}H NMR analysis using Eu(dcm)$_3$ was 45%, the methyl doublet of the *S* isomer appearing at lower field than that of the *R* isomer.

Dry hydrogen chloride was bubbled into a solution of 0.215 g (0.92 mmol) of **27** and 2 mg of sublimed aluminium chloride in 3 mL of dry benzene for 5 h, and the solvent was removed under a reduced pressure (ca. 100 mmHg). To the residue was added 2 mL (4 mmol) of 2 M methyllithium in ether and the mixture was stirred at room temperature for 5 h. Acid hydrolysis and usual workup followed by bulb-to-bulb distillation (110–120 °C/15 mmHg) gave 0.114 g (72%) of 2-(trimethylsilyl)heptane (**29**): $[\alpha]^{20}_D$ –7.61° (*c* 3.6, benzene); ^{1}H NMR (CCl_4) δ –0.06 (s, 9 H), 0.52–0.60 (m, 1 H), 0.76–1.05 (m, 6 H), 1.05–1.60 (m, 8 H). Since the trimethylsilane **29** is an *S* isomer of 45% ee, the maximum rotation of (*S*)-**29** is calculated to be $[\alpha]^{20}_D$ –16.8° (benzene).

(*E*,*E*)-2-(Trimethylsilyl)-3,5-heptadiene ((*E*,*E*)-14d) and (*Z*,*E*)-14d. Reaction of the Grignard reagent **10** with 1-bromo-1,3-pentadiene (**2d**, *E*,*E*/*Z*,*E* = 55/45) gave a mixture of (*E*,*E*)- and (*Z*,*E*)-**14d** (bulb-to-bulb distillation, 120–140 °C/20 mmHg). The isomers were separated by MPLC (hexane). (*E*,*E*)-**14d**: ^{1}H NMR ($CDCl_3$, 400 MHz) δ –0.036 (s, 9 H), 1.05 (d, J = 7 Hz, 3 H), 1.58 (quint, 1 H), 1.72 (d, J = 7 Hz, 3 H), 5.51 (dq, J = 15 and 7 Hz, 1 H), 5.59 (dd, J = 15 and 8 Hz, 1 H), 5.84 (dd, J = 15 and 10 Hz, 1 H), 6.02 (ddq, J = 15, 10, and 1.3 Hz, 1 H); high-resolution mass spectrum calcd for $C_{10}H_{20}Si$ 168.1334, found 168.1334. Hydrogenation (100 atm H_2, Pd/C in benzene at 60 °C) of (*E*,*E*)-**14d** ($[\alpha]^{20}_D$ –16° (*c* 5.6, benzene)) gave (*S*)-**29** of 35% ee ($[\alpha]^{20}_D$ –5.9° (*c* 5.1, benzene)). (*Z*,*E*)-**14d**: ^{1}H NMR ($CDCl_3$, 400 MHz) δ –0.037 (s, 9 H), 1.03 (d, J = 7.1 Hz, 3 H), 1.75 (dd, J = 6.7 and 1.5 Hz, 3 H), 2.02 (dqd, J = 11, 7.1, and 1.0 Hz, 1 H), 5.10 (t, J = 11 Hz, 1 H), 5.61 (dqt, J = 15, 6.7, and 0.7 Hz, 1 H), 5.84 (t, J = 11 Hz, 1 H), 6.23 (dd of quint, J = 15, 11, and 1.5 Hz, 1 H). Hydrogenation (100 atm H_2, Pd/C in benzene at 60 °C) of (*Z*,*E*)-**14d** ($[\alpha]^{20}_D$ +13° (*c* 5.1, benzene)) gave (*S*)-**29** of 8% ee ($[\alpha]^{20}_D$ –1.4° (*c* 1.1, benzene)).

1-[1-(Trimethylsilyl)ethyl]cyclopentene (21): isolated by bulb-to-bulb distillation (95–105 °C/18 mmHg) followed by preparative GLC (PEG); ^{1}H NMR (CCl_4) –0.03 (s, 9 H), 1.13 (d, J = 7 Hz, 3 H), 1.50–2.05 (m, 2 H), 1.85 (q, J = 7 Hz, 1 H), 2.05–2.45 (m, 4 H), 5.16 (br s, 1 H). Anal. Calcd for $C_{10}H_{20}Si$: C, 71.34; H, 11.97. Found: C, 71.04; H, 11.72. To a suspension of 1.53 g (5.90 mmol) of dichlorobis(acetonitrile)palladium in 50 mL of methanol was added 0.965 g (5.73 mmol) of **21** ($[\alpha]^{20}_D$ –6.2° (*c* 0.5, benzene)), and the mixture was stirred at room temperature for 8 h. Methanol was removed under reduced pressure and the residue was passed through a short alumina column with chloroform as an eluent. Removal of the solvent gave 0.61 g (39%) of bis(μ-chloro)bis(1-methyl-2,3-trimethylene-π-allyl)dipalladium (**32**) as yellow powder: $[\alpha]^{20}_D$ +35.7° (*c* 0.7, chloroform); ^{1}H NMR ($CDCl_3$) δ 1.28 (d, J = 7 Hz, 3 H), 1.70–2.86 (m, 6 H), 3.80–4.12 (m, 2 H). To a solution of 57 mg (0.24 mmol) of the (π-allyl)-palladium **32** in 1 mL of THF was added at 0 °C a solution of sodium salt of *d*,*d*-dicampholylmethane[26] in THF which was prepared by adding 77 mg (0.24 mmol) of *d*,*d*-dicampholylmethane to a suspension of 27 mg (0.57 mmol) of sodium hydride (50% in mineral oil) in 1 mL of THF. The mixture was stirred at room temperature for 5 min, hydrolyzed with 5 mL of water, and extracted with ether. The ether extract was dried over anhydrous magnesium sulfate and evaporated to give 125 mg (100%) of (*d*,*d*-dicampholylmethanato)(1-methyl-2,3-trimethylene-π-allyl)palladium (**31**). ^{1}H NMR ($CDCl_3$, 200 MHz) of **31** showed the presence of two diastereomeric isomers in a ratio of 67:33. The methine singlets of the methanato group which appeared at δ 5.37 and 5.40 were used for the determination of the ratio.

(*E*)-3-(Trimethylsilyl)-2-pentene ((*E*)-14b): isolated by distillation (68–75 °C/26 mmHg) followed by preparative GLC (PEG); ^{1}H NMR (CCl_4) δ –0.09 (s, 9 H), 1.16 (d, J = 7 Hz, 3 H), 1.61 (quint, J = 7 Hz, 1 H), 1.80 (d, J = 6 Hz, 3 H), 5.26 (dq, J = 15 and 6 Hz, 1 H), 5.53 (dd, J = 7 and 15 Hz, 1 H). To a solution of 0.72 g (5.07 mmol) of (*E*)-**14b** ($[\alpha]^{20}_D$ –15.7° (*c* 1.4, benzene)) and 0.47 g (5.46 mmol) of trimethylacetaldehyde in 20 mL of dry dichloromethane was added 0.56 mL (5.07 mmol) of titanium chloride at –78 °C under a dry nitrogen atmosphere. The mixture was stirred at 0 °C for 3 h, hydrolyzed with water, and extracted with ether. The organic layer was washed with water, dried over anhydrous magnesium sulfate, and concentrated by evaporation. Preparative TLC on silica gel (chloroform) gave 0.41 g (52%) of (*E*,3*R*,4*S*)-2,2,4-trimethyl-5-hepten-3-ol (**33**) (96% pure by GLC): $[\alpha]^{20}_D$ –5.74° (*c* 2.0, chloroform); ^{1}H NMR (CCl_4) δ 0.94 (s, 9 H), 1.03 (d, J = 7 Hz, 3 H), 1.19 (br s, 1 H), 1.47 (d, J = 5 Hz, 3 H), 2.35 (m, 1 H), 5.17–5.68 (m, 2 H). The ^{1}H NMR in the presence of Eu(fod)$_3$ revealed that the coupling constant between two olefinic protons is 16 Hz. To a solution of 44.7 mg (0.286 mmol) of the homoallyl alcohol **33** in 8 mL of *tert*-butyl alcohol was added 123 mg (0.886 mmol) of potassium carbonate in 5 mL of water. A solution of 489 mg (2.29 mmol) of sodium periodate and 57 mg (0.36 mmol) of potassium permanganate in 8 mL of water was added, and the solution was adjusted to pH 8.5 with 2 N sodium hydroxide. The mixture was stirred at room temperature for 13 h and *tert*-butyl alcohol was evaporated. The residue was acidified with concentrated hydrochloric acid to pH 1 and sodium bisulfate was added to destroy the MnO_2. The solution was made basic with 2 N sodium hydroxide, washed with ether, acidified with

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concentrated hydrochloric acid, and extracted with ether. The ether extracts were washed with water, dried over anhydrous magnesium sulfate, and concentrated under reduced pressure to give 35.5 mg (77%) of *erythro*-2,4,4-trimethyl-3-hydroxypentanoic acid, whose stereochemistry (erythro or threo) was determined by ^{1}H NMR in acetone-d_6.[54] The acid was esterified with ethereal diazomethane to give methyl ester (2*R*,3*R*)-**34** (55% ee): ^{1}H NMR (CCl_4) δ 0.93 (s, 9 H), 1.14 (d, J = 7 Hz, 3 H), 2.15 (br s, 1 H), 2.63 (dq, J = 4 and 7 Hz, 1 H), 3.53 (d, J = 4 Hz, 1 H), 3.65 (s, 3 H). The enantiomeric purity was determined by ^{1}H NMR in the presence of Eu(facam)$_3$ and the absolute configuration was determined by comparison of the NMR with that of an authentic sample, the OCH_3 singlet of (2*R*,3*R*)-**34** appearing at a higher field than that of the enantiomer.

(*E*)-3-(Triethylsilyl)-2-pentene ((*E*)-16b): isolated by distillation (76–80 °C/17 mmHg) followed by preparative GLC (PEG); ^{1}H NMR (CCl_4) δ 0.52 (q, J = 7 Hz, 6 H), 0.96 (t, J = 7 Hz, 9 H), 1.05 (d, J = 7 Hz, 3 H), 1.65 (d, J = 6 Hz, 3 H), 1.4–1.8 (m, 1 H), 5.15 (dq, J = 15 and 6 Hz, 1 H), 5.44 (dd, J = 15 and 7 Hz, 1 H). Anal. Calcd for $C_{11}H_{24}Si$: C, 71.65; H, 13.12. Found: C, 71.46; H, 13.00. Reaction of (*E*)-**16b** ($[\alpha]^{20}_D$ −20.4° (*c* 2.6, benzene)) with trimethylacetaldehyde and titanium chloride in dichloromethane in a similar manner to that of (*E*)-**14b** gave 20% yield of **33**, which was converted into (2*R*,3*R*)-**34** (65% ee) by oxidation with $KMnO_4/NaIO_4$ followed by methylation (CH_2N_2).

3-(Trimethylsilyl)-1-butene (14a): isolated by distillation (55–58 °C/10 mmHg) (lit.[55] bp 111–112 °C/760 mmHg); ^{1}H NMR (CCl_4) 0.01 (s, 9 H), 1.10 (d, J = 7 Hz, 3 H), 1.62 (quint, J = 7 Hz, 1 H), 4.65–4.95 (m, 2 H), 5.85 (ddd, J = 7, 11, and 18 Hz, 1 H).

3-(Dimethylphenylsilyl)-1-butene (15a): isolated by bulb-to-bulb distillation (50–60 °C/3 mmHg) followed by preparative GLC (PEG); ^{1}H NMR (CCl_4) δ 0.24 (s, 6 H), 1.01 (d, J = 7 Hz, 3 H), 1.78 (quint, J = 7 Hz, 1 H), 4.59–4.89 (m, 2 H), 5.74 (ddd, J = 7, 11, and 17 Hz, 1 H), 7.09–7.49 (m, 5 H). Anal. Calcd for $C_{12}H_{18}Si$: C, 75.72; H, 9.53. Found: C, 75.88; H, 9.81. Reaction of **15a** ($[\alpha]^{20}_D$ −23.5° (*c* 4.4, benzene)) with trimethylacetaldehyde (1.1 equiv) and titanium chloride (1.0 equiv) in dichloromethane at −78 °C for 10 min gave a 47% yield of (*R*,*E*)-2,2-dimethyl-5-hepten-3-ol (**35**) which was contaminated with 4–5% of the *Z* isomer: ^{1}H NMR (CCl_4) δ 0.85 (s, 9 H), 1.50 (br s, 1 H), 1.70 (d, J = 5 Hz, 3 H), 1.74–2.38 (m, 2 H), 3.15 (dd, J = 3 and 11 Hz, 1 H), 5.40 (m, 2 H). The enantiomeric purity of **35** was determined to be 49% by ^{1}H NMR in the presence of Eu(dcm)$_3$. The *tert*-butyl singlet of major enantiomer appeared at a higher field than that of minor one. The configuration *R* of **35** was assumed by comparison of the ^{1}H NMR using Eu(dcm)$_3$ with that of the analogous optically active homoallyl alcohol, 2,2-dimethyl-6-phenyl-5-hepten-3-ol.[32]

3-(Triethylsilyl)-1-butene (16a): isolated by distillation (70–73 °C/18 mmHg); ^{1}H NMR (CCl_4) δ 0.54 (q, J = 8 Hz, 6 H), 0.97 (t, J = 8 Hz, 9 H), 1.08 (d, J = 7 Hz, 3 H), 1.73 (quint, J = 7 Hz, 1 H), 4.60–4.71, 4.76–4.85 (m, 2 H), 5.78 (ddd, J = 7, 10, and 17 Hz, 1 H). Anal. Calcd for $C_{10}H_{22}Si$: C, 70.50; H, 13.02. Found: C, 70.46; H, 13.17. Reaction of **16a** ($[\alpha]^{20}_D$ −27.2° (*c* 3.5, benzene)) with trimethylacetaldehyde under the same reaction conditions as those for **15a** gave a 22% yield of a mixture of (*R*,*E*)-**35** (46% ee) and (*Z*)-**35** in a ratio of 9:1.

Preparation of (*S*)-1-Phenyl-3-(trichlorosilyl)butane (25). The optically active alcohol, (*S*)-4-phenyl-2-butanol (**26**), $\alpha^{18.5}_D$ +0.671° (0.1 dm, neat), 49% optically pure,[56] whose purity was confirmed as 50 ± 3% ee by ^{1}H NMR spectroscopy using the chiral shift reagent Eu(dcm)$_3$, was obtained by oxidation of (*R*,*E*)-1-phenyl-1-(trimethylsilyl)-2-butene ((*E*)-**3b**) with MCPBA[31] followed by catalytic hydrogenation of the resulting allyl alcohol. According to the procedure shown for the preparation of (−)-2-chloropentane from 2-pentanol with inversion,[57] 2.23 g (14.9 mmol) of the alcohol (*S*)-**26** (ca. 50% ee) was treated with 2.90 mL (16.0 mmol) of chlorodiphenylphosphine. Distillation (70–73 °C/0.5 mmHg) gave 1.01 g (40%) of 4-phenyl-2-chlorobutane (**23**): ^{1}H NMR (CCl_4) δ 1.50 (d, J = 7 Hz, 3 H), 1.97 (q, J = 7 Hz, 2 H), 2.5–3.0 (m, 2 H), 3.86 (sextet, J = 7 Hz, 1 H), 7.10 (br s, 5 H).

To a solution of 1.01 g (5.97 mmol) of the chloride **23** in 1.5 mL of THF was added at 0 °C a solution of 18 mmol of (triphenylsilyl)lithium in THF (1.0 M, 18 mL). The mixture was stirred at 0 °C for 2 h, hydrolyzed with 10% hydrochloric acid, and extracted four times with ether. The extract was washed with aqueous sodium bicarbonate, dried over magnesium sulfate, and stripped of solvent. The residue was chromatographed on silica gel (hexane) to give 1.66 g (71%) of 4-phenyl-2-(triphenylsilyl)-butane (**24**): $[\alpha]^{20}_D$ +3.84° (*c* 2.3, benzene); ^{1}H NMR (CCl_4) δ 1.20 (d, J = 7 Hz, 3 H), 1.35–1.65 (m, 2 H), 1.85–2.30 (m, 1 H), 2.35–3.00 (m, 2 H), 6.95–7.30 (m, 20 H).

Dry hydrogen chloride was slowly bubbled into a solution of 1.59 g (4.06 mmol) of the triphenylsilane **24** and a catalytic amount (10 mg) of aluminium chloride in 20 mL of dry benzene. The stepwise conversion of the triphenylsilyl group into trichlorosilyl by way of diphenylchlorosilyl and phenyldichlorosilyl was followed by GLC. The conversion was completed after the bubbling was continued for 10 h, and the mixture was stripped of solvent in vacuo to give crude 1-phenyl-3-(trichlorosilyl)butane (**25**), which was used for the oxidation and methylation without further purification.

Methylation of the Trichlorosilane (*S*)-25 into (*S*)-4-Phenyl-2-(trimethylsilyl)butane (22). To a solution of the crude trichlorosilane (*S*)-**25** (3.0 mmol) in 10 mL of THF was added a solution of methylmagnesium bromide (30 mmol) in ether. The mixture was refluxed for 6 h and hydrolyzed with 10% hydrochloric acid. Usual workup followed by bulb-to-bulb distillation (50–60 °C/2 mmHg) gave 0.45 g (72%) of 4-phenyl-2-(trimethylsilyl)butane (**22**): $[\alpha]^{20}_D$ −18.5° (*c* 2.8, benzene).

Oxidation of the Trichlorosilane (*S*)-25 into (*S*)-4-Phenyl-2-butanol (26). To a suspension of 0.345 g (2.52 mmol) of $CuF_2{\cdot}2H_2O$ in 0.5 mL of ether was added the crude trichlorosilane (*S*)-**25** (1.0 mmol) at 0 °C, and the mixture was stirred at room temperature for 14 h. Pentane (5 mL) was added and white-green precipitates were filtered off. The filtrate was dried over anhydrous sodium sulfate and the solvent was removed under reduced pressure to give 0.17 g of crude 4-phenyl-2-(trifluorosilyl)butane. To the crude trifluorosilane was added successively DMF (5 mL), potassium fluoride (89 mg, 1.54 mmol), and MCPBA (0.19 g, 0.87 mmol) at 0 °C. The mixture was stirred at room temperature for 2 h, hydrolyzed with water, and extracted with ether. The ether extract was washed successively with aqueous sodium thiosulfate, aqueous sodium bicarbonate, and water and dried over anhydrous magnesium sulfate. Evaporation of the solvent followed by preparative TLC on silica gel (chloroform) gave 73 mg (49%) of (*S*)-4-phenyl-2-butanol (**26**). The enantiomeric purity was determined to be 52% by ^{1}H NMR analysis in the presence of chiral shift reagent (Eu(dcm)$_3$, the methyl doublet of the *S* isomer appearing at a lower field than that of the *R* isomer. Thus, the trimethylsilane **22** whose optical rotation is $[\alpha]^{20}_D$ −18.5° (*c* 2.8, benzene) was determined to be an *S* isomer of 52% ee.

Registry No. 1, 57482-85-6; **2a**, 593-60-2; (*E*)-**2b**, 590-15-8; (*Z*)-**2b**, 590-13-6; (*E*)-**2c**, 588-72-7; (*Z*)-**2c**, 588-73-8; (*E*,*E*)-**2d**, 103980-84-3; (*Z*,*E*)-**2d**, 103980-85-4; (*R*)-**3a**, 82537-19-7; (*S*)-**3a**, 103980-86-5; (*E*,*R*)-**3b**, 82570-93-2; (*Z*,*R*)-**3b**, 82570-94-3; (*E*,*R*)-**3c**, 82537-20-0; (*Z*,*R*)-**3c**, 82537-21-1; (*R*)-**4a**, 103980-87-6; (*S*)-**4a**, 103980-90-1; (*R*)-**4b**, 104013-59-4; (*S*)-**4b**, 103980-91-2; (*R*)-**4c**, 86234-22-2; (*S*)-**4c**, 103980-92-3; (*E*)-**5a**, 873-66-5; (*Z*)-**5a**, 766-90-5; (*Z*)-**5b**, 1560-09-4; (*Z*)-**5c**, 1138-83-6; (*S*)-**6a**, 103980-88-7; (*S*)-**6b**, 104089-93-2; (*S*)-**6c**, 103980-89-8; (*S*)-**7a**, 613-87-6; (*S*)-**7b**, 22135-49-5; (*S*)-**7c**, 64439-32-3; **8**, 932-87-6; (*S*)-**9**, 86234-21-1; **10**, 103980-95-6; **11**, 103980-96-7; **12**, 103980-97-8; **13**, 103980-98-9; (*S*)-**14a**, 103981-03-9; (*E*,*S*)-**14b**, 104068-38-4; (*E*,*S*)-**14c**, 88113-27-3; (*Z*,*S*)-**14c**, 88133-09-9; (*E*,*E*,*S*)-**14d**, 103981-07-3; (*Z*,*E*,*S*)-**14d**, 103981-08-4; (*S*)-**15a**, 103981-05-1; (*E*,*S*)-**15c**, 104068-37-3; (*E*,*E*,*S*)-**15d**, 103981-09-5; (*S*)-**16a**, 103981-06-2; (*E*,*S*)-**16b**, 103981-

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02-8; (*E,S*)-**16c**, 103980-99-0; (*Z,S*)-**16c**, 103981-00-6; (*E,S*)-**17c**, 103981-01-7; **19**, 1192-04-7; **20**, 103981-04-0; **21**, 103981-10-8; (*S*)-**22**, 83972-44-5; (*R*)-**23**, 83972-40-1; (*S*)-**24**, 83972-41-2; (*S*)-**25**, 83972-42-3; (*S*)-**26**, 22148-86-3; (*S*)-**27**, 103981-11-9; (*S*)-**28**, 6033-23-4; (*S*)-**29**, 103981-12-0; (1*R*,2*S*,3*S*)-**30**, 88076-44-2; (1*S*,2*R*,3*R*)-**30**, 88155-41-3; **31** (isomer 1), 104033-86-5; **31** (isomer 2), 104111-04-8; **32**, 104111-03-7; (*E*,3*R*,4*S*)-**33**, 103981-13-1; (2*R*,3*R*)-**34**, 92999-39-8; (*E,R*)-**35**, 104068-39-5; (*Z,R*)-**35**, 104068-40-8; (*R,S*)-PPFA, 55700-44-2; (*S*)-Valphos, 74492-09-4; $PdCl_2$[1*R*,*S*)-PPFA], 76374-09-9; $PdCl_2$[(*R,S*)-BPPFA], 79723-33-4; $PdCl_2$[(*S*)-Valphos], 104013-74-3; $NiCl_2$[(*S*)-prophos], 104069-06-9; $NiCl_2$[(−)-DIOP], 41677-72-9; $NiCl_2$, 7718-54-9; (*Z*)-β-bromostyrene, 588-73-8; (1-chloroethyl)trichlorosilane, 7787-82-8; crotonaldehyde, 4170-30-3; (*S*)-1-phenyl-1-(trifluorosilyl)propane, 103980-93-4; (*S*)-1-phenyl-1-(trifluorosilyl)butane, 103980-94-5; 1-(trimethylsilyl)ethyl chloride, 7787-87-3; 1-(dimethylphenylsilyl)ethyl chloride, 17877-00-8; 1-(triethylsilyl)ethyl chloride, 18279-74-8; 1-(triphenylsilyl)ethyl chloride, 103981-16-4; 1-(trichlorosilyl)ethyl chloride, 7787-82-8; 1-(phenyldichlorosilyl)ethyl chloride, 18236-52-7; trimethylacetaldehyde, 630-19-3.

Supplementary Material Available: Preparation of 1-(trimethylsilyl)ethyl chloride, 1-(dimethylphenylsilyl)ethyl chloride, 1-(triethylsilyl)ethyl chloride, and 1-(triphenylsilyl)ethyl chloride (2 pages). Ordering information is given on any current masthead page.

Studies of Methyl Isocyanate Chemistry in the Bhopal Incident†

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Following the methyl isocyanate leak from Tank 610 at the Bhopal plant, the residual material from the tank was analyzed for its contents. Approximately 70% of the residue was comprised of three cyclic materials: 1,3,5-trimethyl-1,3,5-triazine-2,4,6(1*H*,3*H*,5*H*)-trione or methyl isocyanate trimer (**5**), 1,3-dimethyl-1,3,5-triazine-2,4,6(1*H*,3*H*,5*H*)-trione or dimethyl isocyanurate (**6**), and dihydro-1,3,5-trimethyl-1,3,5-triazine-2,4-(1*H*,3*H*)-dione or dihydrotrimethyltriazinedione (**7**). Minor quantities of methyl-substituted ureas, biurets, and amine hydrochlorides were also found. The composition of the residue was replicated very closely by the products obtained when a mixture of methyl isocyanate (84.4%), chloroform (12.0%), and water (3.6%) was heated at 225 °C under pressure in a stainless steel reactor. Experimental results are consistent with the view that under these conditions methyl isocyanate reacts initially with water to form 1,3-dimethylurea (**1**) and 1,3,5-trimethylbiuret (**2**). At temperatures between 100 °C and 225 °C these products decompose to reactive intermediates which further react exothermically to form the aforementioned cyclic materials, trimethylurea, and mono-, di-, and trimethylamine hydrochlorides. The decomposition of **1** and **2** is facilitated by the presence of chloroform and metals. Other experiments involving ^{13}C-enriched chloroform have given support to the proposed mechanisms for formation of **6** and **7**.

The investigation of the methyl isocyanate incident in Bhopal, India, required not only understanding what residues or products were formed during the reaction(s) which occurred in Tank 610 but also developing an understanding of the probable chemistry which could result in such a mixture. Thus, this aspect of the total investigation addressed the following issues: (1) What starting materials and reaction conditions could lead to product mixtures qualitatively and quantitatively like that found in Tank 610? (2) What are the likely mechanisms by which these starting materials lead to the observed product mixture?

This paper presents the results of these experiments directed to the aforementioned issues but does not address in any way the possible events which led to the incident.

Basic Methyl Isocyanate Chemistry. The electrophilic nature of isocyanates as indicated by their reactivity with a variety of nucleophilic reagents is well-recognized.[1-3] The most characteristic reactions of isocyanates, and methyl isocyanate (MIC) in particular, are those involving compounds with an active hydrogen. These include hydroxylated compounds such as water, alcohols, phenols, and oximes, and also amino compounds, among others.

Water reacts exothermically with MIC to form 1,3-dimethylurea (**1**) and 1,3,5-trimethylbiuret (**2**) with evolution of carbon dioxide. Excessive water leads to predominantly **1** and limited amounts of water (excess MIC) to **2**.

excess water

$$\underset{\text{MIC}}{CH_3N{=}C{=}O} + H_2O \rightarrow [CH_3NHCOOH] \rightarrow CH_3NH_2 + CO_2$$

$$CH_3NH_2 + CH_3N{=}C{=}O \rightarrow \underset{\mathbf{1}}{CH_3NHCONHCH_3}$$

excess MIC

$$\underset{\mathbf{1}}{CH_3NHCONHCH_3} + CH_3N{=}C{=}O \rightarrow \underset{\mathbf{2}}{CH_3NHCONCH_3CONHCH_3}$$

Methyl isocyanate is also known to react with itself under a variety of conditions to form cyclic dimer and trimer, as well as linear polymers, with cyclotrimerization being the most common.[1-3] Metal salts[4,5] and bases[6] are

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