Cross-Coupling

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Palladium-Catalyzed Annulation of *vic*-Bis(pinacolatoboryl)alkenes and -phenanthrenes with 2,2′-Dibromobiaryls: Facile Synthesis of Functionalized Phenanthrenes and Dibenzo[*g*,*p*]chrysenes**

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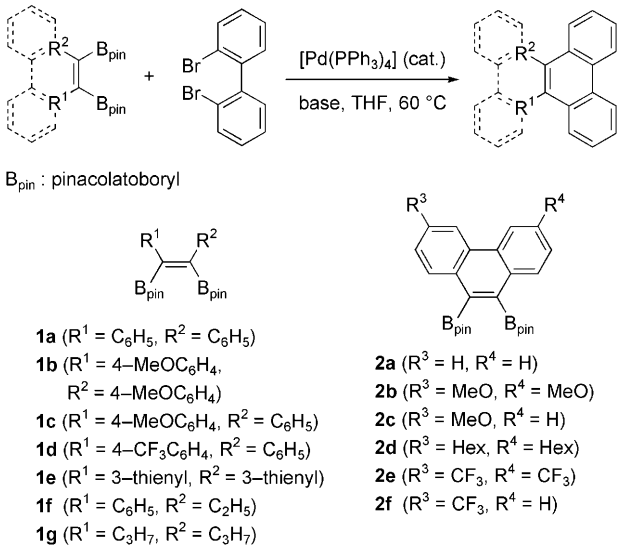
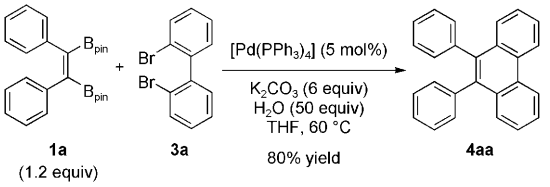
Because of the progress in organic electronics, such as light-emitting diodes, field-effect transistors, and solar cells, there has been extensive research on polycyclic aromatic hydrocarbons (PAHs).[1] Efficient syntheses of PAHs bearing the appropriate functional groups to control optical and electronic properties is important, and different structural motifs are essential for the exploration and improvement of materials derived from PAHs. Conventional synthetic methods for making functionalized PAHs include electrophilic or nucleophilic substitutions,[2] cross-coupling reactions,[3] and directed-metalation,[4] in which the introduction of the functional groups and the substitution patterns are strongly dependent on the reactivity of the parent PAHs framework. Alternatively, formation of the aromatic ring by transition-metal-catalyzed annulation of functionalized precursors provides a more flexible and versatile synthesis for functionalized PAHs by overcoming the drawbacks of the conventional synthetic approach.[5,6]

Since the cross-coupling reaction of organoboron compounds (Suzuki–Miyaura coupling) is useful for stereospecific C_{sp^2}–C_{sp^2} bond formation and is compatible with a broad range of functional groups,[7] we focused our attention on *vic*-diborylalkenes[8] as potential precursors for our annulation approach.[9] Various *vic*-diborylated alkenes have been converted into multisubstituted acyclic alkenes by stepwise cross-coupling reactions with two organic halides,[10] whereas the double cross-coupling reaction of *vic*-diborylated compounds with aromatic dihalides as a synthetic method for functionalized PAHs remains unexplored.[11–13] We report herein a palladium-catalyzed double cross-coupling reaction of *vic*-diborylated alkenes (**1**) and phenanthrenes (**2**) with 2,2′-dibromobiaryl compounds. The annulation provides a convenient synthesis of a variety of phenanthrenes and dibenzo[*g*,*p*]chrysenes, as well as dithienobenzenes and triphenyleno[1,2-*b*:4,3-*b*′]dithiophene, in good to excellent yields (Scheme 1).



Scheme 1. Palladium-catalyzed double cross-coupling reaction of *vic*-diborylated alkenes (**1**) and phenanthrenes (**2**) with 2,2′-dibromobiaryl compounds.

Initially, we chose (*Z*)-1,2-bis(pinacolatoboryl)stilbene (**1a**) as a model *vic*-diborylalkene and 2,2′-dibromobiphenyl (**3a**) as a coupling partner [Eq. (1)]. Initial attempts revealed



(1)

that protodeborylation of **1a** was a major side reaction, presumably resulting from the steric hindrance of both **1a** and **3a**. After screening various reaction conditions,[14] the desired 9,10-diphenylphenanthrene (**4aa**)[15] was isolated in 80% yield using $[Pd(PPh_3)_4]$ (5 mol%), K_2CO_3 (6 equiv), and H_2O (50 equiv) in THF at 60 °C for 24 hours. The presence of water was crucial for the reaction.[16] The optimized conditions were applicable to gram-scale preparation of the annulated rings,[17] and neither oligomers nor polymers were detected.

The scope of the annulation reaction leading to functionalized phenanthrenes (**4**) is summarized in Table 1. The

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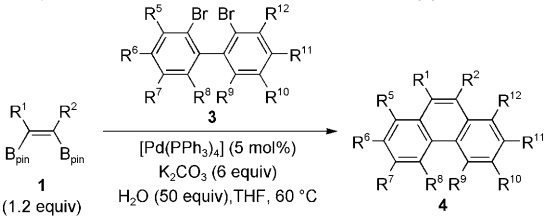
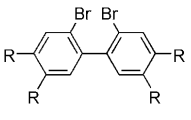
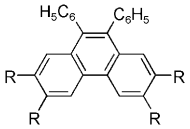
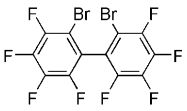
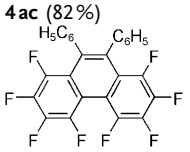
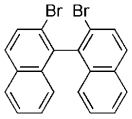
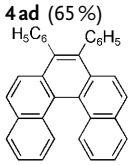
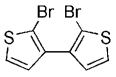
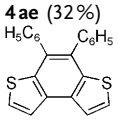
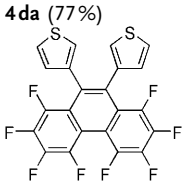
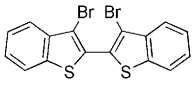
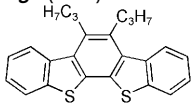
Table 1: Synthesis of functionalized phenanthrenes (**4**).[a]



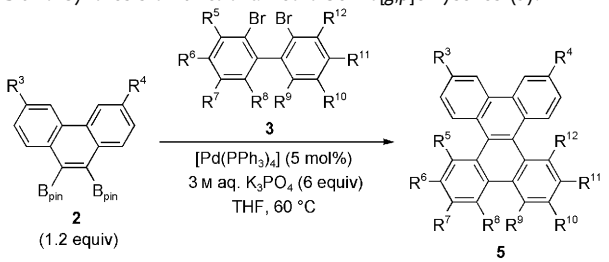
Entry	1	Dibromide 3	Product 4 (yield)[b]
			
1	**1a**	**3b** (R = Me)	**4ab** (85%)
2	**1a**	**3c** (R = OMe)	**4ac** (82%)
			
3	**1a**	**3d**	**4ad** (65%)
			
4	**1a**	**3e**	**4ae** (32%)
			
5	**1a**	**3f**	**4af** (84%)
6	**1b**	**3a**	**4ba** (92%)
7	**1b**	**3d**	**4bd** (85%)
8	**1c**	**3a**	**4ca** (81%)
9	**1d**	**3a**	**4da** (77%)
			
10	**1e**	**3d**	**4ed** (90%)
11[c]	**1f**	**3a**	**4fa** (99%)
12[d]	**1g**	**3a**	**4ga** (81%)
			
13[e]	**1g**	**3g**	**4gg** (57%)

[a] Reaction conditions: **1** (1.2 mmol), **3** (1.0 mmol), $[Pd(PPh_3)_4]$ (58 mg, 0.05 mmol), and K_2CO_3 (0.83 g, 6.0 mmol), H_2O (0.90 mL, 50 mmol), THF (20 mL), 60 °C, 48 h. [b] Yield of the isolated product. [c] 3 M aq K_3PO_4 (6 equiv) was used in place of K_2CO_3/H_2O. [d] 3 M aq NaOH (6 equiv) was used in place of K_2CO_3/H_2O. [e] $[PdCl_2(dppf)]$ (5 mol%) and 3 M aq K_3PO_4 (6 equiv) was used in place of $[Pd(PPh_3)_4]$ and K_2CO_3/H_2O, respectively. dppf = 1,1′-bis(diphenylphosphanyl)ferrocene.

tetramethyl- and tetramethoxy-substituted dibromobiphenyls **3b** and **3c** were coupled with **1a** to give **4ab** and **4ac**, respectively, in high yields (Table 1, entries 1 and 2). The reaction of 2,2′-dibromooctafluorobiphenyl (**3d**) with **1a** also proceeded smoothly under the optimized reaction conditions to produce octafluorinated phenanthrene **4ad** in 65% yield (Table 1, entry 3). When 2,2′-dibromobinaphthyl (**3e**) and bithiophene **3f** were used with **1a**, [5]helicene **4ae** and dithieno[l,2-6:4,3-6′]benzene **4af** were obtained, respectively (Table 1, entries 4 and 5). Substituted diborylstilbenes **1b–d** also underwent the annulation to give both symmetrical and unsymmetrical phenanthrenes **4ba**, **4bd**, **4ca**, and **4da** in high yields (Table 1, entries 6–9). Additionally, diboryldithienylethene **1e**, 1,2-diboryl-1-phenylbut-1-ene **1f**, and 4,5-diboryloct-4-ene **1g** reacted with **3** to give annulated products **4ed**, **4fa**, **4ga**, and **4gg** (Table 1, entries 10–13); a slight modification to the reaction conditions was necessary in cases of **1f** and **1g**.[18]

Next we examined the annulation of *vic*-diborylated arenes such as **2**, which were readily prepared by photocyclization of **1** and subsequent in situ oxidation.[14] By using the optimized conditions determined for the annulation of **1**, the reaction of **2a** with **3a** gave dibenzo[*g*,*p*]chrysene **5aa** in 68% yield. After re-screening the reaction conditions, 3 M aq. K_3PO_4 was found to be the best base for this system, producing **5aa** in a quantitative yield. The scope of the annulation reaction leading to functionalized dibenzo[*g*,*p*]chrysenes (**5**) is summarized in Table 2. Various dibenzo[*g*,*p*]chrysenes (**5**) substituted with electron-donating and electron-withdrawing groups are not easily accessible by previous methods,[19] but they were isolated in moderate to good yields by using our annulation chemistry. Notably, fluorinated dibenzo[*g*,*p*]chrysenes **5ad**, **5bd**, **5cd**, **5dd**, and **5fd** were generally produced in high to excellent yields (Table 2, entries 3, 6, 8, 9, and 11). The annulation was also

Table 2: Synthesis of functionalized dibenzo[*g*,*p*]chrysenes (**5**).[a]

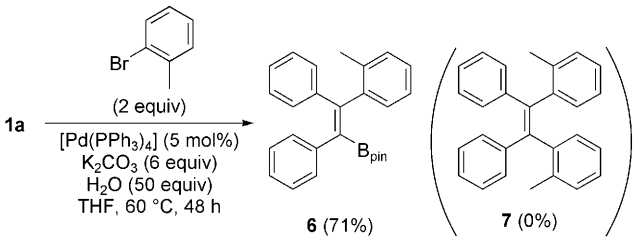


Entry	2	3	5	Yield [%][b]
1	**2a**	**3a**	**5aa**	>99
2[c]	**2a**	**3c**	**5ac**	54
3	**2a**	**3d**	**5ad**	63
4	**2a**	**3f**	**5af**	88
5	**2b**	**3a**	**5ba**	64
6	**2b**	**3d**	**5bd**	94
7	**2c**	**3a**	**5ca**	61
8	**2c**	**3d**	**5cd**	80
9	**2d**	**3d**	**5dd**	82
10	**2e**	**3c**	**5ec**	40
11[d]	**2f**	**3d**	**5fd**	96

[a] Reaction conditions: **2** (0.06 mmol), **3** (0.05 mmol), $[Pd(PPh_3)_4]$ (2.9 mg, 2.5 μmol), and 3 M aq K_3PO_4 (0.1 mL, 0.3 mmol), THF (1.0 mL), 60 °C, 48 h. [b] Yield of isolated product. [c] 12 M aq K_3PO_4 (0.6 mmol) was used at 80 °C. [d] K_2CO_3 (0.3 mmol) and H_2O (2.5 mmol) were used.

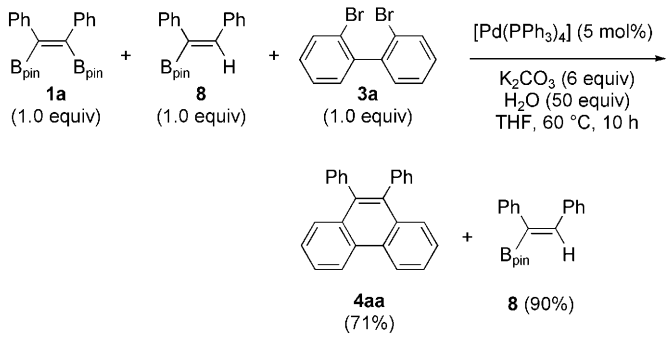
applicable to the preparation of triphenyleno[1,2-*b*:4,3-*b*′]-dithiophene (**5af**; Table 2, entry 4).

To gain mechanistic insight into the annulation reaction, we carried out the reaction of **1a** with *o*-bromotoluene (2 equiv) under the optimized conditions (Scheme 2). The only product obtained was the singly coupled product (**6**) in 71% yield; the doubly coupled product (**7**) was not observed. This result indicated that an second intermolecular transmetalation for the coupling of a second equivalent of *ortho*-substituted bromobenzene with **1a** was unfavorable. Accordingly, the use of 2,2′-dibromobiaryl compounds as the coupling partner is crucial for the success of the annulation, as it suppresses oligomerization/polymerization.



Scheme 2. Coupling reaction of **1a** with *o*-bromotoluene.

Additionally, the coupling reaction of **1a** with **3a** (1 equiv) was effected in the presence of one equivalent of pinacolatoboryl-1,2-diphenylethene (**8**) as illustrated in Scheme 3. Interestingly, **4aa** was the sole coupling product isolated



Scheme 3. Comparison of reactivity between **1a** and **8**.

in 71% yield with 90% recovery of **8**, indicating that *vic*-diborylethene was much more reactive than a monoborylethene under the reaction conditions.[20] The higher reactivity of the *vic*-diborylated compound may play a key role in overcoming the intrinsic difficulty in the coupling reactions of sterically hindered halides with boron reagents.

In summary, we have demonstrated that the palladium-catalyzed double cross-coupling reaction of *vic*-diborylated compounds with 2,2′-dibromobiaryls provides a new annulation approach to functionalized PAHs. This methodology efficiently provides functionalized phenanthrenes and dibenzo[*g*,*p*]chrysenes, which have attracted attention in recent years as modules for the development of π-conjugated materials such as luminescent polymers, thin-field effect transistors, and molecular wires.[21] Helicene and thiophene-fused PAHs can also be synthesized easily. The results herein shed new light on the synthetic utility of *vic*-diborylated compounds in organic synthesis. The extension of the use of dihalides and diboron reagents for annulation reactions are in progress in our laboratory.

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[1] Reviews on PAHs for organic electronics: a) J. Wu, W. Pisula, K. Müllen, *Chem. Rev.* **2007**, *107*, 718–747; b) A. R. Murphy, J. M. J. Fréchet, *Chem. Rev.* **2007**, *107*, 1066–1096; c) A. C. Grimsdale, K. Müllen, *Macromol. Rapid Commun.* **2007**, *28*, 1676–1702; d) S. Sergeyev, W. Pisula, Y. H. Geerts, *Chem. Soc. Rev.* **2007**, *36*, 1902–1929; e) J. E. Anthony, *Chem. Rev.* **2006**, *106*, 5028–5048; f) M. Bendikov, F. Wudl, D. F. Perepichka, *Chem. Rev.* **2004**, *104*, 4891–4945; g) M. D. Watson, A. Fechtenkötter, K. Müllen, *Chem. Rev.* **2001**, *101*, 1267–1300; h) A. J. Berresheim, M. Muller, K. Müllen, *Chem. Rev.* **1999**, *99*, 1747–1786.

[2] M. B. Smith, J. March in *Advanced Organic Chemistry*, 5th ed., Wiley, New York, **2001**, pp. 675–758 and pp. 850–893.

[3] a) *Metal-catalyzed Cross-coupling Reactions* (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, **1998**; b) *Cross-Coupling Reaction: A Practical Guide*, *Vol. 219* (Ed.: N. Miyaura), Springer, Berlin, **2002**; c) *Metal-Catalyzed Cross-Coupling Reactions* (Eds.: A. de Meijere, F. Diederich), Wiley-VCH, Weinheim, **2004**.

[4] a) V. Snieckus, *Chem. Rev.* **1990**, *90*, 879–933; b) C. G. Hartung, V. Snieckus in *Modern Arene Chemistry* (Ed.: D. Astruc), Wiley-VCH, Weinheim, **2002**, pp. 330–367; c) R. E. Mulvey, F. Mongin, M. Uchiyama, Y. Kondo, *Angew. Chem.* **2007**, *119*, 3876–3899; *Angew. Chem. Int. Ed.* **2007**, *46*, 3802–3824.

[5] a) R. C. Larock, *J. Organomet. Chem.* **1999**, *576*, 111–124; b) S. Saito, Y. Yamamoto, *Chem. Rev.* **2000**, *100*, 2901–2915; c) J. Tsuji in *Palladium Reagents and Catalysts*, 2nd ed., Wiley, Chichester, **2004**, pp. 231–265; d) R. C. Larock in *Palladium in Organic Synthesis* (Ed.: J. Tsuji), Springer, Berlin, **2005**, pp. 147–182.

[6] Review on functionalized organometallics: *Handbook of Functionalized Organometallics* (Ed.: P. Knochel), Wiley-VCH, Weinheim, **2005**.

[7] Reviews on the Suzuki–Miyaura coupling reaction: a) N. Miyaura, A. Suzuki, *Chem. Rev.* **1995**, *95*, 2457–2483; b) A. Suzuki in *Metal-catalyzed Cross-coupling Reactions* (Eds.: F. Diederich, P. J. Stang), Wiley-VCH, Weinheim, **1998**, pp. 49–97; c) N. Miyaura in *Cross-Coupling Reaction: A Practical Guide*, *Vol. 219* (Ed.: N. Miyaura), Springer, Berlin, **2002**, pp. 11–59; d) N. Miyaura in *Metal-Catalyzed Cross-Coupling Reactions*, *Vol. 1* (Eds.: A. d. Meijere, F. Diederich), Wiley-VCH, Weinheim, **2004**, pp. 41–123.

[8] *vic*-Diborylalkenes are readily available by transition-metal-catalyzed 1,2-diboration of alkynes with diboron reagents. Reviews: a) T. B. Marder, N. C. Norman, *Top. Catal.* **1998**, *5*, 63–73; b) T. Ishiyama, N. Miyaura, *J. Organomet. Chem.* **2000**, *611*, 392–402; c) T. Ishiyama, N. Miyaura, *Chem. Rec.* **2004**, *3*, 271–280; d) H. E. Burks, J. P. Morken, *Chem. Commun.* **2007**, 4717–4725.

[9] Reviews on *vic*-diorganometallics: a) I. Beletskaya, C. Moberg, *Chem. Rev.* **1999**, *99*, 3435–3461; b) L.-B. Han, M. Tanaka, *Chem. Commun.* **1999**, 395–402; c) M. Suginome, Y. Ito, *Chem.*

Rev. **2000**, *100*, 3221 – 3256; d) I. Beletskaya, C. Moberg, *Chem. Rev.* **2006**, *106*, 2320 – 2354; e) M. Suginome, T. Matsuda, T. Ohmura, A. Seki, M. Murakami in *Comprehensive Organometallic Chemistry III* (Eds.: H. C. Robert, D. M. P. Mingos), Elsevier, Oxford, **2007**, pp. 725 – 787.

[10] Preparation of tri- and tetra-substituted ethenes using *vic*-diborylethenes: a) T. Ishiyama, N. Matsuda, N. Miyaura, A. Suzuki, *J. Am. Chem. Soc.* **1993**, *115*, 11018 – 11019; b) T. Ishiyama, M. Yamamoto, N. Miyaura, *Chem. Lett.* **1996**, 1117 – 1118; c) S. D. Brown, R. W. Armstrong, *J. Am. Chem. Soc.* **1996**, *118*, 6331 – 6332; d) S. D. Brown, R. W. Armstrong, *J. Org. Chem.* **1997**, *62*, 7076 – 7077; e) C. Baldoli, A. Bossi, C. Giannini, E. Licandro, S. Maiorana, D. Perdicchia, M. Schiavo, *Synlett* **2005**, 1137 – 1141. Diborylbenzenes are reportedly utilized as versatile precursors of functionalized terphenyls: f) H. Noguchi, T. Shioda, C. M. Chou, M. Suginome, *Org. Lett.* **2008**, *10*, 377 – 380; g) M. Shimizu, K. Shimono, T. Kurahashi, S.-i. Kiyomoto, I. Nagao, T. Hiyama, *Bull. Chem. Soc. Jpn.* **2008**, *81*, 518 – 520.

[11] Reviews on polyborylated reagents in organic synthesis: a) V. M. Dembitsky, H. A. Ali, M. Srebnik, *Appl. Organomet. Chem.* **2003**, *17*, 327 – 345; b) M. Shimizu, T. Hiyama, *Proc. Jpn. Acad. Ser. B* **2008**, *84*, 75 – 85.

[12] Such PAHs as benzo[*s*]picenes and thia[7]helicenes were prepared by two-step procedure involving double cross-coupling reaction of diborylated compounds and subsequent cyclization: a) F. J. Zhang, C. Cortez, R. G. Harvey, *J. Org. Chem.* **2000**, *65*, 3952 – 3960; b) Reference [10e]. Triphenylene synthesis by double-cross coupling reaction of 2,2′-diborylbiphenyl and 1,2-dibromobenzene was reported although the yields and the details of the conditions were not described: c) J. W. Goodby, M. Hird, K. J. Toyne, T. Watson, *J. Chem. Soc. Chem. Commun.* **1994**, 1701 – 1702.

[13] Copper-mediated coupling of zirconacyclopentadienes with dihalo aromatic compounds has been developed as a versatile synthetic method for fused aromatic rings: a) T. Takahashi, R. Hara, Y. Nishihara, M. Kotora, *J. Am. Chem. Soc.* **1996**, *118*, 5154 – 5155; b) T. Takahashi, Y. Li, P. Stepnicka, M. Kitamura, Y. Liu, K. Nakajima, M. Kotora, *J. Am. Chem. Soc.* **2002**, *124*, 576 – 582. See also, c) C. L. Hilton, C. R. Jamison, B. T. King, *J. Am. Chem. Soc.* **2006**, *128*, 14824; d) K. I. Kanno, Y. Liu, A. Iesato, K. Nakajima, T. Takahashi, *Org. Lett.* **2005**, *7*, 5453 – 5456.

[14] See the Supporting Information.

[15] Palladium-catalyzed domino reaction of iodobenzenes with diarylacetylenes leading to 9,10-diarylphenanthrenes was reported: G. Dyker, A. Kellner, *Tetrahedron Lett.* **1994**, *35*, 7633 – 7636.

[16] The accelerating effect of H_2O in coupling reactions of organoboron compounds has been observed: a) N. Miyaura, *Top. Curr. Chem.* **2002**, *219*, 20 – 23; b) C. R. Johnson, M. P. Braun, *J. Am. Chem. Soc.* **1993**, *115*, 11014 – 11015; c) C. Zhou, D. E. Emrich, R. C. Larock, *Org. Lett.* **2003**, *5*, 1579 – 1582; d) X. Liu, M. Shimizu, T. Hiyama, *Angew. Chem.* **2004**, *116*, 897 – 900; *Angew. Chem. Int. Ed.* **2004**, *43*, 879 – 882; e) T. E. Barder, S. D. Walker, J. R. Martinelli, S. L. Buchwald, *J. Am. Chem. Soc.* **2005**, *127*, 4685 – 4696; f) C. Zhou, R. C. Larock, *J. Org. Chem.* **2005**, *70*, 3765 – 3777.

[17] Reaction conditions: **1a** (2.16 g, 6 mmol), **3a** (1.56 g, 5 mmol), $[Pd(PPh_3)_4]$ (0.30 g, 0.25 mmol), and K_2CO_3 (4.10 g, 30 mmol), H_2O (4.5 mL, 250 mmol), THF (100 mL), 60 °C, 48 h; **4aa** (1.35 g, 82 % yield).

[18] Previous syntheses of dithienobenzenes: a) H. Watanabe, J. Kumagai, H. Tsurugi, T. Satoh, M. Miura, *Chem. Lett.* **2007**, *36*, 1336 – 1337; b) K. Imamura, D. Hirayama, H. Yoshimura, K. Takimiya, A. Yoshio, T. Otsubo, *Tetrahedron Lett.* **1999**, *40*, 2789 – 2792; c) U. Dahlmann, R. Neidlein, *Helv. Chim. Acta* **1997**, *80*, 111 – 120; d) S. Yoshida, M. Fujii, Y. Aso, T. Otsubo, F. Ogura, *J. Org. Chem.* **1994**, *59*, 3077 – 3081; e) W. J. Archer, R. Cook, R. Taylor, *J. Chem. Soc. Perkin Trans. 2* **1983**, 813 – 819. Triphenyleno[1,2-*b*:4,3-*b*′]dithiophene: f) E. Fischer, J. Larsen, J. B. Christensen, M. Fourmigue, H. G. Madsen, N. Harrit, *J. Org. Chem.* **1996**, *61*, 6997 – 7005.

[19] a) E. Clar, J. F. Guye-Vuilleme, J. F. Stephen, *Tetrahedron* **1964**, *20*, 2107 – 2117; b) K. Suzuki, M. Fujimoto, M. Murakami, M. Minabe, *Bull. Chem. Soc. Jpn.* **1967**, *40*, 1259 – 1261; c) S. K. Talapatra, S. Chakrabarti, A. K. Mallik, B. Talapatra, *Tetrahedron* **1990**, *46*, 6047 – 6052; d) D. A. Klumpp, D. N. Baek, G. K. S. Prakash, G. A. Olah, *J. Org. Chem.* **1997**, *62*, 6666 – 6671; e) S. Yamaguchi, T. M. Swager, *J. Am. Chem. Soc.* **2001**, *123*, 12087 – 12088; f) C. W. Li, C. I. Wang, H. Y. Liao, R. Chaudhuri, R. S. Liu, *J. Org. Chem.* **2007**, *72*, 9203 – 9207.

[20] The reason for the higher reactivity of **1a** is unclear at present. Considering that *ortho*-bis(4,5-diphenyl-1,3-dioxa-2-borolane-2-yl)benzene was reported to form a bis(borate)complex with benzylamine, in which two dioxaborolane groups are coordinated with two amine molecules cooperatively, the bis(borate)complex of *vic*-diborylethene with a base may be generated as highly reactive species: a) K. Nozaki, M. Yoshida, H. Takaya, *Bull. Chem. Soc. Jpn.* **1996**, *69*, 2043 – 2052; b) K. Nozaki, M. Yoshida, H. Takaya, *Angew. Chem.* **1994**, *106*, 2574 – 2576; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2452 – 2454. See also: c) W. E. Piers, G. J. Irvine, V. C. Williams, *Eur. J. Inorg. Chem.* **2000**, 2131 – 2142; d) F. P. Gabbaï, *Angew. Chem.* **2003**, *115*, 2318 – 2321; *Angew. Chem. Int. Ed.* **2003**, *42*, 2218 – 2221.

[21] a) H. Tian, J. Wang, J. Shi, D. Yan, L. Wang, Y. Geng, F. Wang, *J. Mater. Chem.* **2005**, *15*, 3026 – 3033; b) H. Suh, Y. Jin, S. H. Park, D. Kim, J. Kim, C. Kim, J. Y. Kim, K. Lee, *Macromolecules* **2005**, *38*, 6285 – 6289; c) H. Tian, J. Shi, S. Dong, D. Yan, L. Wang, Y. Geng, F. Wang, *Chem. Commun.* **2006**, 3498 – 3500; d) C. Yang, H. Scheiber, E. J. W. List, J. Jacob, K. Müllen, *Macromolecules* **2006**, *39*, 5213 – 5221; e) B. N. Boden, K. J. Jardine, A. C. W. Leung, M. J. MacLachlan, *Org. Lett.* **2006**, *8*, 1855 – 1858; f) S. H. Park, Y. Jin, J. Y. Kim, S. H. Kim, J. Kim, H. Suh, K. Lee, *Adv. Funct. Mater.* **2007**, *17*, 3063 – 3068; g) R. Grisorio, G. P. Suranna, P. Mastrorilli, C. F. Nobile, *Org. Lett.* **2007**, *9*, 3149 – 3152; h) S. Song, Y. Jin, K. Kim, S. H. Kim, Y. B. Shim, K. Lee, H. Suh, *Tetrahedron Lett.* **2008**, *49*, 3582 – 3587; i) B. He, H. Tian, Y. Geng, F. Wang, K. Müllen, *Org. Lett.* **2008**, *10*, 773 – 776; j) Reference [19e].

