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Synthesis of Oligo(thienylene-vinylene) by Regiocontrolled Deprotonative Cross-Coupling

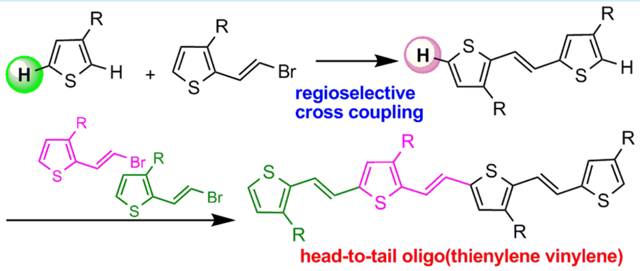
Shota Tanaka,[†] Yuta Fukui,[†] Naoki Nakagawa,[†] Kohei Murakami,[†] Takurou N. Murakami,[*,‡] Nagatoshi Koumura,[‡] and Atsunori Mori[*,†]

[†]Department of Chemical Science and Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe 657-8501, Japan

[‡]Research Center for Photovoltaics (RCPV), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan

Ⓢ *Supporting Information*

ABSTRACT: Concise synthesis of oligo(thienylene-vinylene) with a head-to-tail type structure is achieved by regioselective deprotonative coupling of 3-hexylthiophene. The palladium catalyzed reaction of 3-hexylthiophene with (*E*)-2-(2-bromoethenyl)-3-hexylthiophene takes place to afford head-to-tail type *trans*-1,2-dithienylethene. Further extension of a vinylthiophene unit is similarly performed in an iterative manner.



Oligothiophene and polythiophene derivatives have attracted much attention as π-conjugated material for organic advanced materials. In particular, these compounds are expected to be applied for organic electronic materials such as organic transistors,[1] organic solar cells,[2] and liquid crystals.[3] It is therefore important to develop concise and practical synthesis of oligo- and polythiophenes in materials science as well as synthetic organic chemistry. We have been engaged in practical synthesis of oligothiophenes and polythiophenes with a head-to-tail (HT) type regioregular structure, which generally exhibits higher performance as a material because of its minimum steric repulsion leading to planar π-conjugated conformation, using a transition-metal-catalyzed cross-coupling reaction at the C−H bond forming a thiophene−thiophene bond.[4]

The related π-conjugated oligomers and polymers of thiophenes bearing a vinylene spacer between two thiophene rings have also been of much interest as advanced materials by further extended π-conujugation and cancellation of steric hindrance from the direct connection of thiophene−thiophene.[5] Various (thienylene-vinylene)s have been prepared to date and revealed to show a lower band gap than corresponding oligothiophenes or polythiophenes.[6] Indeed, development of a practical synthesis of a thienylene-vinylene polymer with a head-to-tail-type structure has been a major concern and several syntheses employing transition metal catalysis produced thienylene-vinylene polymers.[6g−i] On the other hand, it is also intriguing to afford thienylene-vinylenes with a well-defined molecular size and structure via stepwise construction by repeating unit reactions affording the corresponding oligomers with monodispersity.[7] Several synthetic pathways to well-defined thienylene-vinylene have been shown so far, namely, by a Horner−Wadsworth−Emmons (HWE) reaction[6a] of aldehyde with phosphate, McMurry coupling[6b] of thiophene aldehydes, and cross-coupling reactions by transition metal catalysis.[7] Although these reactions are effective tools to introduce carbon−carbon double bond adjacent to the thiophene ring, a subsequent transformation is necessary prior to an additional extension of the unit structure. Thus, multistep reactions are required to achieve preparation of a certain number of oligomers. We have been successful in the stepwise synthesis of head-to-tail-type oligothiophenes by a nickel-catalyzed coupling reaction to form a thiophene−thiophene bond via regioselective deprotonation at the C−H bond of thiophene, with which each thiophene unit can be extended in a single manipulation.[4a,b] Thus, the well-defined monodisperse oligomer was shown to be obtained in a highly concise manner. We envisaged that a similar approach with regioselective deprotonation of 3-alkylthiophene **1** to react with (*E*)-2-(2-bromoethenyl)-3-alkylthiophene **2** gives (*E*)-1,2-dithienylethene in a regioregular manner. In addition, repeating the regioselective deprotonation of the obtained oligomer and the following coupling brings about a practical stepwise synthesis of oligo(thienylene-vinylene)s, which would also involve only a single step in each extension of the thienylene-vinylene unit (Scheme 1). Herein, we describe the synthesis of head-to-tail-type regioregular oligo(thienylene-vinylene)s, catalyzed by a palladium complex.

We first focused our concern on the development of the efficient synthesis of thiophene-substituted vinyl bromide **2a** with a readily available thiophene derivative 2-formyl-3-hexylthiophene **1a-CHO**. As shown in Scheme 2, the reaction

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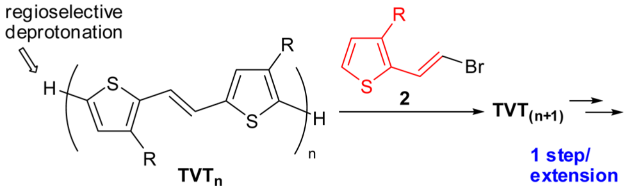
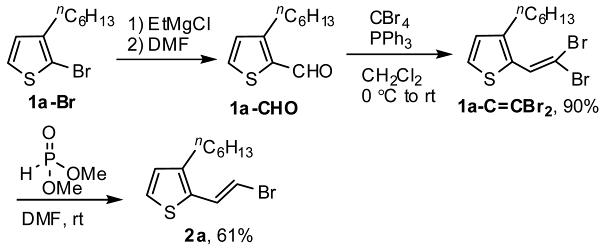
Scheme 1. Synthetic Strategy of Thienylene-Vinylene Oligomers



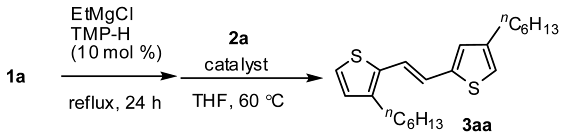
Scheme 2. Synthesis of *E*-Alkenyl Bromide 2a



of **1a-Br** with a Grignard reagent effected halogen−metal exchange. Following treatment with *N*,*N*-dimethylformamide (DMF), the formyl group was introduced at the 2-position to afford **1a-CHO** in 90% yield. The Corey−Fuchs reaction of **1a-CHO** with PPh_3 and carbon tetrabromide (CBr_4) afforded vinylidene bromide **1a-C═CBr$_2$** in 90% yield.[8] Selective debromination leading to *trans*-vinyl bromide **2a** was achieved by the reaction of dimethylphosphite in 61% yield.[9]

The reaction of the thus obtained vinyl bromide **2a** with 3-hexylthiophene (**1a**) was examined with several transition-metal catalysts. Treatment of **1a** with EtMgCl in the presence of 10 mol % 2,2,6,6-tetramethylpiperidine (TMPH) induced deprotonative metalation regioselectively after stirring for 24 h under reflux in THF.[4] The metalated thiophene was then subjected to the coupling reaction with **2a** in the presence of a transition metal catalyst. Results are summarized in Table 1. When **2a** and a nickel(II) catalyst bearing *N*-heterocyclic carbene (NHC) $NiCl_2(PPh_3)IPr$,[10] which showed excellent catalyst performance in thiophene-thiophene coupling,[4] was added to a THF solution of metalated thiophene, head-to-tail-type *trans*-1,2-dithienylethene **3aa** was obtained in a moderate yield (71%) after stirring at room temperature for 24 h. The reaction with $NiCl_2(PPh_3)IPr$ at an elevated temperature (60 °C) slightly increased the yield to 89%. Other nickel catalysts with bidentate diphosphine as a ligand, $NiCl_2(dppp)$ or $NiCl_2(dppf)$, afforded **3aa** in only 44% and 36% yields, respectively, accompanied by unreacted **2a**, which was confirmed by TLC analysis. A palladium catalyst was also shown to undergo the reaction. When ubiquitous palladium complex $PdCl_2(PPh_3)_2$ (2 mol %) was employed as a catalyst, **3aa** was obtained in 62% yield. The reaction of the palladium catalyst with bulky alkylphosphine ligand $Pd(P^tBu_3)_2$ also took place to afford **3aa** in 42% yield. Higher catalyst performance was observed in the reaction with palladium bearing NHC ligand Pd-PEPPSI-IPr[11] (77% yield), and the reaction at 120 °C in toluene with Pd-PEPPSI-IPr resulted in giving a quantitative yield whereas the reaction in hexane was shown to be less effective (at 60 °C, 59% yield).

Table 1. Coupling of 1a with Vinyl Bromide 2a[a]

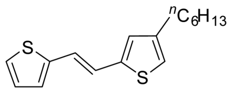
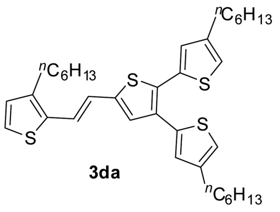
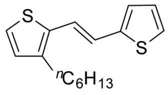
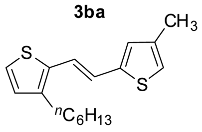
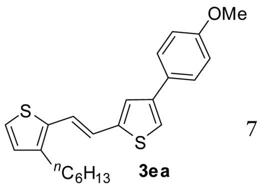
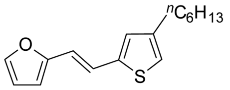
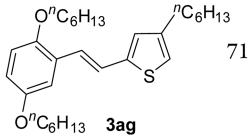


entry	catalyst	solvent	yield/%[b]
1[c]	$NiCl_2(PPh_3)IPr$	THF	71
2	$NiCl_2(PPh_3)IPr$	THF	89
3	$NiCl_2(dppp)$	THF	44
4	$NiCl_2(dppf)$	THF	36
5	$PdCl_2(PPh_3)_2$	THF	62
6	$Pd(P^tBu_3)_2$	THF	42
7	Pd-PEPPSI-IPr	THF	77
8[d]	Pd-PEPPSI-IPr	toluene	98
9	Pd-PEPPSI-IPr	hexane	59

[a] Unless noted, the reaction was carried out with **1a** (0.5 mmol), EtMgCl (0.6 mmol), **2a** (0.6 mmol), and catalyst (0.01 mmol) in THF at 60 °C for 24 h. [b] Isolated yield. [c] The reaction was carried out at room temperature. [d] The reaction was performed at 120 °C.

We next studied the reaction with a variety of thiophene derivatives with several *trans*-vinyl bromides. The deprotonative metalation of thiophenes at the 5-position proceeded in a regioselective manner. In addition to 3-hexylthiophene (**1a**), unsubstituted thiophene, 3-methylthiophene, branched terthiophene,[4b] and 3-arylthiophene bearing a 4-methoxyphenyl group underwent the coupling reaction with **2a** and the corresponding heteroarene-vinylene-heteroarene **3** in 70−86% yields. *trans*-Vinyl bromide bearing unsubstituted thiophene and furan reacted with **2a** to afford **3ab** and **3af** in 45% and 37% yields, respectively. Vinyl bromide bearing an aryl substituent also reacted with **1a** to provide **3ag** in 71% yield. These results are summarized in Table 2.

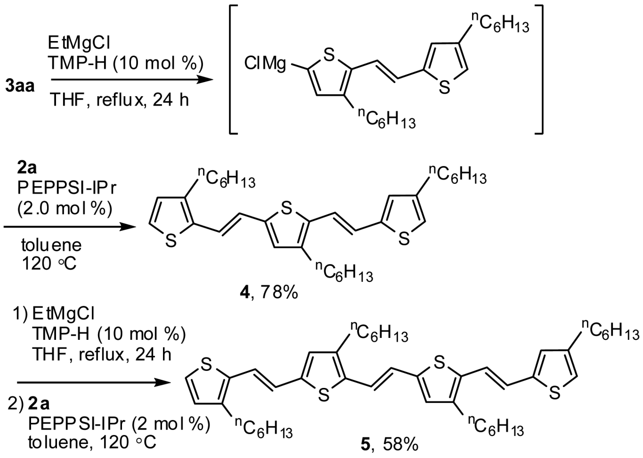
Table 2. Regioselective Cross-Coupling of Various 3-Substituted Thiophenes[a]

product	yield /%[b]	product	yield/ %[b]
 **3ab**	45	 **3da**	74
 **3ba**	72		
 **3ca**	86	 **3ea**	70
 **3af**	37	 **3ag**	71

[a] The reaction was carried out with 3-substituted thiophene (0.5 mmol), EtMgCl (0.6 mmol), vinyl bromide (0.6 mmol), and Pd-PEPPSI-IPr (0.01 mmol) in toluene at 120 °C for 24 h. [b] Isolated yield.

With the optimized coupling conditions, further extension of the vinylthiophene unit was performed as shown in Scheme 3.

Scheme 3. Stepwise Extension of Vinylthiophene Unit



Selective metalation of **3aa** was carried out in a similar manner with EtMgCl and 10 mol % of TMP-H under reflux for 24 h resulting in deprotonation at the less-hindered position. The following reaction with vinyl bromide **2a** in the presence of the Pd-PEPPSI-IPr catalyst gave the thienylene-vinylene oligomer bearing three thiophene units and two C−C double bond **4** in 78% yield. The regioselective cross-coupling of **4** with **2a** also proceeded to afford oligomer **5** with four thiophenes and three vinylenes in 58% yield.

Measurements of UV−vis absorption and photoluminescent spectra of oligo(thienylene-vinylene)s **3aa**, **4**, and **5** revealed an increase in molar absorbance coefficient ε as the extension of the repeating thienylene-vinylene unit (Table 3). Remarkable shifts in the absorption and emission maxima were also observed. From comparison of the absorption spectrum of **4a** bearing only two thiophene units (λ_{max} = 424 nm) with that of head-to-tail-type terthiophene **3T** (λ_{max} = 341 nm), a thiophene oligomer bearing a vinylene spacer suggests more extended π-conjugation.

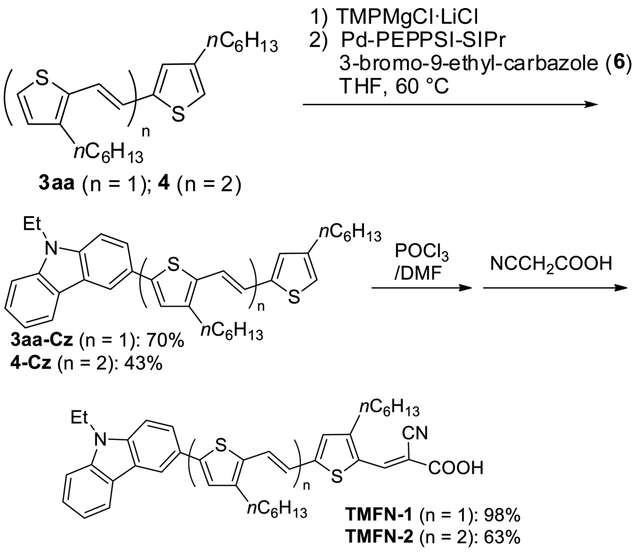
Table 3. UV−vis Absorption and Photoluminescent Spectra of Thienylene-Vinylene Oligomers with Regioregular Head-to-Tail Structure

compd	log ε	λ_{abs}/nm[a]	λ_{em}/nm[b]	$\Phi \times 10^3$[c]
3aa: TVT	4.42	350[d]	417	5
4: $(TV)_2T$	4.66	424[d]	512	3
5: $(TV)_3T$	4.88	472	526	0.2

[a] Absorption spectrum measured as a chloroform solution (1.0×10^{-5} M). [b] Photoluminescent spectrum as a 1.0×10^{-6} M chloroform solution. [c] The quantum yield Φ was estimated based on 7-diethylamino-4-methylcoumarin as 0.01 mM solution of ethyl acetate (Φ = 0.99). [d] λ_{abs} of head-to-tail-type bithiophene **2T**: 300 nm; **3T**: 341 nm; **4T**: 367 nm.

Functionalization of the obtained thienylene-vinylene oligomers **3aa**, **4**, and **5** was then carried out. Since a head-to-tail-type oligothiophene bearing a carbazole moiety is well-known as a MK-dye for organic dye-sensitized solar cells (DSSCs) that exhibit high performance,[2b] we envisaged synthesizing the related analog, which would show absorption to longer wavelengths. Introduction of carbazole to oligo(thienylene-vinhylene)s was performed by a regioselective cross-coupling reaction with 3-bromo-9-ethyl-carbazole (**6**). Treatment of **3aa** with a Knochel−Hauser base (TMPMgCl·LiCl) induced deprotonation regioselectively, and palladium-catalyzed coupling with **6** followed to afford the corresponding coupling product **3aa-Cz** in 70% yield. The reaction of **4** bearing three thiophenes and two vinylenes also proceeded in a similar manner to afford **4-Cz** in 43% yield. The obtained **3aa-Cz** and **4-Cz** were subjected to the treatment of $POCl_3$/DMF leading to the formylated products (98% and 63%, respectively), which were transformed to the corresponding cyanoacrylates **TMFN-1** and **TMFN-2** both in quantitative yields[2b] (Scheme 4).

Scheme 4. Synthesis of MK-Dye Analogs of Thienylene-Vinylene Oligomers



The obtained products **TMFN-1** and **TMFN-2** were employed as an organic dye for DSSCs. Table 4 shows the preliminary results related to photocurrent density−voltage characteristics.[12] The short-circuit photocurrent density (J_{sc}) was found to be ca. 6.5−8.7 mA cm^{-2}, and the open-circuit photovoltage (V_{oc}) was 0.7 V in **TMFN-1** and **TMFN-2**. The fill factor (FF) value was ca. 0.7, and the power conversion efficiency (η%) was estimated to be 4.37 (**TMFN-1**) and 3.02 (**TMFN-2**), respectively, suggesting that a carbazole dye bearing a thienylene vinylene moiety with a simple synthetic pathway showed moderate performance for DSSCs, albeit formation of the cell device has not yet been fully optimized to such a specific structure.

Table 4. DSSC Performance Parameters of TMFN-1 and TMFN-2 Dyes[a]

compd	J_{sc}/mA cm^{-2}	V_{oc}/V	FF	η%
TMFN-1	8.69	0.710	0.707	4.37
TMFN-2	6.47	0.671	0.695	3.02

[a] For details, see Supporting Information.

In conclusion, concise synthesis of oligo(thienylene-vinylene) with a head-to-tail-type structure was achieved by regioselective deprotonative coupling of 3-hexylthiophene (**1a**) with thiophene-substituted vinyl bromide **2a**. By repeating regioselective cross-coupling, oligomers bearing up to four thiophene and three vinylene units was successfully synthesized. UV–vis absorption maxima of the obtained oligomers shifted to a longer wavelength as the number of repeating units extended. Functionalization of oligomers was achieved to introduce carbazole and cyanoacrylate groups at both ends of the oligomers, which are recognized as the analog of MK-dyes employed for organic dyes for dye-sensitized solar cells (DSSC), although certain optimization should be made in the device fabrication to the specific conditions for thienylene vinylenes to improve the performance.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b03567.

Experimental section, spectroscopic data, and details on characterization of **TMFN-1** and **TMFN-2** as DSSC (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: amori@kobe-u.ac.jp.
*E-mail: takurou-murakami@aist.go.jp.

Notes

The authors declare no competing financial interest.

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(12) For experimental details concerning DSSC cell formation: see Supporting Information.