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COMMUNICATION

The effect of solvent in direct arylation polycondensation of substituted thiophenes

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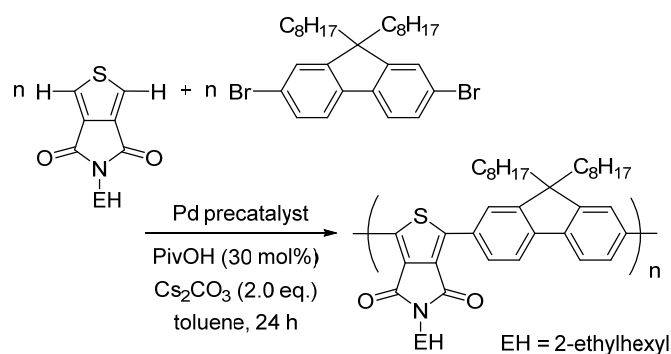
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In the direct arylation polycondensation of thiophene derivatives, toluene was found to be a suitable solvent for electron-deficient thiophenes, whereas dimethylacetamide (DMAc) was suitable for electron-rich thiophenes.

Polycondensation via dehydrohalogenative cross-coupling reactions, so-called direct arylation,¹ has recently been recognized as an efficient synthetic protocol for the production of π -conjugated polymers.²⁻¹⁰ As opposed to conventional polycondensation reactions carried out via cross coupling, this protocol has advantages with respect to decreasing the number of reaction steps for monomer preparation and reducing undesired waste from organometallic monomers.¹¹ The reduced amount of waste leads to high-purity polymers because of reducing potential impurity,^{10d} and the highly pure polymer shows high performance in organic field-effect transistors and organic photovoltaics.⁹ However, direct arylation polycondensation is being further developed as a reliable synthetic method for π -conjugated polymer materials because its application range is still limited in comparison to those of conventional methods.¹¹ Therefore, fundamental research regarding direct arylation polycondensation is required to produce a large variety of π -conjugated polymers with high molecular weights and purities. Notably, the discovery of efficient catalytic systems and their optimization play important roles in metal-catalysed polycondensation reactions. In the first report regarding direct arylation polycondensation, Pd(OAc)₂ with a large amount of tetrabutylammonium bromide in dimethylformamide (DMF) was used for synthesis of poly(3-alkylthiophene-2,5-diyl).³ However, this catalytic system only afforded low-molecular-weight polymers ($M_n = 3100$). Takita, Ozawa, and co-workers reported that the Herrmann catalyst with P(C₆H₄-*o*-NMe₂)₃ in THF promoted efficient direct arylation polycondensation, affording poly(3-hexylthiophene-2,5-diyl) with a high molecular weight ($M_n = 32600$) in excellent yield.⁴ The catalytic system was further developed⁵ and applied in the preparation of organic photovoltaics materials.⁶ Our group examined direct arylation polycondensation using Pd(OAc)₂ without a phosphine ligand in DMAc.^{8,9} The polycondensation reaction of 3,4-ethylenedioxythiophene (EDOT) with 2,7-dibromo-9,9-dioctylfluorene under the utilized reaction conditions afforded the corresponding polymer with a high molecular weight ($M_n = 39400$) in 89% yield.^{8d} However, under the same conditions, the reaction of

5-(2-ethylhexyl)-thieno-[3,4-*c*]pyrrole-4,6-dione (TPD) did not afford a polymeric product (Scheme S1). In contrast, the direct arylation polycondensation of TPD derivatives was successfully demonstrated by Ozawa⁵ and Leclerc⁷ *et al.* using THF or toluene as solvents. These observations prompted us to assess the effect of solvent in direct arylation polycondensation reactions; we envisioned that the optimal solvents and catalytic systems would be influenced by the chemical nature of the thiophene monomers. As a proof of concept, we first focused on toluene as a solvent for the polycondensation of TPD, and the polycondensation of various thiophene monomers bearing electron-donating or electron-withdrawing substituents was demonstrated under two types of conditions, namely the newly established toluene-based conditions and the reported DMAc-based conditions. Herein, we report the relationship between the reaction conditions and the nature of the thiophene monomers, which allowed for the preparation of a variety of thiophene-based conjugated polymers via direct arylation polycondensation.



Scheme 1 Direct arylation polycondensation in toluene.

The reaction of TPD with 2,7-dibromo-9,9-dioctylfluorene in toluene was conducted under the conditions reported by Leclerc and co-workers (Scheme 1).^{7a} The reaction was carried out using the Herrmann catalyst with P(C₆H₄-*o*-OMe)₃ in the presence of pivalic acid and Cs₂CO₃. Because the reaction temperature (120 °C) was higher than the boiling point of toluene, a pressure-tight vessel was

utilized in the reaction. The reaction afforded poly[(5-(2-ethylhexyl)-thieno-[3,4-*c*]pyrrole-4,6-dione-1,3-diyl)-(9,9-dioctylfluorene-2,7-diyl)] (PTPDF) with a molecular weight of 20200 in 78% yield (Table 1, Entry 1). The use of $\text{PCy}_3\cdot\text{HBF}_4$ rather than $\text{P}(\text{C}_6\text{H}_4\text{-}o\text{-OMe})_3$ provided a polymer with a higher molecular weight in a higher yield (Entry 2). The results from Entry 3 and 4 revealed that the Herrmann catalyst was not an essential precatalyst; the reactions with $\text{Pd}_2(\text{dba})_3$ or $\text{Pd}(\text{OAc})_2$ afforded polymers with somewhat higher molecular weights in higher yields. In addition, the combination of $\text{Pd}(\text{OAc})_2$ and $\text{PCy}_3\cdot\text{HBF}_4$ allowed for a decrease in the reaction temperature (to 110 °C), which was less than the boiling point of toluene and avoided high reaction pressures (Entry 5). Comparable polymerization results were obtained upon reducing the Pd loading to 2 mol% (Entry 6 and 7). The reaction was conducted at 100 °C under the optimized catalytic conditions for comparison with the reported examples⁸ of direct arylation polycondensation in DMAc at 100 °C. The reaction at 100 °C afforded a comparable result (Entry 8), whereas the reaction at 80 °C yielded only oligomeric products (Entry 9). Figure 1 shows the ¹H NMR spectrum of PTPDF. Each signal can be assigned to the repeating unit, and the signal of the terminal unit was not observed. The

integral ratio of the signals agreed with the assignments and was consistent with the alternating structure of the polymer.

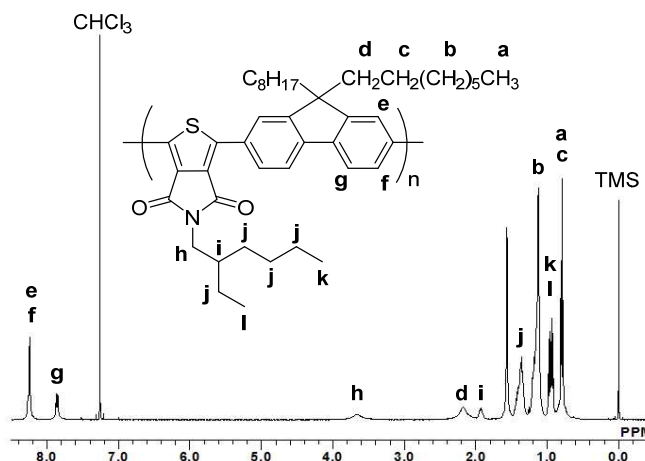


Fig. 1 ¹H NMR spectrum of PTPDF (400 MHz, CDCl_3).

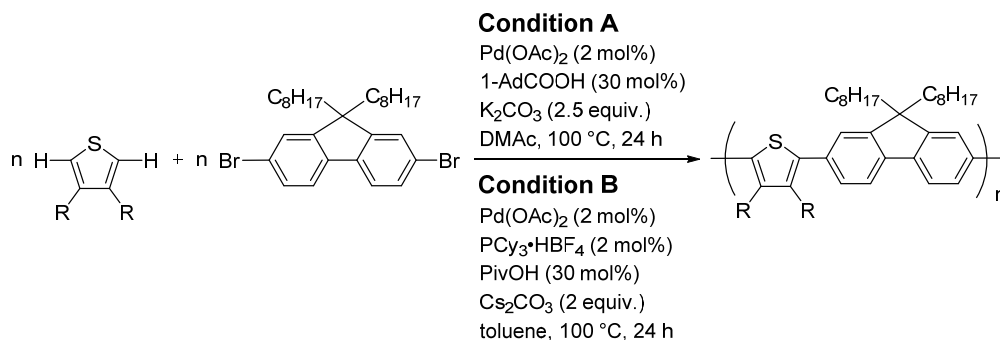
Table 1 Polycondensation of thieno[3,4-*c*]pyrrole-4,6-dione with 2,7-dibromo-9,9-dioctylfluorene in toluene

Entry	Pd precatalyst (mol%)	Ligand ^a	Temp. / °C	Yield / % ^b	M_n^c	M_w/M_n^c
1 ^d	Herrmann catalyst (8)	$\text{P}(\text{C}_6\text{H}_4\text{-}o\text{-OMe})_3$	120	78	20200	1.8
2 ^d	Herrmann catalyst (8)	$\text{PCy}_3\cdot\text{HBF}_4$	120	85	37000	2.4
3 ^d	$\text{Pd}_2(\text{dba})_3$ (8)	$\text{PCy}_3\cdot\text{HBF}_4$	120	83	44600	2.5
4 ^d	$\text{Pd}(\text{OAc})_2$ (8)	$\text{PCy}_3\cdot\text{HBF}_4$	120	85	46400	2.6
5	$\text{Pd}(\text{OAc})_2$ (8)	$\text{PCy}_3\cdot\text{HBF}_4$	110	96	44400	2.3
6	$\text{Pd}(\text{OAc})_2$ (4)	$\text{PCy}_3\cdot\text{HBF}_4$	110	88	44300	2.0
7	$\text{Pd}(\text{OAc})_2$ (2)	$\text{PCy}_3\cdot\text{HBF}_4$	110	85	45500	1.9
8	$\text{Pd}(\text{OAc})_2$ (2)	$\text{PCy}_3\cdot\text{HBF}_4$	100	93	46300	1.9
9	$\text{Pd}(\text{OAc})_2$ (2)	$\text{PCy}_3\cdot\text{HBF}_4$	80	0	-	-

^a Equimolar amount of the phosphine ligand to a Pd center was added. ^b The products were obtained by reprecipitation from $\text{CHCl}_3/\text{CH}_3\text{OH}$. ^c Estimated by GPC calibrated on polystyrene standards. ^d Average values of duplicated runs.

The optimization of the reaction conditions revealed that direct arylation polycondensation of TPD in toluene afforded the corresponding polymer with a high molecular weight in good yield. The reaction of TPD in DMAc did not afford a polymeric product (Scheme S1), although DMAc promoted several direct arylation polycondensation reactions of thiophene derivatives such as 2,3-

dimethylthiophene and EDOT.^{8b-f} Therefore, thiophenes with substituents at the 3 and 4 positions were investigated in the direct arylation polycondensation reaction under the two types of conditions (Scheme 2). Table 2 summarizes the results of the reactions carried out using the DMAc system (Condition A) and the toluene system (Condition B).



Scheme 2 Direct arylation polycondensation of thiophene derivatives under conditions A and B.

Table 2 Direct arylation polycondensation of thiophene monomers with various substituents under Conditions A and Condition B

Entry	Monomer	Condition A ^a			Condition B ^b		
		Yield / % ^c	M_n^d	M_w/M_n^d	Yield / % ^c	M_n^d	M_w/M_n^d
1 ^e		87 ^f	42700 ^f	2.7 ^f	0	-	-
2		98	11300	1.8	0	-	-
3		79	13700	2.4	0	-	-
4 ^g		72	7000	2.3	55 ^h	8300	4.7
5		0	-	-	93	46300	1.9
6 ^e		0	-	-	54 ^h	76000 (32500 ⁱ)	3.3 (5.9 ⁱ)

^a Pd(OAc)₂ (2 mol%), 1-Adamantanecarboxylic acid (1-AdCOOH, 30 mol%), K₂CO₃ (2.5 equiv.), DMAc, 100 °C, 24 h. ^b Pd(OAc)₂ (2 mol%), PCy₃·HBF₄ (2 mol%), Pivalic acid (PivOH, 30 mol%), Cs₂CO₃ (2 equiv.), toluene, 100 °C, 24 h. ^c The yields of the CHCl₃-soluble and CH₃OH-insoluble fraction. ^d Estimated by GPC calibrated on polystyrene standards with CHCl₃ as eluent at 40 °C. ^e Reaction time is 6 h. ^f Reference 8d. ^g Reaction time is 3 h. ^h CHCl₃-insoluble fraction was also formed. ⁱ Estimated by GPC with *o*-dichlorobenzene as eluent at 140 °C.

The reaction of EDOT under Condition A afforded the corresponding polymer in a good yield (Table 2, Entry 1),^{8d} whereas the reaction under Condition B afforded no polymeric product. In the reactions with 3,4-dioctyloxythiophene and 3,4-dimethylthiophene,^{8b} the reaction under Condition A only afforded the corresponding polymers (Entry 2 and 3). The reaction of 3,4-dichlorothiophene afforded the polymer under Conditions A and B (Entry 4). A low yield (55%) under Condition B was caused by formation of a CHCl₃-insoluble fraction, owing to the low solubility of a high-molecular-weight component. High temperature NMR spectroscopy of the polymers revealed that the structure of the CHCl₃-insoluble fraction was essentially the same as that of the soluble fraction (Figure S9). On the other hand, similar to the reaction of TPD (Entry 5), the reaction of 3,4-dicyanothiophene yielded a polymer under Condition B (Entry 6). The low yield (54%) was due to the formation of a CHCl₃-insoluble fraction. The molecular weight of the CHCl₃-soluble fraction (76000) was overestimated by the GPC measurement at 40 °C presumably due to aggregation; high temperature GPC measurement showed molecular weight of 32500. On the basis of these results, it is clear that the optimal reaction conditions strongly depended on the structure of the thiophenes. In particular, thiophenes with electron-donating substituents reacted better under Condition A, while thiophenes with electron-withdrawing substituents reacted more suitably under Condition B (Table S2). These insights are valuable for the development of direct arylation polycondensation reactions because the optimal reaction conditions can be rapidly estimated on the basis of the structures of the monomers.

DMAc is typically used as the solvent in direct arylation reactions of small molecules.¹ However, the use of toluene was reported in the reaction of thiophenes with electron-withdrawing

substituents, such as 2-cyanothiophene and 2-formylthiophene.¹² In addition, the direct arylation of 3,4-dicyanothiophene was conducted in xylene, and resulted in a good yield.¹³ Recently, Liu *et al.* reported superior yields of the direct arylation reactions of TPD derivatives in toluene than those conducted in polar solvents such as DMF and NMP.¹⁴ These results were consistent with the trend observed in this study. The absence or presence of the phosphine ligand as well as solvent were the significant differences between Conditions A and B. To determine if the phosphine ligand considerably affected the polycondensation or not, the reaction of TPD under Condition A was conducted following the addition of PCy₃·HBF₄ (Scheme S2). Because the reaction afforded no polymeric product, the phosphine ligand did not contribute to the large difference observed owing to the varying conditions. The reactions in 1,4-dioxane were conducted to investigate the effect of solvent because 1,4-dioxane has similar polarity and boiling point to toluene (Scheme S3). The reaction of TPD in 1,4-dioxane instead of toluene afforded no polymeric product although the other conditions were same as Condition B. This result shows that low polarity of toluene is not a dominant factor for smooth polymerization of TPD under Condition B. In addition, a reaction of EDOT in 1,4-dioxane afforded only oligomeric products (Scheme S3). A rate-determining step in direct arylation is known to depend on a substrate.¹⁵ The electronic nature of the substrate may change the rate-determining step leading to affect the suitable reaction conditions. Mechanistic studies are currently in progress to clearly establish the dominant factor.

In summary, this research facilitated the synthesis of high-molecular-weight polymers by direct arylation polycondensation in toluene, which possesses a high solubilizing ability toward π -conjugated polymers, high boiling point, and generality. The established conditions are suitable for thiophene monomers with

electron-withdrawing substituents. In contrast, thiophene monomers with electron-donating substituents reacted more favourably in DMAc. These insights are valuable for development of direct arylation polycondensation reactions because the optimal reaction conditions can be rapidly estimated on the basis of the structures of the monomers. Because the relationship between the thiophene structure and reaction conditions should be applicable to wide range of direct arylation reactions, including coupling reactions of small molecules, the fundamental findings described here may provide essential insights regarding direct arylation reactions in general.

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Experimental Part

Synthesis of PTPDF (Table 1, Entry 8). A mixture of Pd(OAc)₂ (1.1 mg, 0.0050 mmol), PCy₃·HBF₄ (1.8 mg, 0.0050 mmol), pivalic acid (8.6 μL, 0.075 mmol), Cs₂CO₃ (163 mg, 0.50 mmol), 2,7-dibromo-9,9-dioctylfluorene (137 mg, 0.25 mmol), *N*-(2-ethylhexyl)thieno[3,4-*c*]pyrrole-4,6-dione (66 mg, 0.25 mmol) was stirred in anhydrous toluene (1.25 mL) for 24 h at 100 °C under nitrogen atmosphere. After cooling to room temperature, the mixture was poured into an aqueous solution of ethylenediaminetetraacetic acid disodium salt (pH = 8). The suspension was stirred overnight at room temperature. The precipitate was separated by filtration and washed with 0.1 M HCl solution, distilled water, CH₃OH, and hexane. The precipitate was dissolved in CHCl₃ and the solution was filtered through a plug of Celite to remove insoluble material. A reprecipitation from CHCl₃/CH₃OH gave PTPDF as yellow solid in 93% yield. *M*_n = 46 300, *M*_w/*M*_n = 1.90. ¹H NMR (400 MHz, CDCl₃): δ 8.24 (overlapped, 4H), 7.86 (d, *J* = 8.0 Hz, 2H), 3.66 (br, 2H), 2.17 (br, 4H), 1.93 (m, 1H), 1.35–1.45 (br, 8H), 1.12–1.18 (br, 20H), 0.97 (t, *J* = 7.2 Hz, 3H), 0.95 (t, *J* = 6.8 Hz, 3H), 0.79 (overlapped, 10H). ¹³C{¹H} NMR (100 MHz, CDCl₃): δ 163.3, 152.4, 145.2, 142.2, 130.5, 130.2, 127.5, 122.9, 120.6, 55.8, 42.6, 40.1, 38.3, 31.8, 30.6, 30.0, 29.2, 29.2, 28.5, 23.9, 23.1, 22.6, 14.1, 14.1, 10.5 (One signal of the alkyl group was overlapped).

Notes and references

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† Electronic Supplementary Information (ESI) available: Experimental procedure, NMR spectra. See DOI: 10.1039/c000000x/

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