

A Convenient One-Pot Procedure to Arylcyclobutenes from Arylacetylenes

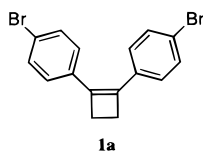
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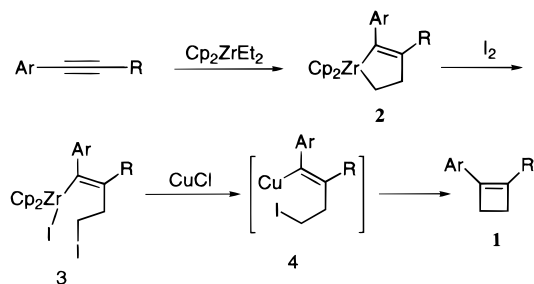
Introduction

The design and synthesis of conjugated polymers or oligomers with various repeat units are of great current interest.^{1–3} Small rings such as cyclobutenes with a well-defined skeleton have not been used as units or monomers in conjugated polymers, to our knowledge. One major reason is the limited number of convenient preparative methods of conjugated cyclobutene derivatives such as 1,2-diaryl cyclobutenes.⁴ Negishi et al.^{4d} have recently reported that 1,2-disubstituted cyclobutene derivatives can be prepared from the reaction of ^tBuLi and 1,4-diiodo-1-alkenes which are isolated from treatment of zirconacyclopentenes⁵ with I₂. However, the use of ^tBuLi does not tolerate other functional groups in the starting diiodides. In fact, preparation of **1a** by this



method did not give a satisfactory result. On the other hand, we have already reported selective halogenation

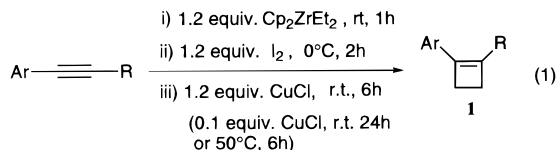
Scheme 1



reactions⁶ and CuCl-assisted new carbon–carbon bond formation reactions⁷ of zirconacyclopentenes. In the course of our further investigations, we found that an intramolecular coupling between alkyl iodide and the alkenylcopper moiety in **4** led to the formation of cyclobutene derivatives as shown in Scheme 1. And this combination can provide a convenient one-pot procedure from readily available arylacetylene and Cp₂ZrEt₂ to arylcyclobutenes. Furthermore, the use of CuCl could tolerate a wide variety of functional groups, and thus, preparation of **1a** would become easily available. Herein we would like to report a convenient one-pot procedure which affords **1a** and various other 1,2-diaryl cyclobutene derivatives.

Results and Discussion

We have reported that, when the substituent in the position of a zirconacyclopentene is an aryl group, monoiodinolysis of the zirconacyclopentene gives only monoalkyl iodide in high yield.⁶ As we expected, addition of 1.2 equiv of I₂ to the zirconacyclopentene of bis(4-bromophenyl)acetylene, followed by addition of 1.2 equiv of CuCl in a one-pot reaction, afforded a clean formation of 1,2-bis(4-bromophenyl)cyclobutene (**1a**) in 64% isolated yield (eq 1, Table 1). The aryl bromides remained intact



during this reaction. Also, aryl chloride in **1b**, aryl bromide in **1c**, and aryl iodide in **1d** were all tolerated. Symmetrically substituted cyclobutene and unsymmetrically substituted cyclobutenes with aryl groups could be readily prepared by this one-pot operation. In addition, we found that the CuCl-mediated cyclization for cyclobutene formation could be a catalytic reaction. Addi-

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(1) *Organic Materials for Non-Linear Optics II*; Hann, R. A., Bloor, D., Eds.; Redwood Press: Melksham, England, 1991.

(2) (a) *Introduction to Molecular Electronics*; Petty, M. C., Bryce, M. R., Bloor, D., Eds.; Oxford University Press: New York, 1995. (b) Tour, J. M. *Chem. Rev.* **1996**, 96, 537.

(3) (a) Pearson, D. L.; Tour, J. M. *J. Org. Chem.* **1997**, 62, 1376. (b) Jones, L., II; Schumm, J. S.; Tour, J. M. *J. Org. Chem.* **1997**, 62, 1388.

(4) (a) *Houben-Weyl's Methods of Organic Chemistry, Additional and Supplementary Volumes to the 4th Edition*; de Meijere, A., Ed; Georg Thieme Verlag: Stuttgart, Germany, 1997; Col. E 17f, pp 615–826. (b) Durst, T.; Breau, L. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon: Tokyo, 1991; Vol. 5, p 675. (c) Negishi, E.; Liu, F.; Choueiry, D.; Mohamud, M. M.; Silveira, A., Jr.; Reeves, M. *J. Org. Chem.* **1996**, 61, 8325. (d) Newman, M. S.; Kaugars, G. *J. Org. Chem.* **1965**, 30, 3295. (e) Fry, A. J.; Moore, R. H. *J. Org. Chem.* **1968**, 33, 425. (f) Hill, E. A.; Engel, M. R. *J. Org. Chem.* **1971**, 36, 1356. (g) Photis, J. M.; Paquette, L. A. *J. Am. Chem. Soc.* **1974**, 96, 4715. (h) Hill, E. A. *J. Am. Chem. Soc.* **1972**, 94, 7462. (i) Snider, B. B.; Rodini, D. J.; Conn, R. S. E.; Sealfon, S. *J. Am. Chem. Soc.* **1979**, 101, 5283. (j) Reed, M. W.; Pollart, D. J.; Perri, S. T.; Foland, L. D.; Moore, H. W. *J. Org. Chem.* **1988**, 53, 2477. (k) Kasai, K.; Liu, Y.; Hara, R.; Takahashi, T. *Chem. Commun.* **1998**, 1989. (l) Liu, Y.; Sun, W.-H.; Nakajima, K.; Takahashi, T. *Chem. Commun.* **1998**, 1133. (m) Takahashi, T.; Xi, Z.; Rischer, R.; Huo, S.; Xi, C.; Nakajima, K. *J. Am. Chem. Soc.* **1997**, 119, 4561.

(5) Takahashi, T.; Kageyama, M.; Denisov, V.; Hara, R.; Negishi, E. *Tetrahedron Lett.* **1993**, 34, 687.

(6) (a) Takahashi, T.; Aoyagi, K.; Hara, R.; Suzuki, N. *J. Chem. Soc., Chem. Commun.* **1993**, 1042. (b) Takahashi, T.; Aoyagi, K.; Kondakov, D. Y. *J. Chem. Soc., Chem. Commun.* **1994**, 747. (c) Aoyagi, K.; Kasai, K.; Kondakov, D. Y.; Hara, R.; Suzuki, N.; Takahashi, T. *Inorg. Chim. Acta* **1994**, 220, 319.

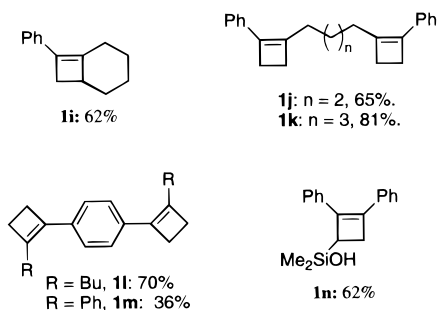
(7) (a) Takahashi, T.; Xi, Z.; Kotora, M.; Xi, C.; Nakajima, K. *Tetrahedron Lett.* **1996**, 37, 7521. (b) Kasai, K.; Kotora, M.; Suzuki, N.; Takahashi, T. *J. Chem. Soc., Chem. Commun.* **1995**, 109. (c) Takahashi, T.; Kotora, M.; Kasai, K.; Suzuki, N. *Tetrahedron Lett.* **1994**, 35, 5685. See also: (d) Takahashi, T.; Kotora, M.; Kasai, K.; Suzuki, N.; Nakajima, K. *Organometallics* **1994**, 13, 3, 4183. (e) Takahashi, T.; Kotora, M.; Xi, Z. *J. Chem. Soc., Chem. Commun.* **1995**, 361. (f) Takahashi, T.; Hara, R.; Nishihara, Y.; Kotora, M. *J. Am. Chem. Soc.* **1996**, 118, 5154.

Table 1. One-Pot Preparation of Arylcyclobutene Derivatives via Zirconacyclopentenes

Ar	R	Product	Isolated yield (%)
		1a	64
		1b	65
		1c	63
		1d	61
		1e	51
		1f	86
	-C ₁₀ H ₂₁ ⁿ	1g	59
	-C ₄ H ₉ ⁿ	1h	76

tion of 0.1 equiv of CuCl instead of 1.2 equiv of CuCl afforded similar results. However, it required a longer reaction time (24 h) or higher reaction temperature (50 °C, 6 h).

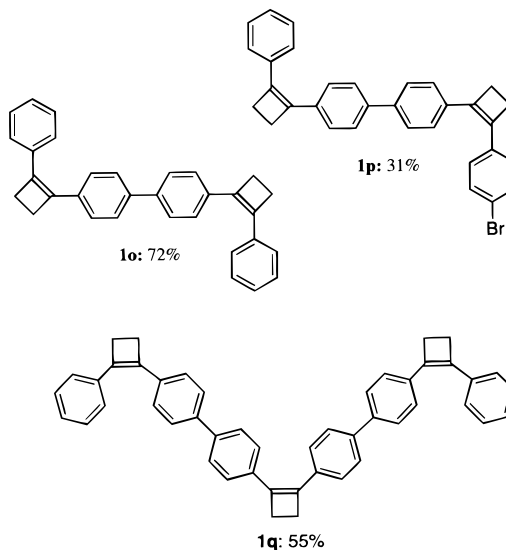
Bicyclic compound **1i** was obtained in 62% isolated yield from its corresponding bicyclic zirconacyclopentene.⁸ Bridged 1,2-disubstituted cyclobutenes **1j–m** were also



easily prepared in good isolated yields (**1j**, 65%; **1k**, 81%; **1l**, 70%; **1m**, 36%) starting from their corresponding bridged zirconacyclopentenes.⁹ Trisubstituted cyclobutene derivative **1n** was obtained in 62% yield. Formation of the bridged 1,2-disubstituted cyclobutene **1m** has been further verified by X-ray crystallography (see the Supporting Information).¹⁰

As demonstrations using the halide-substituted cyclobutene derivatives as monomers, a variety of bridged 1,2-disubstituted cyclobutene derivatives containing two cyclobutene units (**1o**, 72%; **1p**, 31%) and three cyclo-

butene units (**1q**, 55%) could be readily obtained by applying the known methods.¹¹



Experimental Section¹²

Representative Procedure for the Preparation of 1,2-Disubstituted Cyclobutenes: Synthesis of 1,2-Bis(4-bromophenyl)cyclobutene (1a). To a solution of Cp₂ZrCl₂ (2.4 mmol, 700 mg) in THF (15 mL) was added ethylmagnesium bromide (4.8 mmol, 5.05 mL, 0.95 mol/L THF solution) at −78 °C. After the solution was stirred for 1 h at −78 °C, 1,2-bis(4-bromophenyl)acetylene (672 mg, 2.0 mmol) was added and the reaction mixture was allowed to be warmed to 0 °C for 3 h. Iodine (2.4 mmol, 609 mg) was then added at 0 °C, and the mixture was stirred for an additional 3 h. Copper(I) chloride (2.4 mmol, 238 mg) was added, and the mixture was stirred at room temperature for 6 h. The reaction mixture was then quenched with 3 N HCl and extracted with hexane. The extract was washed with water, NaHCO₃ (20% aqueous solution), water, Na₂O₃, water, and brine and dried over MgSO₄. Filtration and evaporation provided a solid substance. Column chromatography on silica gel with hexane as the eluent afforded 466 mg (64%, purity > 98%) of the desired compound: mp 118.0–119.0 °C; ¹H NMR (CDCl₃, Me₄Si) δ 7.44 (d, $J = 8.5$ Hz, 4H), 7.34 (d, $J = 8.5$ Hz, 4H), 2.74 (s, 4H); ¹³C NMR (CDCl₃, Me₄Si) δ 138.20, 134.62, 131.51, 127.52, 121.40, 26.80. Anal. Calcd for C₁₆H₁₂Br₂: C, 52.78; H, 3.32; Br, 43.89. Found: C, 52.44; H, 3.43; Br, 43.23. HRMS: calcd for C₁₆H₁₂Br₂, 361.9305; found, 361.9311.

When a catalytic amount of CuCl (0.1 equiv) was used, the reaction mixture was stirred for 24 h at room temperature or for 6 h at 50 °C.

For preparation of bridged cyclobutenes **1j–m**, the procedure was essentially the same as the above. The ratio of the reagents was as follows: 1.2 mmol of Cp₂ZrCl₂; 2.4 mmol of EtMgBr; 0.5 mmol of diyne; 1.2 mmol of I₂; 1.2 mmol of CuCl.

1-Phenyl-2-(2-thienyl)cyclobutene (1e): ¹H NMR (CDCl₃, Me₄Si) δ 7.64–7.62 (m, 2H), 7.37–7.17 (m, 5H), 7.01–6.97 (m, 1H), 2.81–2.77 (m, 4H); ¹³C NMR (CDCl₃, Me₄Si) δ 136.54, 131.60, 131.40, 128.34, 128.31, 127.49, 127.08, 126.04, 125.13, 124.46, 27.53, 26.69. HRMS: calcd for C₁₄H₁₂S, 212.0659; found, 212.0656.

1,2-Diphenylcyclobutene (1f):¹³ mp 134.8–135.2 °C; ¹H NMR (CDCl₃, Me₄Si) δ 7.52 (d, $J = 7.2$ Hz, 4H), 7.31 (t, $J = 7.2$ Hz, 4H), 7.23 (t, $J = 7.2$ Hz, 2H), 2.77 (s, 4H); ¹³C NMR (CDCl₃,

(8) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, 27, 2829.

(9) (a) Takahashi, T.; Xi, Z.; Nishihara, Y.; Huo, S.; Kasai, K.; Aoyagi, K.; Denisov, V.; Negishi, E. *Tetrahedron* **1997**, 53, 9123. (b) Takahashi, T.; Kasai, K.; Xi, Z.; Denisov, V. *Chem. Lett.* **1995**, 347.

(10) The X-ray data for **1m** have been deposited in the Cambridge Crystallographic Data Center: C₂₆H₂₂; fw = 334.46; monoclinic space group P2₁ (No. 4); $a = 10.0508(6)$, $b = 7.6936(5)$, $c = 11.861(1)$ Å; $b = 92.197(6)^\circ$; $V = 916.5(1)$ Å³; $R = 0.047$, $R_w = 0.055$ based on 1860 observed reflections.

(11) King, A. O.; Negishi, E.; Villani, F. J.; Silveira, A. *J. Org. Chem.* **1978**, 43, 358.

(12) For a general Experimental Section, see our recent paper: Takahashi, T.; Xi, Z.; Yamazaki, A.; Liu, Y.; Nakajima, K.; Kotora, M. *J. Am. Chem. Soc.* **1998**, 120, 1672–1680.

(13) (a) Newman, M. S.; Kaugars, G. *J. Org. Chem.* **1965**, 30, 3295. (b) Dodson, R. M.; Zielske, A. G. *J. Org. Chem.* **1967**, 32, 28. (c) McMurry, J. E.; Kees, K. L. *J. Org. Chem.* **1977**, 42, 2655.

Me₄Si) δ 138.74, 136.20, 128.29, 127.45, 126.06, 26.79. HRMS: calcd for C₁₆H₁₄, 206.1095; found, 206.1096.

1-Octyl-2-phenylcyclobutene (1g): ¹H NMR (CDCl₃, Me₄Si) δ 7.38–7.19 (m, 5H), 2.67–2.65 (m, 2H), 2.49–2.42 (m, 4H), 1.59–1.53 (m, 2H), 1.42–1.32 (m, 14H), 0.96–0.93 (t, *J* = 7 Hz, 3H); ¹³C NMR (CDCl₃, Me₄Si) δ 143.58, 137.04, 136.34, 128.22, 126.28, 125.54, 31.96, 30.13, 29.79, 29.67, 29.60, 29.38, 27.60, 27.30, 25.75, 22.72, 14.09. HRMS: calcd for C₂₀H₃₀, 270.2346; found, 270.2345.

1-Butyl-2-(1-naphthyl)cyclobutene (1h): ¹H NMR (CDCl₃, Me₄Si) δ 8.35–8.33 (d, *J* = 8 Hz, 1H), 7.95–7.83 (m, 2H), 7.59–7.52 (m, 4H), 3.07–3.06 (m, 2H), 2.73–2.71 (m, 2H), 2.37 (m, 2H), 1.62–1.45 (m, 4H), 1.03–0.99 (t, *J* = 7.5 Hz, 3H); ¹³C NMR (CDCl₃, Me₄Si) δ 145.65, 137.54, 134.56, 133.85, 131.23, 128.27, 126.99, 125.98, 125.54, 125.47, 125.32, 125.23, 30.18, 29.74, 29.46, 28.18, 22.74, 13.91. HRMS: calcd for C₁₈H₂₀, 236.1564; found, 236.1569.

7-Phenylbicyclo[4.2.0]oct-6(7)-ene (1i): ¹H NMR (CDCl₃, Me₄Si) δ 7.34–7.15 (m, 5H), 2.83–2.76 (m, 2H), 2.45–2.31 (m, 2H), 2.19–2.07 (m, 2H), 1.91–1.75 (m, 2H), 1.41–1.27 (m, 2H), 1.18–1.12 (m, 1H); ¹³C NMR (CDCl₃, Me₄Si) δ 146.65, 136.58, 131.83, 128.22, 126.20, 125.41, 37.66, 34.41, 33.20, 27.22, 26.78, 25.03. HRMS: calcd for C₁₄H₁₆, 184.1251; found, 184.1269.

1,3-Bis(2-phenylcyclobutenyl)butane (1j): ¹H NMR (CDCl₃, Me₄Si) δ 7.32–7.14 (m, 10H), 2.61–2.59 (m, 4H), 2.43–2.42 (m, 8H), 1.61–1.58 (m, 4H); ¹³C NMR (CDCl₃, Me₄Si) δ 143.21, 137.28, 136.23, 128.27, 126.36, 125.54, 29.92, 27.60, 27.28, 25.78. HRMS: calcd for C₂₄H₂₆, 314.2033; found, 314.2031.

1,4-Bis(2-phenylcyclobutenyl)pentane (1k): ¹H NMR (CDCl₃, Me₄Si) δ 7.45–7.11 (m, 10H), 2.57–2.13 (m, 10H), 1.69–1.29 (m, 8H); ¹³C NMR (CDCl₃, Me₄Si) δ 143.44, 137.13, 136.27, 128.27, 126.34, 125.54, 30.02, 29.77, 27.60, 27.15, 25.77. HRMS: calcd for C₂₅H₂₈, 328.2190; found, 328.2181.

1,4-Bis(2-butylcyclobutenyl)benzene (1l): ¹H NMR (CDCl₃, Me₄Si) δ 7.26 (m, 4H), 2.59–2.36 (m, 12H), 1.52–1.35 (m, 8H), 0.94–0.90 (t, *J* = 7.5 Hz, 6H); ¹³C NMR (CDCl₃, Me₄Si) δ 143.35, 136.96, 134.40, 125.47, 29.92, 29.49, 27.68, 25.73, 22.83, 13.99. HRMS: calcd for C₂₂H₃₀, 294.2346; found, 294.2355.

1,4-Bis(2-phenylcyclobutenyl)benzene (1m): mp 158.4–159.0 °C; ¹H NMR (CDCl₃, Me₄Si) δ 7.53–7.48 (m, 8H), 7.33–7.21 (m, 6H), 2.76 (s, 8H); ¹³C NMR (CDCl₃, Me₄Si) δ 138.98, 138.46, 136.27, 135.22, 128.30, 127.46, 126.13, 125.93, 26.89, 26.65. Anal. Calcd for C₂₆H₂₂: C, 93.37; H, 6.63. Found: C, 93.44; H, 6.64. HRMS: calcd for C₂₆H₂₂, 334.1720; found, 334.1717.

Synthesis of 1,2-Diphenyl-3-(hydroxydimethylsilyl)cyclobutene (1n). To a solution of Cp₂ZrCl₂ (701 mg, 2.4 mmol) in THF (10 mL) was added ethylmagnesium bromide (4.8 mmol, 4.706 mL, 1.02 mol/L THF solution) at –78 °C. After the solution was stirred for 1 h at –78 °C, diphenylacetylene (356 mg, 2.0 mmol) was added. And then the reaction mixture was warmed to 0 °C and stirred for 3 h. Then ethoxydimethylvinylsilane (4.0

mmol, 521 mg) was added and the mixture was stirred for 3 h at 50 °C. After this, iodine (2.4 mmol, 609 mg) was added at –78 °C and the mixture was warmed to room temperature and stirred for 1 h. Finally copper(I) chloride (2.4 mmol, 238 mg) was added and the mixture was stirred at 50 °C for 1 h. The reaction mixture was quenched with water and extracted with ether. The organic phase was washed with water, NaHCO₃ (20% aqueous solution), water, Na₂S₂O₃ (saturated aqueous solution), water, and brine, and dried over MgSO₄. Filtration, evaporation, and column chromatography on silica gel (1:1 hexane/Et₂O, v/v) afforded 349 mg (62%) of the desired compound (pale yellow oily substance): ¹H NMR (CDCl₃, Me₄Si) δ 7.58–7.49 (m, 4H), 7.37–7.21 (m, 6H), 2.92–2.87 (m, 1H), 2.81–2.79 (m, 1H), 2.71–2.67 (m, 1H); ¹³C NMR (CDCl₃, Me₄Si) δ 141.19, 136.88, 136.53, 135.90, 128.32 (2C), 128.26 (2C), 127.51, 127.14, 126.58 (2C), 125.54 (2C), 31.55, 27.59, –1.54, –1.85. HRMS: calcd for C₁₈H₂₀O_{Si}, 280.1282; found, 280.1286.

Representative Procedure for the Preparation of 1o—p: Synthesis of 1,1'-Bis(2-phenylcyclobutenyl)-4,4'-biphenyl (1o). To a THF solution of 1-(4-bromophenyl)-2-phenylcyclobutene (**1c**) (2.0 mmol), prepared and isolated as described above, was added *n*-BuLi (2 mmol), and the mixture was stirred at 0 °C for 1 h. After addition of flame-dried zinc chloride (3.0 mmol), to the reaction mixture was added 1-(4-bromophenyl)-2-phenylcyclobutene (**1c**) (2.0 mmol) and a catalytic amount of Pd(PPh₃)₄ (0.1 mmol) at room temperature.¹¹ After being heated to 50 °C and stirred for 6 h, the reaction mixture was quenched with 3 N HCl and extracted with Et₂O. The extract was washed with water, NaHCO₃ (20% aqueous solution), water, Na₂S₂O₃, water, and brine, and dried over MgSO₄. Filtration and evaporation provided a solid substance. Column chromatography on silica gel with hexane as the eluent afforded 592 mg (72% isolated yield, purity > 98%) of the desired compound: mp 180.5–182.5 °C (decomp); ¹H NMR (CDCl₃, Me₄Si) δ 7.61–7.23 (m, 18H), 2.81 (s, 8H); ¹³C NMR (CDCl₃, Me₄Si) δ 139.66, 139.12, 138.34, 136.27, 135.21, 128.35, 127.52, 126.72, 126.52, 126.14, 26.94, 26.78. HRMS: calcd for C₃₂H₂₆, 410.2033; found, 410.2044.

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Supporting Information Available: Text providing characterization data for **1b–d,p,q** and experimental details for the X-ray analysis of **1m**, an X-ray structure of **1m**, tables of crystallographic data, positional and thermal parameters, and bond lengths and angles for **1m**, and ¹H and ¹³C NMR spectra of **1a–q** (26 pages). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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