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Stereoselective synthesis of unsymmetrical conjugated dienes and trienes utilizing silacyclobutenes

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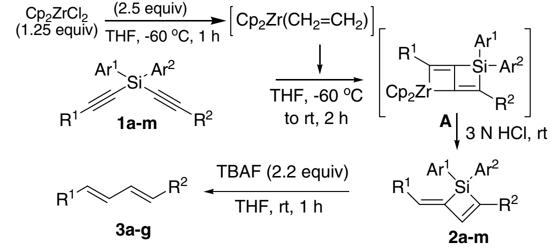
Abstract—Treatment of the different kinds of alkynyl-substituted dialkynyldiarylsilanes with zirconocene–ethylene complex $Cp_2Zr(CH_2{=}CH_2)$ followed by acidification with 3 N HCl gave regio- and stereoselectively the corresponding silacyclobutenes in good yields. Desilylation of the silacyclobutenes with tetrabutylammonium fluoride afforded stereoselectively unsymmetrical conjugated (1*E*,3*E*)-dienes and -trienes (R^1 or $R^2 = 1$-cyclohexenyl) in excellent yields.

Conjugated dienes and polyenes are often found in the structures of biologically active natural products.[1] Stereoselective synthesis of conjugated dienes is very important both for their use in diene-containing natural products and for their application to other reactions such as Diels–Alder reactions[2] and oxygen 1,4-cycloaddition reactions.[3] Thus, a number of methods for synthesizing the conjugated dienes and polyenes have been developed by exploiting various organometallic compounds involving boron,[4] silicon,[5] copper,[6] nickel,[7] zirconium,[8] and titanium[9] atoms. In recent years, Negishi and co-workers have explored and disclosed a number of fascinating reactions utilizing zirconium catalysts.[10]

Several years ago, Takahashi and co-workers reported an interesting zirconocene-mediated intramolecular carbon–carbon bond formation between two identical alkyn- yl groups in bis(alkynyl)silanes.[8b,c] However, only bis(alkynyl)silanes bearing the same alkynyl groups were exclusively employed for the desirable zirconocene-mediated reactions, and thus treatment of the resulting silacyclobutenes with CuCl afforded only symmetrical conjugated dienes.[8b,c] In general, silacyclobutenes have been synthesized by utilizing the cycloaddition of alkynes to silenes[11] or the reaction of silyl-substituted alkynes with polysilanes.[12]

Recently, we established an efficient procedure for synthesizing dialkynyldiarylsilanes bearing different kinds of alkynyl groups,[13] which seemed to be remarkably useful for the synthesis of various conjugated dienes, trienes, and other functional organosilicon molecules. Herein we describe a novel procedure for synthesizing unsymmetrical conjugated (1*E*,3*E*)-dienes and -trienes involving the reaction of the different kinds of alkynyl-substituted dialkynyldiarylsilanes with a zirconocene complex $Cp_2Zr(CH_2{=}CH_2)$ (Takahashi reagent)[8b,c] formed in situ from Cp_2ZrEt_2, followed by treatment of the resulting silacyclobutenes with tetrabutylammonium fluoride (TBAF), as shown in Scheme 1. We also discuss two kinds of possible reaction mechanisms for



Scheme 1. A stereoselective synthesis of unsymmetrical conjugated (*E*,*E*)-alkadienes via desilylation of silacyclobutenes.

Keywords: Dialkynyldiarylsilane; Zirconium complex; Silacyclobutene; Tetrabutylammonium fluoride; Conjugated diene.

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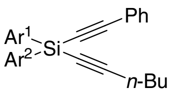
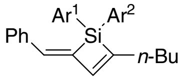
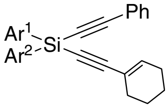
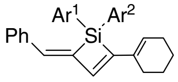
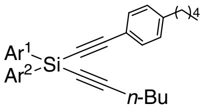
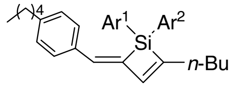
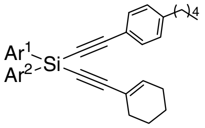
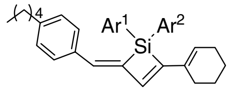
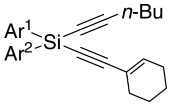
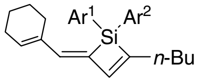
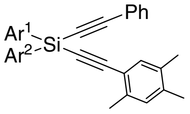
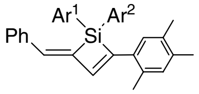
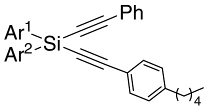
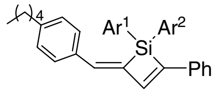
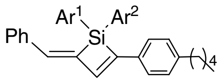
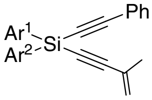
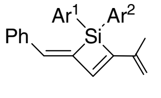
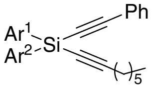
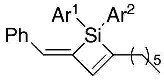
regioselective formation of zirconacyclobutene–silacyclobutene fused-ring intermediates **A** toward silacyclobutenes **2a**–**m**.

To a solution of $Cp_2Zr(CH_2{=}CH_2)$ in THF, obtained from the procedure of Takahashi,[8b,c] was added phenyl-(2,4,6-triisopropylphenyl(Tip))(butylethynyl)(phenylethynyl)silane (**1a**) at −60 °C. The resulting mixture was allowed to warm gradually to room temperature over 1 h with stirring and then stirred for an additional 1 h to form a zirconacyclobutene–silacyclobutene fused-ring intermediate **A** ($R^1 = Ph$, $R^2 = n$-Bu, $Ar^1 = Ph$, $Ar^2 = Tip$).[8b,c] The crude intermediate was treated with 3 N HCl to afford exclusively a novel *Z*-phenylmethylene-silacyclobutene **2a** ($R^1 = Ph$, $R^2 = n$-Bu, $Ar^1 = Ph$, $Ar^2 = Tip$) in a stereo- and regioselective manner and in 80% yield based on **1a** (Table 1, entry 1). Other new *Z*-type-methylene-silacyclobutenes **2b**–**m** were also

Table 1. Stereo- and regioselective synthesis of silacyclobutene derivatives utilizing Takahashi's procedure

Entry	Dialkynylsilane		Ar^1	Ar^2	Product		Yield[a] (%)
1		**1a**	Ph	Tip[b]		**2a**	80
2		**1b**	Ph	Tmp[c]		**2b**	67
3		**1c**	Tmp[c]	Tmp[c]		**2c**	85
4		**1d**	Ph	Tip[b]		**2d**	69
5		**1e**	Ph	Tmp[c]		**2e**	51
6		**1f**	Ph	Tip[b]		**2f**	83
7		**1g**	Ph	Tmp[c]		**2g**	82
8		**1h**	Ph	Tmp[c]		**2h**	65
9		**1i**	Ph	Tmp[c]		**2i**	65
10		**1j**	Ph	Tip[b]		**2j**	86
11		**1k**	Ph	Tip[b]		**2k-1**	78[d]
						**2k-2**	
12		**1l**	Ph	Tmp[c]		**2l**	48
13		**1m**	Ph	Tmp[c]		**2m**	72

[a] Isolated yields.

[b] Tip = 2,4,6-triisopropylphenyl.

[c] Tmp = 2,4,6-trimethylphenyl.

[d] A 1:1 (**2k-1**:**2k-2**) ratio was determined by ^1H NMR (400 MHz, $CDCl_3$) analysis.

stereo- and regioselectively obtained in 48–86% yields based on **1b**–**m** by the reactions described above (Table 1, entries 2–10, 12, and 13). In the case of **1k**, an inseparable mixture of silacyclobutenes (**2k-1** and **2k-2**) was obtained in 78% total yield with a 1:1 (**2k-1**:**2k-2**) ratio (Table 1, entry 11). All results are summarized in Table 1. The structures of **2c** and **2d** were precisely determined by X-ray crystallographic analyses, as shown in Figure 1.[14]

Other products were reasonably assigned to be structures **2a**,**b** and **2e**–**m** based on their spectroscopic and elemental analyses in comparison with those of **2c** and **2d**. Interestingly, we recognized that aromatic groups occupied the R^1 site in products **2a**–**h** and **2l**,**m** and that the R^1 group was cyclohexenyl in **2i**.

On the basis of the experimental results in Table 1, we can now comment on the proposed mechanisms for the formation of silacyclobutenes from bis(alkynyl)silanes by Takahashi and his co-workers.[8b,c] Although Takahashi proposed two mechanisms, an insertion route (**4**→**5**→**A**) and a vinylidene route (**4**→**6**→**A**) for the formation of the zirconacyclobutene–silacyclobutene fused-ring intermediates **A** (Scheme 2),[8b,c] the former must involve carbocationic intermediates **7** or **8** to obtain **A** or **B**. Because the benzylic carbocationic intermediates (R^1 = phenyl or 4-substituted phenyl groups) **8** are more stable than the aliphatic carbocationic intermediates (R^2 = *n*-butyl, *n*-hexyl, and cyclohexenyl groups) **7** in the insertion route, the resulting predominant intermediates should be **B**, rather than the observed intermediates **A**, to afford silacyclobutenes **2a**–**m**. Thus, the exclusive products **2a**–**m** may be obtained via the vinylidene (**4**→**6**→**A**) route although there is no direct evidence of the vinylidene mechanism.[15] In the vinylidene route, initial preferential replacement of ethylene ligand of $Cp_2Zr(CH_2{=}CH_2)$ with a more electron-rich alkynyl group than another alkynyl group in the molecule of **1a**–**m** seems to be essential for differentiation between two kinds of alkynyl groups in the same molecules.[15]

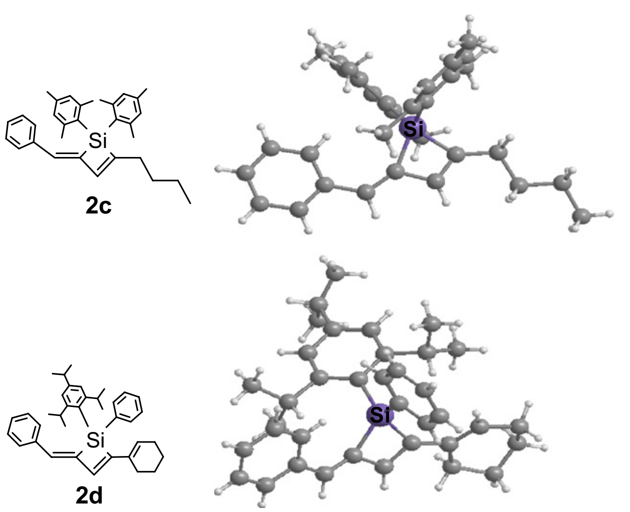
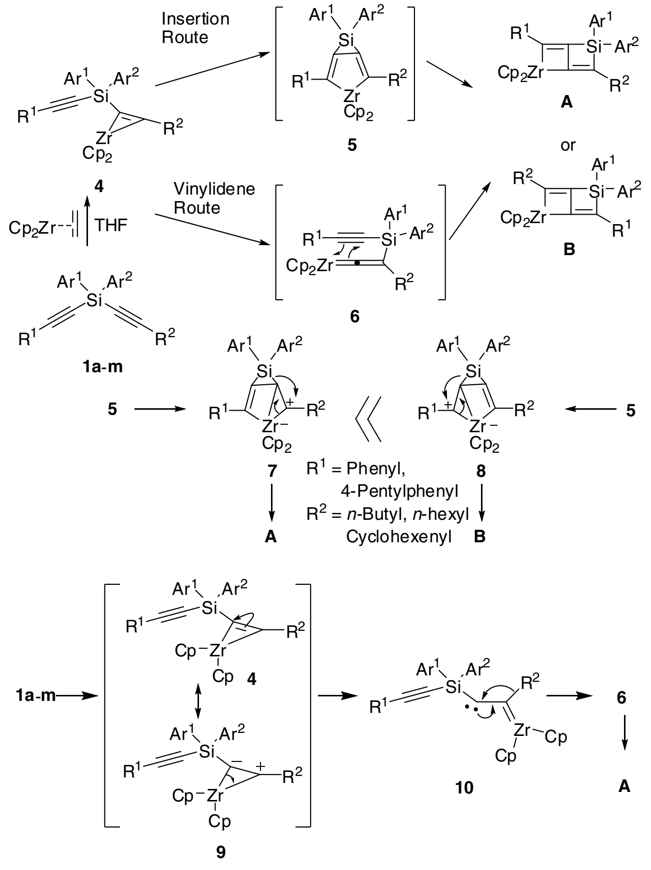


Figure 1. Computer-generated drawing derived from the X-ray coordinates of compounds **2c** and **2d**.



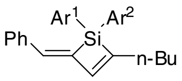
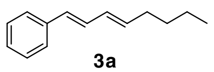
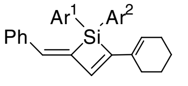
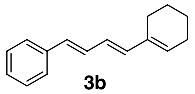
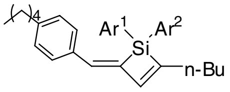
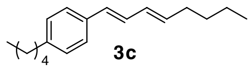
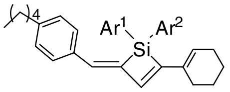
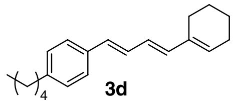
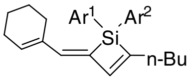
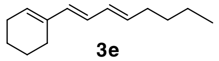
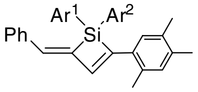
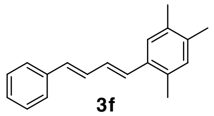
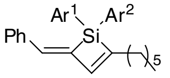
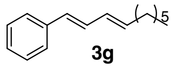
Scheme 2. Plausible mechanisms for the formation of zirconacyclobutene–silacyclobutene fused-ring intermediates **A**.

However, in the silacyclobutenes formation of compound **1k** having similar phenyl-substituted ethynyl groups, the replacement of ethylene ligand of $Cp_2Zr(CH_2{=}CH_2)$ with an alkynyl group may be equally performed at both of the alkynyl moieties of **1k** to give a 1:1 mixture of **2k-1** and **2k-2**. In the case of compound **1j** having the different kinds of phenyl-substituted ethynyl groups, the preferential ligand replacement reaction can be done at more electron-rich Tmp-ethynyl moiety than the phenyl-ethynyl moiety to give an exclusive product **2j** in 86% yield. Two resonance types of alkyne–zirconium complex **4** and **9** probably due to α-anion and/or β-cation stabilization by the Si–C bond would be converted to a carbene type intermediate **10**,[16] in which 1,2-alkyl shift may proceed to give vinylidene zirconium complex **10** and then **A**.

Finally, we achieved the highly stereoselective conversion of silacyclobutenes **2a**,**b**, **2d**–**j**, and **2m** into the corresponding unsymmetrical conjugated (1*E*,3*E*)-dienes and -trienes **3a**–**g** in very high yields by utilizing TBAF, as shown in Table 2. Namely, a solution of **2a** in THF was treated with a solution of a 2.2 mol equiv of TBAF in THF at room temperature for 1 h to give (1*E*,3*E*)-1-phenyl-1,3-octadiene **3a** in 99% yield (Table 2, entry 1).[17]

Similar treatment of other silacyclobutenes **2b**,**d**,**e**, **2h**–**j**, and **2m** with TBAF in THF at room temperature for 1 h

Table 2. Synthesis of unsymmetrical conjugated dienes and trienes

Entry	Silacyclobutene		Ar^1	Ar^2	Product	Yield[a] (%)
1		**2a**	Ph	Tip[b]	 **3a**	99
2		**2b**	Ph	Tmp[c]		99
3		**2d**	Ph	Tip[b]	 **3b**	98
4		**2e**	Ph	Tmp[c]		97
5		**2f**	Ph	Tip[b]	 **3c**	92[d]
6		**2g**	Ph	Tmp[c]		99[d]
7		**2h**	Ph	Tmp[c]	 **3d**	98
8		**2i**	Ph	Tmp[c]	 **3e**	96
9		**2j**	Ph	Tip[b]	 **3f**	96
10		**2m**	Ph	Tmp[c]	 **3g**	97

[a] Isolated yields.

[b] Tip = 2,4,6-triisopropylphenyl.

[c] Tmp = 2,4,6-trimethylphenyl.

[d] Reaction time: 20 h.

afforded the corresponding conjugated (1*E*,3*E*)-dienes and -trienes **3a**,**b**, and **3d**–**g** in 96–99% yields, respectively (Table 2, entries 2–4 and 7–10). The reaction of **2f** and **2g** with TBAF in THF required 20 h to give the same conjugated (1*E*,3*E*)-diene **3c** in 92% and 99% yields, respectively (Table 2, entries 5 and 6). The structure and geometry of all of the conjugated (1*E*,3*E*)-dienes and -trienes **3a**–**g** were reasonably assigned on the basis of their spectroscopic [^{1}H NMR (400 MHz, $CDCl_3$) $J_{E\text{-type}} = 14$–16 Hz, $J_{Z\text{-type}} = 11$–12 Hz] and elemental analyses data.

In conclusion, we have demonstrated that the reactions of different kinds of alkynyl-substituted dialkynyldiarylsilanes with a zirconocene complex $Cp_2Zr(CH_2{=}CH_2)$ proceeded stereo- and regioselectively to give new types of silacyclobutene derivatives, which were treated with TBAF to furnish the corresponding unsymmetrical conjugated (1*E*,3*E*)-dienes and -trienes in excellent yields.

Acknowledgment

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14. The crystallographic data of compounds **2c** and **2d** are as follows. For **2c**: $C_{32}H_{38}Si$, FW = 450.74, triclinic, space group $P\bar{1}(\#2)$, $a = 8.7014(5)$ Å, $b = 8.880(5)$ Å, $c = 17.8342(10)$ Å, $Z = 2$, $V = 1317.87(13)$ Å^3, $D_{\mathrm{calc}} = 1.136$ g/cm^3, $R = 0.0411$; for **2d**: $C_{37}H_{44}Si$, FW = 516.84, triclinic, space group $P\bar{1}(\#2)$, $a = 9{,}5280(4)$ Å, $b = 9.8361(3)$ Å, $c = 32.9469(10)$ Å, $Z = 4$, $V = 3053.23(18)$ Å^3, $D_{\mathrm{calc}} = 1.124$ g/cm^3, $R = 0.0875$.
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