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Improved Synthesis of Aryl-Substituted Anthracenes and Heteroacenes

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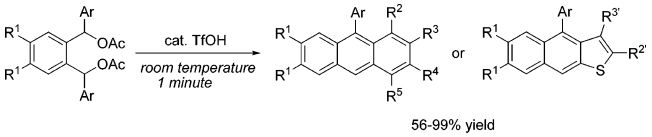

A Brønsted acid-catalyzed highly efficient construction of substituted arylanthracenes and heteroacenes is described, which is assumed to be initiated through the facile formation of a benzylic cation intermediate. This method offers several advantages in comparison with known aromatic cyclodehydration reactions such as high selectivities, mild reaction conditions, and easily accessible starting materials.

Anthracene and its derivatives are one of the most important classes of polycyclic aromatic compounds.[1] Due to their unique electronic and photonic properties, they have been proved extremely versatile in material science such as in organic field effect transistors (OTFT),[2] organic light-emitting diodes (OLED),[3] sensors in biological and supramolecular systems,[4] organic gellators,[5] etc. For example, 9,10-di-2-naphthylanthracene[3f] and 9,10-di(triisopropylsilyl)ethynylanthracene[3g] have been used successfully as blue emitters with efficient electroluminescene. Furthermore, anthracenes possess efficient photochromic properties that can find a variety of applications in data storage or molecular switches.[6] Substituted anthracenes have been prepared by Friedel−Crafts reaction,[7] aromatic cyclodehydration,[8] E1bs reaction,[9] Lewis acid-induced Bradsher-type reaction from diarylmethanes,[10] homologation mediated by metallacycles,[11] and so on. Nevertheless, enhancing the efficiency of the synthesis of these compounds that allow selective formation of anthracenes from readily available precursors is still highly attractive. In 1966, Miller reported that various substituted anthracenes could be obtained by acids-promoted transannular cyclodehydration of 1,2-bis(α-hydroxy-substituted-benzyl)benzenes (prepared by reduction of 1,2-diaroylbenzene).[12] However, the reaction generally required high reaction temperatures and large amounts of strong Brønsted acids, and it was noncatalytic. The preparation of starting 1,2-diaroylaromatics also presented difficulty. It was demonstrated that in the reaction, the undesired phthalan formation still remained a problem.[12,13] On the basis of our recent work,[14] we found that anthracenes could be constructed selectively by a TfOH-catalyzed cyclization reaction. Herein, we described a highly efficient and a mild, one-pot procedure by a Brønsted acid-catalyzed intramolecular Friedel−Crafts reaction/aromatization to substituted arylanthracenes and heteroacenes (Scheme 1). The yield of this process ranged from 56% to 99% and the side product of the phthalan derivative was below 10% in most cases.

The requisite substrates of aromatic diols and its ester derivatives could be easily prepared in generally good to high yields as a diastereomeric mixture through Grignard addition to phthalaldehyde.[15] In view of the highly catalytic activity in our work on TfOH-catalyzed reactions,[14] we first examined the

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(1) (a) Becker, H. -D. *Chem. Rev.* **1993**, *93*, 145. (b) Desvergne, J.-P.; Fages, F.; Bouas-Laurent, H.; Marsau, P. *Pure Appl. Chem.* **1992**, *64*, 1231. (c) Bouas-Laurent, H.; Castellan, A.; Desvergne, J.-P. *Pure Appl. Chem.* **1980**, *52*, 2633.

(2) (a) Anthony, J. E. *Chem. Rev.* **2006**, *106*, 5028. (b) Ito, K.; Suzuki, T.; Sakamoto, Y.; Kubota, D.; Inoue, Y.; Sato, F.; Tokito, S. *Angew. Chem., Int. Ed.* **2003**, *42*, 1159. (c) Ando, S.; Nishida, J.-I.; Fujiwara, E.; Tada, H.; Inoue, Y.; Tokito, S.; Yamashita, Y. *Chem. Mater.* **2005**, *17*, 1261. (d) Meng, H.; Sun, F.; Goldfinger, M. B.; Jaycox, G. D.; Li, Z.; Marshall, W. J.; Blackman, G. S. *J. Am. Chem. Soc.* **2005**, *127*, 2406.

(3) (a) Shi, J.; Tang, C. W. *Appl. Phys. Lett.* **2002**, *80*, 3201. (b) Kim, Y.-H.; Shin, D.-C.; Kim, S.-H.; Ko, C.-H.; Yu, H.-S.; Chae, Y.-S.; Kwon, S.-K. *Adv. Mater.* **2001**, *13*, 1690. (c) Zhang, Z. L.; Jiang, X. Y.; Zhu, W. Q.; Zheng, X. Y.; Wu, Y. Z.; Xu, S. H. *Synth. Met.* **2003**, *137*, 1141. (d) Zhang, X. H.; Liu, M. W.; Wong, O. Y.; Lee, C. S.; Kwong, H. L.; Lee, S. T.; Wu, S. K. *Chem. Phys. Lett.* **2003**, *369*, 478. (e) Liu, T.-H.; Shen, W.-J.; Yen, C.-K.; Iou, C.-Y.; Chen, H.-H.; Banumathy, B.; Chen, C. H. *Synth. Met.* **2003**, *137*, 1033. (f) Shi, J.; Tang, C. W. *Appl. Phys. Lett.* **2002**, *80*, 3201. (g) Landis, C. A.; Parkin, S. R.; Anthony, J. E. *Jpn. J. Appl. Phys.* **2005**, *44*, 3921. (h) Duong, H. M.; Bendikov, M.; Steiger, D.; Zhang, Q.; Sonmez, G.; Yamada, J.; Wudl, F. *Org. Lett.* **2003**, *5*, 4433. (i) Xu, Q.; Duong, H. M.; Wudl, F.; Yang, Y. *Appl. Phys. Lett.* **2004**, *85*, 3357. (j) Mondal, R.; Shah, B. K.; Neckers, D. C. *J. Org. Chem.* **2006**, *71*, 4085.

(4) (a) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev.* **1997**, *97*, 1515. (b) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; McCoy, C. P.; Maxwell, P. R. S.; Rademacher, J. T.; Rice, T. E. *Pure Appl. Chem.* **1996**, *68*, 1443.

(5) (a) Brotin, T.; Utermohlen, R.; Fages, F.; Bouaslaurent, H.; Desvergne, J. P. *J. Chem. Soc., Chem. Commun.* **1991**, *6*, 416. (b) Placin, F.; Desvergne, J. P.; Belin, C.; Buffeteau, T.; Desbat, B.; Ducasse, L.; Lassegues, J. C. *Langmuir* **2003**, *19*, 4563.

(6) (a) Bouas-Laurent, H.; Desvergne, J.-P. In *Photochromism, Molecules and Systems*; Dürr, H., Bouas-Laurent, H., Eds.; Elsevier: Amsterdam, The Netherlands, 1990, pp 561−630. (b) Bouas-Laurent, H.; Castellan, A.; Desvergne, J.-P.; Lapouyade, R. *Chem. Soc. Rev.* **2000**, *29*, 43.

(7) Barclay, L. R. C. In *Friedel-Crafts and Related Reactions*; Olah, G. A., Ed.; Interscience: New York, 1964; Vol. 2, Chapter 22.

(8) Bradsher, C. K. *Chem. Rev.* **1946**, *38*, 447.

(9) Fieser, L. F. *Org. React.* **1942**, *1*, 129.

(10) (a) Yamato, T.; Sakaue, N.; Shinoda, N.; Matsuo, K. *J. Chem. Soc., Perkin Trans. 1* **1997**, 1193. (b) Ahmed, M.; Ashby, J.; Ayad, M.; Meth-Cohn, O. *J. Chem. Soc., Perkin Trans. 1* **1973**, 1099.

(11) (a) Takahashi, T.; Kitamura, M.; Shen, B.; Nakajima, K. *J. Am. Chem. Soc.* **2000**, *122*, 12876. (b) Takahashi, T.; Li, S.; Huang, W.; Kong, F.; Nakajima, K.; Shen, B.; Ohe, T.; Kanno, K. *J. Org. Chem.* **2006**, *71*, 7967.

(12) (a) Miller, J. B. *J. Org. Chem.* **1966**, *31*, 4082. See also: (b) Guyot, A.; Catel, J. *Bull. Soc. Chim. France* **1906**, *35*, 1121. (c) Guyot, A.; Catel, J. *Bull. Soc. Chim. France* **1906**, *35*, 567.

(13) We did not find the related work after this study.

(14) Zhou, S.; Li, G.; Liu, Y.; Wang, P. Submitted for publication.

(15) See the Supporting Information.

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SCHEME 1

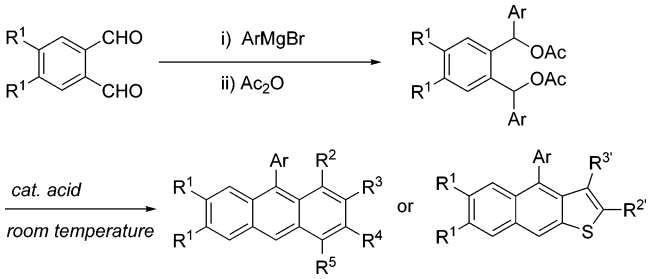
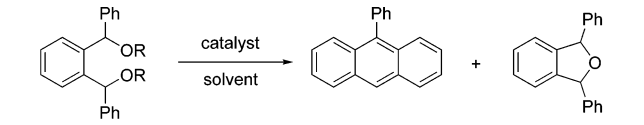


TABLE 1. Optimization Studies for the Brønsted or Lewis Acid-catalyzed Cyclization Reactions



entry	substrate	catalyst	solvent	temp / time	yield (%)[a,b]	ratio of **3a** / **4a**[c]
1	**1a**	10% TfOH	CH_2Cl_2	rt / 1 min	>99[d]	<1:99
2	**1a**	10% TfOH	$ClCH_2CH_2Cl$	80 °C / 5 h	>99	96:4
3	**1a**	20% TsOH·H_2O	$ClCH_2CH_2Cl$	80 °C / 30 h	79	<1:99
4	**1a**	20% CF_3COOH	$ClCH_2CH_2Cl$	80 °C / 30 h	50	<1:99
5	**1a**	20% H_2SO_4	$ClCH_2CH_2Cl$	80 °C / 24 h	94	52:48
6	**1a**	100% HBr	$ClCH_2CH_2Cl$	80 °C / 24 h	52	10:90
7	**1a**	4% $AuCl(PPh_3)$ 4% AgOTf	$ClCH_2CH_2Cl$	80 °C / 24 h	86	<1:99
8	**2a**	10% TfOH	CH_2Cl_2	rt / 1 min	>99	90:10
9	**2a**	5% TfOH	CH_2Cl_2	rt / 1 min	>99	83:17
10	**2a**	20% TfOH	CH_2Cl_2	rt / 1 min	>99	94:6
11	**2a**	20% TsOH·H_2O	CH_2Cl_2	rt/ 24 h	58	69:31
12	**2a**	20% H_2SO_4	CH_2Cl_2	rt / 0.5 h	80	63:37
13	**2a**	100% HBr	CH_2Cl_2	rt / 6 h	78	74:26
14	**2a**	50% AcOH	CH_2Cl_2	rt / 24 h	NR[e]	
15	**2a**	20% CF_3COOH	CH_2Cl_2	rt / 24 h	NR[e]	

[a] Reactions were conducted with 0.1 M substrate in CH_2Cl_2 or $Cl(CH_2)_2Cl$. [b] Combined yield, which was determined by ^1H NMR of the crude reaction mixture. [c] Determined by NMR. [d] **4a** was isolated in 73% yield. [e] NR = no reaction.

cyclization of diol **1** in the presence of TfOH (Table 1). Treatment of **1a** with 10% TfOH in CH_2Cl_2 at room temperature for 1 min resulted in the formation of phthalan 1,3-diphenyl-1,3-dihydroisobenzofuran **4a** as a sole product in >99% NMR yield (Table 1, entry 1). Anthracene **3a** was not detected even after a prolonged reaction time of 12 h. According to Miller's report, it was suggested that phthalan was the kinetically controlled product, while the anthracene was the thermodynamically controlled product.[12] We then investigated the reaction under higher temperatures. To our delight, the reaction occurred smoothly at 80 °C for 5 h to afford 9-phenylanthracene **3a** and phthalan **4a** in >99% combined yield with high selectivity (**3a**/**4a** = 96:4) (Table 1, entry 2). Other Brønsted acids such as TsOH·H_2O, CF_3CO_2H, H_2SO_4, or HBr were also examined, and they either gave low selectivity or afforded phthalan as a main product (Table 1, entries 3−6). Employment of cationic gold complexes $AuCl(PPh_3)$/AgOTf afforded only phthlan **4a** in 86% yield (Table 1, entry 7). We next envisioned that a catalytic cycle could be readily initiated through the formation of benzylic cation by using diester **2**. Thus diacetate **2a** was prepared to test the hypothesis. It turned out that **2a** cyclized smoothly at room temperature in the presence of 10% TfOH to give **3a** and **4a** in >99% combined yield with the ratio of 90:10 within 1 min (Table 1, entry 8). This is in contrast to the above result of diol **1a**, in which the kinetic product of phthlan was obtained predominantly. Decreasing or increasing the catalyst loading did not improve the selectivities significantly. The use of TsOH·H_2O, H_2SO_4, or HBr could afford some conversions at room temperature, however, with lower selectivities (Table 1, entries 11−13). According to the results in Table 1, entries 2 (method A) and 8 (method B) seem to be the best conditions. However, attempts to perform the analogous reaction with method A of the diols bearing substituents on the aromatic ring such as 1,2-phenylenebis(*p*-tolylmethanol) **1b** resulted in an inseparable mixture of two isomers with a combined yield of 94% (the ratio of the two isomers is 1:1), one of which was confirmed to be the desired 2-methyl-9-aryl-substituted anthracene **3b**, and the other was suggested to be an alkyl-group migration product[16] derived from **3b** since the migration of alkyl groups under Friedel−Crafts conditions has been observed previously.[17] We then chose method B with milder conditions for subsequent experiments.

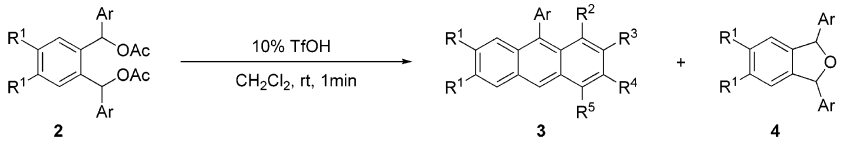
The cyclization reaction was successfully extended to various diacetates and good to high yields were realized for all cases (Table 2). The functionalities of Me, MeO, and ^{t}Bu groups on the aromatic ring were well tolerated during the reaction, furnishing the corresponding products **3b**−**g** in 74−99% yields with high selectivities (**3**/**4** ≥ 93:7, Table 2, entries 1−6). No side reaction of alkyl group migrations was observed. It should be noted that the selectivity of **3** vs **4** was influenced by the electronic nature of the aryl substituent of the starting diacetate **2**. The biphenyl-substituted **2h** afforded 9-(biphenyl-4-yl)-2-phenylanthracene **3h** in 86% yield with the lower selectivity (**3h**/**4h** = 89:11) (Table 2, entry 7). The use of multialkyl-substituted acetate **2i** generated a mixture of **3i** and **4i** in a ratio of 76:24. Interestingly, employment of **2j**−**p** bearing more reactive substituents such as 1-naphthyl, 2-naphthyl, and 9-phenanthryl resulted in the formation of the corresponding **3j**−**p** with high selectivities (**3**/**4** > 99:1) and high yields (83−99%) (Table 2, entries 9−15). In the cases of 2-naphthyl-substituted **2k** and **2o**, two regioisomeric products are possible; however, only one anthracene isomer was obtained as a sole product, which indicated that the F−C reaction occurred always at the α-position of naphthyl substituent (Table 2, entries 10 and 14). It was pointed out that this reaction provided a useful tool in the introduction of polycyclic aromatic rings into the anthracene nucleus.

Heteroacenes constitute one of the most common classes of small-molecular electronic materials.[2a] Interestingly, we found that our method could be readily extended to heteroacenes. Treatment of bis(thienyl)-substituted acetate **2q** with 10% TfOH resulted in the formation of 4-thien-2-ylnaphtho[2,3-*b*]thiophene **5a** immediately (1 min) in 83% yield (Table 3, entry 1). The substrates bearing a 3-benzothiophene unit cyclized smoothly to afford **5c** in 79% yield (Table 3, entry 3). Similarly, the diesters derived from naphthalene-2,3-dicarbaldehyde afforded heterotetracene (**5e**, **5f**) or -pentacene (**5g**) in 56−87% yields (Table 3, entries 5−7). In addition, we did not observe any detectable byproducts in these reactions except **5g**. The struc-

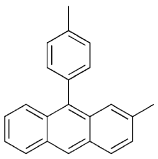
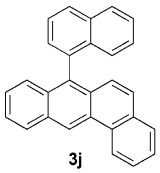
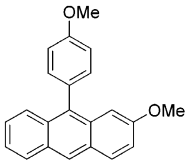
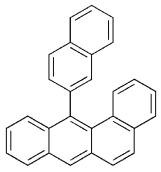
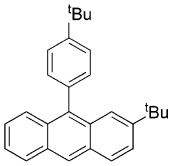
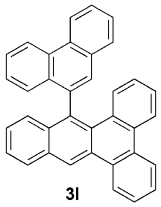
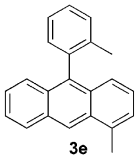
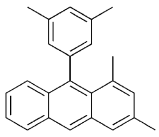
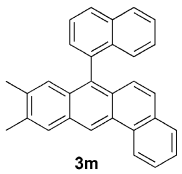
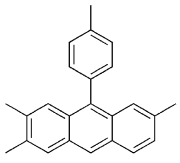
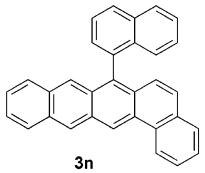
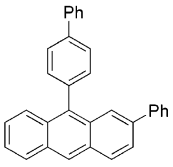
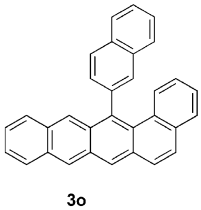
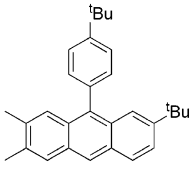
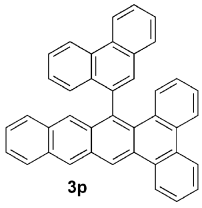
(16) The exact structure of this isomer could not be defined.

(17) Balaban, A. T.; Nenitzescu, C. D. *Friedel-Crafts and Related Reaction*; Olah, G. A., Ed.; Wiley & Sons: New York, 1964; Vol. 2, pp 979−1047.

TABLE 2. Formation of 9-Arylanthracene Derivatives

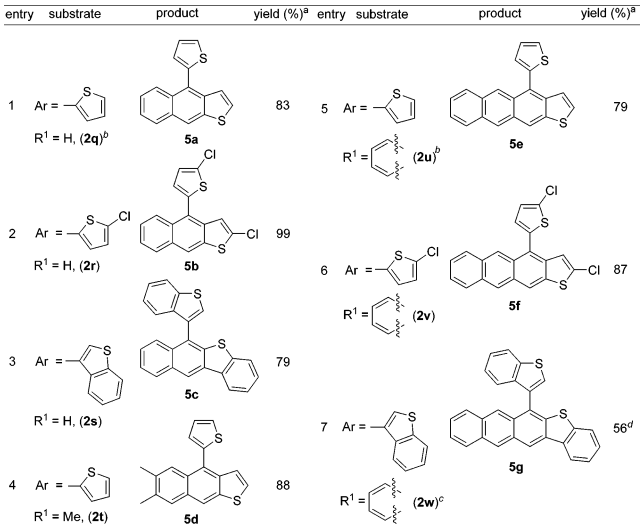


2 3 4

entry	substrate	product	yield (%)[a,b,c]	entry	substrate	product	yield (%)[a,b,c]
1	Ar = *p*-MeC_6H_4, R^1 = H, (**2b**)	 **3b**	83 (96:4)	9	Ar = 1-naphthyl, R^1 = H, (**2j**)	 **3j**	99 (>99:1)
2	Ar = *p*-$MeOC_6H_4$, R^1 = H, (**2c**)	 **3c**	74 (99:1)[d]	10	Ar = 2-naphthyl, R^1 = H, (**2k**)	 **3k**	98 (>99:1)
3	Ar = *p*-$^tBuC_6H_4$, R^1 = H, (**2d**)	 **3d**	83 (94:6)	11	Ar = 9-phenanthryl, R^1 = H, (**2l**)	 **3l**	96 (>99:1)
4	Ar = *o*-MeC_6H_4, R^1 = H, (**2e**)	 **3e**	99 (95:5)				
5	Ar = 3,5-diMeC_6H_3, R^1 = H, (**2f**)	 **3f**	84 (>99:1)[d]	12	Ar = 1-naphthyl, R^1 = Me, (**2m**)	 **3m**	93 (>99:1)
6	Ar = *p*-MeC_6H_4, R^1 = Me, (**2g**)	 **3g**	91 (93:7)	13	Ar = 1-naphthyl, R^1 =  **2n**	 **3n**	95 (>99:1)
7	Ar = *p*-phenylC_6H_4, R^1 = H, (**2h**)	 **3h**	86 (89:11)	14	Ar = 2-naphthyl, R^1 =  **2o**	 **3o**	83 (>99:1)
8	Ar = *p*-$^tBuC_6H_4$, R^1 = Me, (**2i**)	 **3i**	87 (76:24)	15	Ar = 9-phenanthryl, R^1 =  **2p**	 **3p**	97 (>99:1)

[a] Reactions were conducted with 0.05 M substrate in CH_2Cl_2. [b] Isolated yields after chromatography. [c] The ratio of **3**/**4** is given in parentheses. Unless noted, all the ratios were determined by ^1H NMR of the isolated material after chromatography. [d] Determined by ^1H NMR of the reaction crude.

TABLE 3. Formation of Heteroacenes



[a] Isolated yields after chromatography. [b] Pivalate was used. [c] **2w** was contaminated with small amounts of impurities. [d] Isolated yields after recrystallization.

tures of **3** and **5** were unambiguously confirmed by X-ray single-crystal analyses of **3c** and **5c**.[15]

In summary, we have developed a convenient and catalytic protocol for the synthesis of arylanthracenes or heteroacenes including benzanthracenes, dibenzo[*a*,*c*]naphthacene, naphtho-[2,3-*b*]thiophene, benzo[*b*]naphtho[2,3-*d*]thiophene, etc. This method offers several advantages in comparison with known aromatic cyclodehydration reactions such as high selectivities, mild reaction conditions, and easily accessible starting materials. We are currently exploring the synthetic potential of this new cyclization reaction for the construction of polycyclic aromatic compounds.

Experimental Section

A Typical Procedure for the Synthesis of 14-Phenanthren-9-yl-benzo[*b*]triphenylene (3l) (Table 2, entry 11). Acetic acid [2-(acetoxyphenanthren-9-ylmethyl)phenyl]phenanthren-9-ylmethyl ester **2*l*** (0.2 mmol, 115 mg) was added to a 25-mL round-bottomed flask containing a stirring bar, and then 4 mL of dry CH_2Cl_2 was added under N_2 atmosphere. To the mixture was added TfOH (0.02 mmol, 1.78 μL). The resulting solution was stirred at room temperature for 1 min. An appropriate amount of silica gel was added to the mixture and the solvent was evaporated in vacuo at room temperature. The residue was purified by flash chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) to afford the desired product in 96% yield as a yellow solid. Mp 276−278 °C; ^{1}H NMR ($CDCl_3$, Me_4Si) δ 6.61−6.66 (m, 1H), 7.11−7.32 (m, 5H), 7.39−7.44 (m, 1H), 7.48−7.78 (m, 7H), 7.76 (dd, J = 8.4, 0.6 Hz, 1H), 7.06 (d, J = 8.1 Hz, 1H), 8.35 (d, J = 7.5 Hz, 1H), 8.43 (d, J = 8.4 Hz, 1H), 8.74−8.84 (m, 3H), 9.21 (s, 1H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 122.7, 122.8, 123.1, 123.17, 123.22, 123.9, 125.86, 125.91, 126.1, 126.8, 126.81, 126.89, 126.9, 127.28, 127.3, 127.5, 127.6, 127.7, 128.2, 128.4, 128.6, 128.9, 129.4, 129.7, 130.2, 130.3, 130.4, 130.5, 130.6, 131.4, 131.7, 132.2, 132.6, 133.0, 135.0, 139.0; IR (neat) 3068, 2958, 2925, 2854, 1712, 1601, 1528, 1495, 1449, 1360, 1250, 1220, 1040, 999, 950, 886, 750, 725 cm^{-1}; HRMS (MALDI/DHB) for $C_{36}H_{22}Na$ [M]$^+$ calcd 477.1614, found 477.1627.

A Typical Procedure for the Synthesis of 2-Chloro-4-(5-chlorothien-2-yl)naphtho[2,3-*b*]thiophene (5b) (Table 3, entry 2). Acetic acid {2-[acetoxy-(5-chlorothien-2-yl)-methyl]phenyl}-(5-chlorothien-2-yl)methyl ester **2r** (0.2 mmol, 91 mg) was added to a 25-mL round-bottomed flask containing a stirring bar, and then 4 mL of dry CH_2Cl_2 was added under N_2 atmosphere. To the mixture was added TfOH (0.02 mmol, 1.78 μL). The resulting solution was stirred at room temperature for 1 min. An appropriate amount of silica gel was added to the mixture and the solvent was evaporated in vacuo at room temperature. The residue was purified by flash chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) to afford the desired product in 99% yield as a light yellow solid. Mp 90−92 °C; ^{1}H NMR ($CDCl_3$, Me_4Si) δ 6.91 (d, J = 3.9 Hz, 1H), 7.04 (d, J = 3.9 Hz, 1H), 7.14 (s, 1H), 7.40−7.49 (m, 2H), 7.82−7.85 (m, 1H), 7.95−7.98 (m, 1H), 8.16 (s, 1H); ^{13}C NMR ($CDCl_3$, Me_4Si) δ 121.3, 122.1, 124.4, 125.6, 125.7, 126.1, 126.4, 127.5, 128.2, 130.5, 130.8, 134.1, 136.6, 137.1, 138.4; IR (neat) 3096, 3054, 2924, 2853, 1700, 1517, 1487, 1452, 1444, 1408, 1377, 1338, 1248, 1205, 1166, 1062, 1024, 994, 874, 845, 826, 799, 745 cm^{-1}; HRMS (EI) for $C_{16}H_8Cl_2S_2$ calcd 333.9444, found 333.9445.

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Supporting Information Available: Experimental details and spectroscopic characterization of all new compounds and CIF files giving crystallographic data of **3c** and **5c**. This material is available free of charge via the Internet at http://pubs.acs.org.

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