

# A Convenient One-Pot Synthesis of 1,4-Dihalobutadienes from Alkynes via Titanacyclopentadienes and Their Transformation to a Series of Silole Derivatives

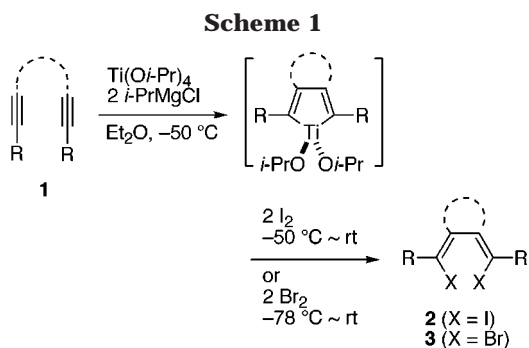
Shigehiro Yamaguchi,<sup>†</sup> Ren-Zhi Jin,<sup>†</sup>  
Kohei Tamao,<sup>\*,†</sup> and Fumie Sato<sup>‡</sup>

*Institute for Chemical Research, Kyoto University, Uji,  
Kyoto 611-0011, Japan, and Department of Biomolecular  
Engineering, Tokyo Institute of Technology,  
4259 Nagatsuta-cho, Midori-ku, Yokohama,  
Kanagawa 226-8501, Japan*

Received July 31, 1998

## Introduction

Butadienes having halogen functionalities on the 1,4-positions constitute an important class of compounds as 1,4-dianion precursors. Indeed, a number of metalloles containing main group elements have been prepared from 1,4-dihalobutadienes through halogen–metal exchange.<sup>1–5</sup> Among a limited number of synthetic routes to 1,4-dihalobutadienes reported so far,<sup>2–7</sup> the most practical way may be the iodination of zirconacyclopentadienes which are prepared from two alkynes.<sup>4,6</sup> This method has recently been improved by Takahashi and co-workers to proceed smoothly and cleanly using CuCl as an additive.<sup>5</sup> 1,4-Diiodobutadienes having a variety of substitution modes can be now accessed by these procedures. However, this zirconacyclopentadiene route has not been applied to the preparation of exocyclic 1,4-dihalobutadienes and 2,3-unsubstituted-1,4-dihalobutadienes,<sup>8</sup> which are crucial precursors to bicyclic and 3,4-unsubstituted metalloles, respectively. We now report a new and



convenient one-pot synthesis of exocyclic and 2,3-unsubstituted-1,4-dihalobutadienes by the halogenolysis of titanacyclopentadienes<sup>9</sup> instead of zirconacyclopentadienes. Transformation of the 1,4-dihalobutadienes to a series of silole derivatives<sup>1c–e,4e–g,5</sup> will also be described.

## Results and Discussion

Our procedure involves the preparation and subsequent halogenolysis of titanacyclopentadienes derived from alkynes with a divalent titanium complex, ( $\eta^2$ -propene)Ti(O-*i*-Pr)<sub>2</sub>, prepared in situ from Ti(O-*i*-Pr)<sub>4</sub> and *i*-PrMgCl, as originally reported by Sato and co-workers (Scheme 1).<sup>10,11</sup> Thus, the titanacyclopentadienes were cleanly formed within 2 h at –50 °C, which were then treated with a slight excess of iodine or bromine, followed by stirring at room temperature for several hours, to afford the corresponding 1,4-dihalobutadienes in good to excellent yields. The entire procedure was carried out in one pot. The results are summarized in Table 1.

There are several significant features to be noted. (1) The present procedure affords various types of exocyclic 1,4-diiodobutadienes containing a four-membered ring as well as a five- and a six membered ring from 1,5-, 1,6-, and 1,7- diynes (entries 1–7).<sup>12b,13</sup> As terminal groups of the diynes, silyl (entries 1 and 2), phenyl (entries 3–5), and even heteroaromatic groups, such as pyridyl (entry 6) and thienyl (entry 7), are applicable. (2) Intermolecular cyclization of internal alkynes to titanacyclopentadienes followed by iodination successfully affords tetrasubstituted 1,4-diiodobutadienes, as exemplified by entry 8. Worthy of special note is that the present method is also applicable to terminal alkynes (entries 9 and 10). This is in sharp contrast to the methodologies using the biscyclopentadienyls “Cp<sub>2</sub>M” (M = Ti and Zr).<sup>6,12</sup> The reaction proceeds in a highly regioselective head-to-head manner to produce the corresponding 2,3-unsubstituted

<sup>†</sup> Kyoto University.

<sup>‡</sup> Tokyo Institute of Technology.

(1) (a) Leavitt, F. C.; Manuel, T. A.; Johnson, F. *J. Am. Chem. Soc.* **1959**, *81*, 3163. (b) Leavitt, F. C.; Manuel, T. A.; Johnson, F.; Matternas, L. U.; Lehman, D. S. *J. Am. Chem. Soc.* **1960**, *82*, 5099. (c) Rühlmann, K. *Z. Chem.* **1965**, *5*, 354. (d) Curtis, M. D. *J. Am. Chem. Soc.* **1967**, *89*, 4241. (e) Dubac, J.; Laporterie, A.; Manuel, G. *Chem. Rev.* **1990**, *90*, 215 and references therein.

(2) Atwell, W. H.; Weyenberg, D. R.; Gilman, H. *J. Org. Chem.* **1967**, *32*, 885.

(3) (a) Ashe, A. J., III; Drone, F. J. *Organometallics* **1984**, *3*, 495.

(b) Ashe, A. J., III; Drone, F. J. *Organometallics* **1985**, *4*, 1478.

(4) (a) Ashe, A. J., III; Kampf, J. W.; Al-Taweel, S. M. *J. Am. Chem. Soc.* **1992**, *114*, 372. (b) Ashe, A. J., III; Kampf, J. W.; Al-Taweel, S. M. *Organometallics* **1992**, *11*, 1491. (c) Ashe, A. J., III; Kampf, J. W.; Pilotek, S.; Rousseau, R. *Organometallics* **1994**, *13*, 4067. (d) Ashe, A. J., III; Al-Ahmad, S.; Pilotek, S.; Puranik, D. B.; Elschenbroich, C.; Behrendt, A. *Organometallics* **1995**, *14*, 2689. (e) Bankwitz, U.; Sohn, H.; Powell, D. R.; West, R. *J. Organomet. Chem.* **1995**, *499*, C7. (f) Freeman, W. P.; Tilley, T. D.; Lioble-Sands, L. M.; Rheingold, A. L. *J. Am. Chem. Soc.* **1996**, *118*, 10457. (g) Yamaguchi, S.; Jin, R.-Z.; Tamao, K. *J. Organomet. Chem.* **1998**, *559*, 73.

(5) Xi, C.; Huo, S.; Afifi, T. H.; Hara, R.; Takahashi, T. *Tetrahedron Lett.* **1997**, *38*, 4099.

(6) (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (b) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336. (c) Buchwald, S. L.; Nielson, R. B. *J. Am. Chem. Soc.* **1989**, *111*, 2870.

(7) Reich, I. L.; Haile, C. L.; Reich, H. J. *J. Org. Chem.* **1978**, *43*, 2402.

(8) In the course of the present study, the preparation of the exocyclic 1,4-dihalobutadienes by the zirconacyclopentadiene route has been reported: Ubayama, H.; Xi, Z.; Takahashi, T. *Chem. Lett.* **1998**, 517.

(9) Iodination of titanacyclopentadienes: Hill, J. E.; Balaich, G.; Fanwick, P. E.; Rothwell, I. P. *Organometallics* **1993**, *12*, 2911.

(10) (a) Urabe, H.; Hata, T.; Sato, F. *Tetrahedron Lett.* **1995**, *36*, 4261. (b) Urabe, H.; Sato, F. *J. Org. Chem.* **1996**, *61*, 6756 and references therein.

(11) The generation of olefin–titanium complexes from Ti(OR)<sub>4</sub> and Grignard reagents was first reported by Kulinkovich et al., See: Kulinkovich, O. G.; Sviridov, S. V.; Vasilevski, D. A. *Synthesis* **1991**, 234. See also: Corey, E. J.; Rao, S. A.; Noe, M. C. *J. Am. Chem. Soc.* **1994**, *116*, 9345.

(12) (a) Nugent, W. A.; Calabrese, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 6422. (b) Nugent, W. A.; Thorn, D. L.; Harlow, R. L. *J. Am. Chem. Soc.* **1987**, *109*, 2788.

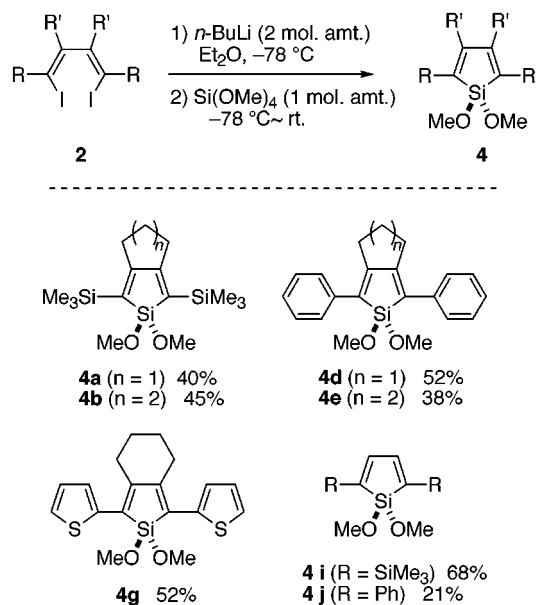
(13) Tillack, A.; Baumann, W.; Lefeber, A. O. C.; Spannenberg, A.; Kempe, R.; Rosenthal, U. *J. Organomet. Chem.* **1996**, *520*, 187.

**Table 1. Preparation of 1,4-dihalobutadienes<sup>a</sup>**

Entry	Diyne and Alkyne	Dihalobutadiene	Yield (%) <sup>b</sup>
1			83
2			89
3			63
4			57
5			40
6			44
7			56
8			75
9			85
10			47
11			78
12			51
13			46

<sup>a</sup> For the iodination and bromination, 2.2–3 molar amounts of **h** and 2.2 molar amounts of Br<sub>2</sub> were used, respectively, with stirring at room temperature for 2–10 h. <sup>b</sup> Isolated yields.

1,4-diiodobutadienes in both cases of (trimethylsilyl)acetylene (entry 9) and phenylacetylene (entry 10). The ratio of the head-to-head product and the head-to-tail product (1,3-disilyl- or 1,3-diphenyl-1,4-diiodobutadiene) is 95/5 for entry 9 and 93/7 for entry 10 as determined by <sup>1</sup>H NMR and isolated yields, respectively. This is in a contrast to the head-to-tail reaction observed in a similar reaction mediated by (ArO)<sub>2</sub>TiCl<sub>2</sub>/Na where Ar denotes the bulky 2,6-diphenylphenyl group.<sup>9</sup> (3) 1,4-Dibromobutadienes were also successfully prepared by the formation of titanacyclopentadienes followed by bromination with bromine (entries 11–13). (4) The halogenolysis of the titanacyclopentadienes proceeds stereospecifically with complete retention of geometry to exclusively form (*Z,Z*)-1,4-dihalobutadienes in all cases. The stereochem-

**Scheme 2**

istries of **2c–e** and **2i, 2j** have been determined by X-ray crystallography, which will be reported elsewhere together with the aspects of their unique thermoisomerization. (5) The present procedures do not require any additives such as CuCl. This is a superior advantage for the titanacyclopentadiene route in comparison with the zirconacyclopentadiene route.<sup>14</sup> (6) From an economical point of view, the titanium reagent Ti(*i*-Pr)<sub>4</sub> is about one-tenth less expensive than Cp<sub>2</sub>ZrCl<sub>2</sub>, thus providing the most convenient and practically useful methodology for the synthesis of 1,4-dihalobutadienes.

As one example of the synthetic application of 1,4-dihalobutadienes, we have prepared a series of silole derivatives, as shown in Scheme 2. The iodo–lithium exchange of 1,4-diiodobutadienes **2** with *n*-BuLi in ether followed by the coupling with Si(OMe)<sub>4</sub> gave siloles **4** in moderate to good yields. All these siloles except for **4j** are new compounds.<sup>1e</sup> In particular, 2,5-disilylsiloles, **4a**, **4b**, and **4i**, are hardly accessible by other conventional methods, despite their potentials as useful precursors for various 2,5-difunctionalized siloles.<sup>15</sup>

### Experimental Section

**General.** <sup>1</sup>H, <sup>13</sup>C, and <sup>29</sup>Si NMR spectra were measured using a JEOL EX-270 (270 MHz for <sup>1</sup>H, 67.8 MHz for <sup>13</sup>C, and 53.5 MHz for <sup>29</sup>Si) spectrometer in appropriate solvents. Titanium tetraisopropoxide was purchased from the Wako Co. and used without further purification. Tetramethoxysilane was purchased from the Shin-Etsu Chemical Co. and distilled before use. Dienes **1c–g** were prepared by the Pd(0)-catalyzed coupling reaction of the corresponding diynes and aryl halides in the presence of PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub>/CuI in Et<sub>2</sub>NH.<sup>16</sup>

(14) For comparison of the present method with the zirconacyclopentadiene route, we conducted a similar reaction using 1,6-diyne **1a** with “Cp<sub>2</sub>Zr” prepared in situ from Cp<sub>2</sub>ZrCl<sub>2</sub> and *n*-BuLi in THF.<sup>6a</sup> The bicyclic zirconacyclopentadiene was cleanly formed. However, the iodination resulted in the formation of a complex mixture even using an excess amount of iodine, while, under Takahashi’s condition using a 1 molar amount of CuCl as the additive,<sup>5</sup> the iodination proceeded at room temperature for 2 h to afford **2a** in 71% yield.

(15) Synthesis of 2,5-difunctionalized siloles from 2,5-disilylsiloles: Yamaguchi, S.; Jin, R.-Z.; Ohno, S.; Tamao, K. *Organometallics* **1998**, *17*, 5133.

(16) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, *50*, 4467.

**A Typical Procedure for the Preparation of 1,4-Dihalobutadienes. Synthesis of (Z,Z)-1,4-Diiodo-2,3-tetramethylene-1,4-bis(trimethylsilyl)-1,3-butadiene (2b).** To an ether (15 mL) solution of  $\text{Ti}(\text{O}-i\text{-Pr})_4$  (0.36 mL, 1.20 mmol) and **1b** (0.25 g, 1.00 mmol) was added an ether solution of  $i\text{-PrMgCl}$  (1.92 mL, 1.25 M, 2.40 mmol) at  $-70^\circ\text{C}$ . The mixture was warmed to  $-50^\circ\text{C}$  over 1 h. After stirring for an additional 1 h, iodine (0.63 g, 2.50 mmol) was added as a solid to the mixture at  $-50^\circ\text{C}$ . The mixture was warmed to room temperature and stirred for 2 h. A saturated aqueous solution of  $\text{Na}_2\text{S}_2\text{O}_3$  was added, and the mixture was extracted with hexane. The combined extract was washed with brine, dried over  $\text{MgSO}_4$ , filtered, and evaporated. The residue was subjected to column chromatography on silica gel using hexane as an eluent ( $R_f = 0.5$ ) to afford **2b** (0.45 g, 0.89 mmol) in 89% yield as a white solid: mp  $70\text{--}72^\circ\text{C}$ .  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  0.30 (s, 18 H), 1.43–1.62 (m, 2 H), 1.80–1.95 (m, 2 H), 2.12–2.25 (m, 2 H), 2.80–2.89 (m, 2 H).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$  1.71, 29.09, 36.43, 101.58, 165.95. MS (EI)  $m/z$  (rel int) 504 ( $\text{M}^+$ , 1.2), 73 (100). IR (KBr) 2930, 2850,  $1570\text{ cm}^{-1}$ . Anal. Calcd for  $\text{C}_{14}\text{H}_{26}\text{I}_2\text{Si}_2$ : C, 33.34; H, 5.20. Found: C, 33.48; H, 5.26.

**A Typical Procedure for the Synthesis of (Z,Z)-1,4-Dibromobutadiene: Synthesis of (Z,Z)-1,4-Dibromo-2,3-tetramethylene-1,4-bis(trimethylsilyl)-1,3-butadiene (3b).** To an ether (10 mL) solution of  $\text{Ti}(\text{O}-i\text{-Pr})_4$  (0.37 mL, 1.26 mmol) and **1b** (0.25 g, 1.00 mmol) was added an ether solution of  $i\text{-PrMgCl}$  (1.59 mL, 1.70 M, 2.70 mmol) at  $-78^\circ\text{C}$ . The mixture was warmed to  $-50^\circ\text{C}$  over 1 h. After stirring at the same temperature for an additional 1 h, bromine (113  $\mu\text{L}$ , 2.20 mmol) was added at  $-78^\circ\text{C}$ . The mixture was warmed to room temperature and stirred for 2 h. A saturated aqueous solution of  $\text{Na}_2\text{S}_2\text{O}_3$  was added. The mixture was extracted with hexane. The combined extract was washed with brine, dried over  $\text{MgSO}_4$ , filtered, and evaporated. The residue was subjected to column chromatography on silica gel using hexane as an eluent to give **3b** (0.32 g, 0.78 mmol) in 78% yield as a white solid: mp  $53\text{--}55^\circ\text{C}$ .  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  0.28 (s, 18 H), 1.35–1.63 (m, 2 H), 1.79–1.98 (m, 2 H), 2.00–2.15 (m, 2 H), 2.66–2.80 (m, 2 H).  $^{13}\text{C}$  NMR

( $\text{CDCl}_3$ )  $\delta$  0.83, 29.00, 35.92, 119.96, 156.23. MS (EI)  $m/z$  (rel int) 410 ( $\text{M}^+$ , 5), 331 (100). IR (KBr) 2925, 2860, 1580,  $1440\text{ cm}^{-1}$ . Anal. Calcd for  $\text{C}_{14}\text{H}_{26}\text{Br}_2\text{Si}_2$ : C, 40.98; H, 6.39. Found: C, 40.71; H, 6.36.

**A Typical Procedure for the Synthesis of Siloles. Synthesis of 1,1-Dimethoxy-2,5-bis(trimethylsilyl)silole (4i).** To a solution of **2i** (3.70 g, 8.2 mmol) in  $\text{Et}_2\text{O}$  (30 mL) was added a hexane solution of  $n\text{-BuLi}$  (10.6 mL, 1.59 M, 16.9 mmol) at  $-78^\circ\text{C}$ . The solution was stirred for 1 h. Tetramethoxysilane (1.21 mL, 8.2 mmol) was added to the mixture at the same temperature. The resulting mixture was gradually warmed to room temperature and stirred for 12 h. The mixture was hydrolyzed with water and extracted with hexane. The combined extract was washed with brine, dried over  $\text{MgSO}_4$ , filtered, and evaporated. The residue was passed through a short silica gel column and then subjected to HPLC on silica gel (hexane/ $\text{EtOAc} = 60/1$ ;  $R_f = 0.12$ ) to afford **4i** (1.60 g, 5.6 mmol) in 68% yield as light yellow oil:  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  0.11 (s, 18H), 3.44 (s, 6H), 7.19 (s, 2H).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ )  $\delta$   $-1.00$ , 50.12, 138.72, 155.20.  $^{29}\text{Si}$  NMR ( $\text{CDCl}_3$ )  $\delta$   $-6.89$ ,  $-7.51$ . MS (EI)  $m/z$  (rel int) 286 ( $\text{M}^+$ , 42), 271 (100). IR (film) 2950, 2850, 1550,  $1250\text{ cm}^{-1}$ . Anal. Calcd for  $\text{C}_{12}\text{H}_{26}\text{O}_2\text{Si}_3$ : C, 50.29; H, 9.14. Found: C, 50.27; H, 9.35.

**Acknowledgment.** This work was partly supported by Grant-in-Aids (No. 07555280 and 09239103) from the Ministry of Education, Science, Sports and Culture, Japan, and by the Japan High Polymer Center.

**Supporting Information Available:** The detailed experimental procedures and spectral and analytical data for compounds **2–4** (7 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JO981533H