

Synthesis of Nitrogen-Bridged Terthiophenes by Tandem Buchwald–Hartwig Coupling and Their Properties

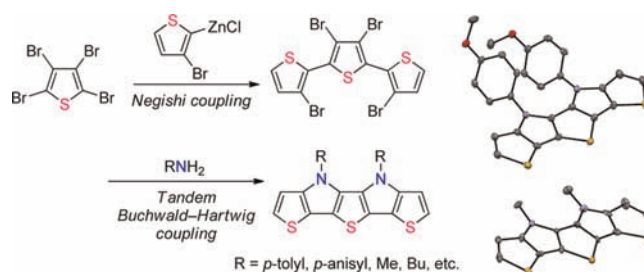
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ABSTRACT



The first synthesis of nitrogen-bridged terthiophenes (NBTTs) has been achieved by a tandem Buchwald–Hartwig coupling of 3,3',3'',4'-tetrabromo-2,2':5',2''-terthiophene. Several NBTT derivatives bearing aryl or alkyl moieties on the N-atoms could be synthesized. Their fundamental electrochemical characteristics and HOMO–LUMO levels were found to be influenced by the substituents on the N-atoms.

Fused dithiophene skeletons, such as 4*H*-dithieno[3,2-*b*:2',3'-*d*]pyrrole (DTP),¹ -thiophene,² -silole,³ -borole,⁴ and

-phosphole,⁵ have received considerable attention as key components of organic materials for use in optical and electronic devices.

Beyond the more common fused bithiophenes, larger heteroacenes with up to seven fused rings have also been reported.^{6,7} In addition to the simple thienoacene series,⁷ these larger heteroacenes also contain numerous examples containing multiple heteroatoms,⁶ although currently all known examples also contain at least one benzene ring in the heteroacene backbone. In this study, we report the first example of a larger heteroacene consisting solely of

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alternating thiophene and pyrrole rings, nitrogen-bridged terthiophenes (NBTTs).

To clarify the effect of π -conjugation on fused oligothiophenes, DFT calculations of nitrogen-bridged thiophenes **1A–3A** and thienoacenes **1B–3B** at the B3LYP/6-31G(d) level of theory were conducted (Figure 1). To investigate the energy level for each skeleton, nitrogen-bridged thiophenes that did not bear any substituents on the N-atoms were used. The band gap of NBTT (**2A**, dithieno[2,3-*d*:2',3'-*d'*]thieno[3,2-*b*:3',2'-*b'*]dipyrrole, 3.92 eV) was smaller than that of dithienopyrrole **1A** (4.58 eV), and further extension of thiophene units led to a smaller band gap. A similar tendency was observed in the case of **1B–3B**. The band gap of nitrogen-bridged thiophene **2A** was close to that of pentathienoacene **2B** (3.83 eV), which exhibited p-type semiconductivity.^{6b} These results prompted us to synthesize NBTT derivatives and clarify their optical and electrochemical characteristics.

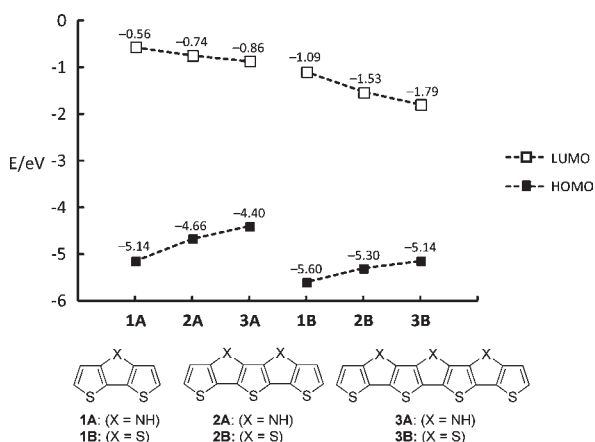
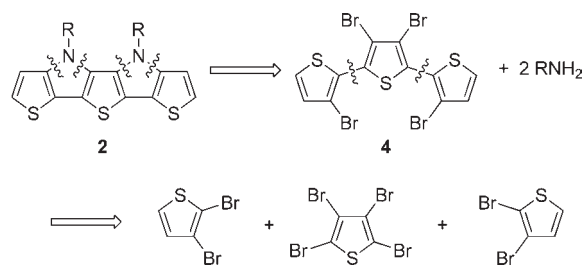


Figure 1. Comparison of the Kohn–Sham HOMO and LUMO energy levels of nitrogen-bridged multi-thiophenes and thienoacenes at the B3LYP/6-31G(d) level of theory.

The strategy for the synthesis of NBTT derivatives is described in Scheme 1. We designed 3,3',3'',4'-tetrabromo-2,2':5',2''-terthiophene (**4**), which could be prepared from 2,3-dibromothiophene and tetrabromothiophene, as a key precursor of NBTT. The Pd-catalyzed tandem Buchwald–Hartwig coupling of **4** and a primary amine would give **2**. We report here the first synthesis of **4** and the first construction of NBTT **2**. X-ray crystallographic analysis and fundamental studies on the electrochemical and optical properties of **2** were also conducted.

First, we attempted to synthesize **4** by Pd-catalyzed Kumada–Tamao–Corriu coupling between tetrabromothiophene and a (3-bromothiophen-2-yl)magnesium halide under several conditions. However, complex mixtures were obtained in all cases, since a bromide–magnesium exchange occurred between tetrabromothiophene and the (3-bromothiophen-2-yl)magnesium halide. After further optimization, we found that Negishi coupling was suitable for the synthesis of **4** (Scheme 2). In the presence of

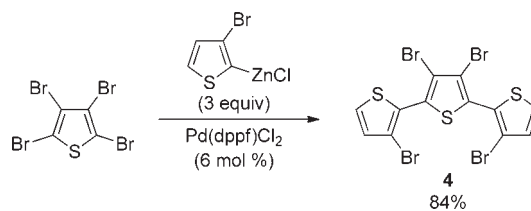
Scheme 1. Retrosynthesis of NBTT



dichloro[1,1'-bis(diphenylphosphino)ferrocene]palladium (Pd(dppf)Cl₂, 6 mol %), the coupling reaction of tetrabromothiophene and 3-bromo-2-thienylzinc chloride (3 equiv) proceeded smoothly to afford **4** in 84% yield.

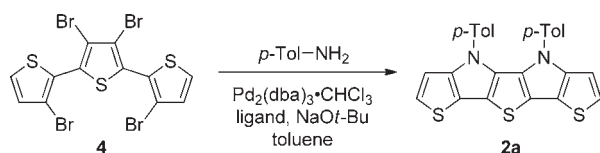
We next carried out a Pd-catalyzed tandem Buchwald–Hartwig coupling for the synthesis of NBTT using *p*-toluidine as an amine (Table 1). In the presence of Pd₂(dba)₃•CHCl₃ (10 mol % of **4**), tri(*tert*-butyl)phosphine (P(*t*-Bu)₃, 0.2 mmol), and NaOtBu (8 mmol), **4** (0.5 mmol) was treated with *p*-toluidine (1.2 mmol) at 110 °C for 12 h to give the desired *N,N'*-di(*p*-tolyl)-dithieno[2,3-*d*:2',3'-*d'*]thieno[3,2-*b*:3',2'-*b'*]dipyrrole (di-*p*-tolyl-NBTT, **2a**) in 16% yield (entry 1). To increase the yield, screening of the ligands was carried out (entries 2–5). With BINAP, the yield of **2a** slightly increased to 29% (entry 2). Alkylene diphosphines such as 1,2-bis(diphenylphosphino)ethane (dppe) and 1,4-bis(diphenylphosphino)butane (dppb) were unsuitable for the reactions (entries 3 and 4). With dppf, the reaction was terminated within 6 h and the yield of **2a** increased to 48% (entry 5). Finally, the Pd source was optimized (entries 6–9). Pd(dba)₂ and [PdCl(η^3 -C₃H₅)₂] were found to be suitable Pd sources for the reactions, and **2a** was obtained in 54% yield in each case (entries 6 and 7). Palladium acetate was not a good Pd source for the reaction. With Pd(OAc)₂, **2a** was obtained in only a 12% yield (entry 8). The use of Pd(dppf)Cl₂ instead of the set of Pd(dba)₂ and dppf gave **2a** in lower yield (18% yield, entry 9).

Scheme 2. Synthesis of 4



Under the optimized conditions, coupling reactions between **4** and several amines were carried out (Table 2). First, substituted anilines were used in the reactions.

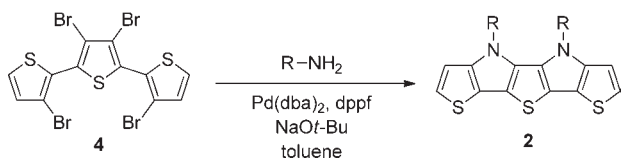
Table 1. Pd-Catalyzed Tandem Buchwald–Hartwig Coupling between **4** and *p*-Toluidine under Various Conditions^a



entry	Pd	ligand	time (h)	yield (%) ^b
1	Pd ₂ (dba) ₃ •CHCl ₃	P(t-Bu) ₃	12	16
2	Pd ₂ (dba) ₃ •CHCl ₃	BINAP	12	29
3	Pd ₂ (dba) ₃ •CHCl ₃	dppe	12	3
4	Pd ₂ (dba) ₃ •CHCl ₃	dppb	12	0
5	Pd ₂ (dba) ₃ •CHCl ₃	dppf	6	48
6	Pd(dba) ₂	dppf	6	54
7	[PdCl(<i>η</i> ³ -C ₃ H ₅) ₂]	dppf	6	54
8	Pd(OAc) ₂	dppf	6	12
9	Pd(dppf)Cl ₂	–	6	18

^a Reaction conditions: **4** (0.5 mmol), *p*-toluidine (1.2 mmol), Pd source (10 mol % Pd based on **4**), ligand (0.2 mmol), NaOtBu (8 mmol), toluene (3.5 mL), 110 °C. ^b Isolated yield.

Table 2. Pd-Catalyzed Tandem Buchwald–Hartwig Coupling between **4** and Several Amines^a



entry	R	2	yield (%) ^b
1	<i>p</i> -Bu-C ₆ H ₄	2b	66
2	<i>p</i> -MeO-C ₆ H ₄	2c	74
3 ^c	Bn	2d	77
4	Oct	2e	44
5 ^c	Bu	2f	74
6 ^{c,d}	Me	2g	51

^a Reaction conditions: **4** (0.5 mmol), amine (1.2 mmol), Pd(dba)₂ (0.05 mmol), dppf (0.20 mmol), NaOtBu (16 equiv), toluene (7 mL), 110 °C. ^b Isolated yield. ^c Reaction was performed at 90 °C. ^d MeNH₂•HCl was used as an amine source.

With *p*-butylaniline, tandem Buchwald–Hartwig coupling gave the corresponding coupling product **2b** in 66% yield (entry 1). Similarly, the reaction with *p*-methoxyaniline afforded **2c** in 74% yield (entry 2). Alkylamines could also be used in the reactions. The tandem coupling reaction with benzylamine afforded dibenzyl-substituted NBTT **2d** in good yield (77%, entry 3). With octylamine and butylamine, corresponding dialkyl-substituted NBTT **2e** and **2f** were obtained in 44% and 74% yields, respectively (entries 4 and 5). These diaryl-NBTTs and dialkyl-NBTTs were

colorless, air-stable solids that were easy to handle under aerobic conditions. With methylamine hydrochloride, dimethyl-NBTT (**2g**) was obtained in 51% yield (entry 6). **2g** was slowly oxidized under aerobic conditions to give a polymerized blue solid.

The crystal structures of **2a–2c** and **2e–2g** were examined via X-ray crystallography. As expected from the DFT calculations, their terthiophene skeletons were in the same plane. The bond lengths of NBTT skeletons were quite similar to those of DTP.^{1a} However, the S–C bonds of **2** were slightly longer than those of DTP.⁸

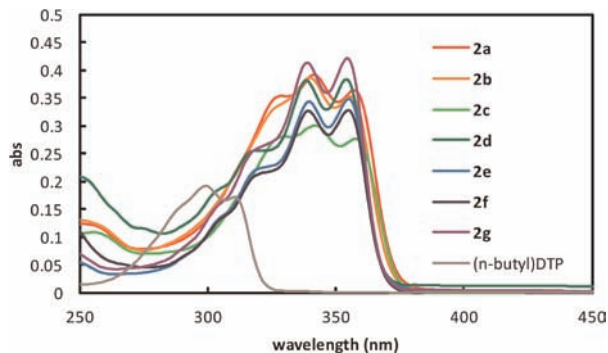


Figure 2. UV–vis spectra of **2a–g** and *n*-butyl-DTP measured in CH₂Cl₂ (1.0 × 10^{−5} M).

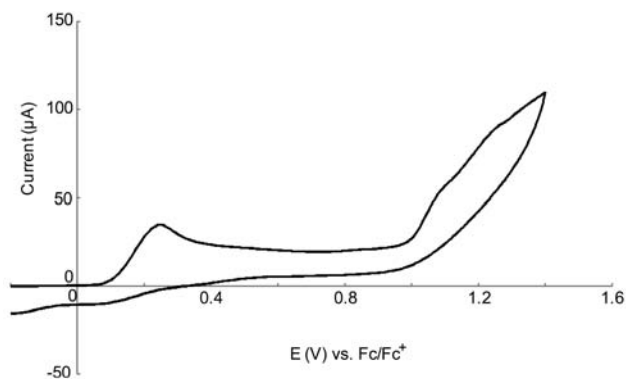


Figure 3. Cyclic voltammogram of **2a**.

We next investigated the optical and electrochemical properties of NBTTs. The UV–vis absorption spectra of **2a–g** and *n*-butyl-DTP are shown in Figure 2. Compounds **2a–g** all exhibited two absorption maxima (λ_{max}) at around 339–357 nm, which are longer wavelengths than those of *n*-butyl-DTP (309 and 298 nm). These results suggest that their optical characteristics were independent

(8) For data for DFT calculations and X-ray analyses, see Supporting Information.

(9) For details of cyclic voltammetry, see Supporting Information.

Table 3. Electrochemical and Optical Data for NBTTs and DTP^a

2	E_{onset} (V)	E_{HOMO} (eV)	λ_{max} (nm)	log ϵ	λ_{onset} (nm)	E_{LUMO} (eV)
2a	0.08	-5.18	357 341	4.34 4.31	379	-1.91
2b	0.04	-5.14	356 340	4.54 4.59	381	-1.89
2c	0.05	-5.15	358 342	4.44 4.48	383	-1.91
2d	0.02	-5.12	354 338	4.58 4.58	375	-1.81
2e	0.01	-5.11	354 339	4.54 4.54	380	-1.85
2f	-0.05	-5.05	355 339	4.51 4.51	388	-1.85
2g	-0.07	-5.03	354 339	4.62 4.62	375	-1.72
DTP ^b	0.15	-5.25	309 298	4.23 4.28	324	-1.42

^a E_{onset} values were determined by the onset of CV in CH₂Cl₂. V vs Fc/Fc⁺ in 0.1 M TBABF₄. E_{HOMO} values were determined in reference to ferrocene (5.1 eV vs vacuum).¹⁰ $E_{\text{LUMO}} = E_{\text{HOMO}} + \lambda_{\text{onset}}$. ^b *n*-Butyl-DTP.

from *N*-functionalization and mainly influenced by the NBTT skeleton. Similar results were reported on DTP.^{1a}

Cyclic voltammetry (CV) of **2a–g** was carried out next.⁹ As shown in Figure 3, the first peak potential for oxidation of **2a** was observed clearly at 0.25 V (vs Fc/Fc⁺), and the second and third oxidation peaks were observed at around 1.0–1.2 V (vs Fc/Fc⁺). The oxidation potential was more negative than that of *n*-butyl-DTP (0.58 V vs Fc/Fc⁺), due to the π -expansion of the structure. The oxidative potentials of NBTTs were highly influenced by the substituents

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on the N-atoms. For instance, that of **2g** was 0.08 eV (vs Fc/Fc⁺). The growth of redox peaks was observed during sequential potential cycling. This result suggests the formation of an electroactive film on the surface of the working electrode. Indeed, a black film was observed on the surface of the electrode.

The combined electrochemical and optical data for NBTTs are illustrated in Table 3 along with the data for *n*-butyl-DTP for comparison. Compounds **2a–g** all had higher HOMO levels than DTP. In particular, the values of E_{HOMO} for **2f** and **2g** were -5.05 and -5.03 eV, respectively. As expected, both E_{HOMO} and E_{LUMO} were influenced by the substituents on the N-atoms. For instance, the HOMO energies were slightly stabilized by the aryl substituents on the N-atoms. The tendency was similar to that of DTP reported by Rasmussen and co-workers.¹¹

In conclusion, we have developed a synthetic strategy that leads to NBTTs, which belong to a new class of fused thiophenes. X-ray single-crystal analyses revealed that they have planar skeletons. Their fundamental characteristics were clarified by UV and CV analyses, and the results suggested that their HOMO–LUMO levels are tuned by the functional group on the N-atoms. Further studies on NBTTs are underway in our laboratory.

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Supporting Information Available. Experimental details, spectral data for all new compounds, results of CV analysis, theoretical calculations, and the crystallographic information file (CIF) of **2a–c** and **2e–g**. These materials are available free of charge via the Internet at <http://pubs.acs.org>.

The authors declare no competing financial interest.