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One-shot Deprotonative Metalation/Transmetalation/Polymerization of Halothiophenes Catalyzed by Nickel Complex for Polythiophene Synthesis

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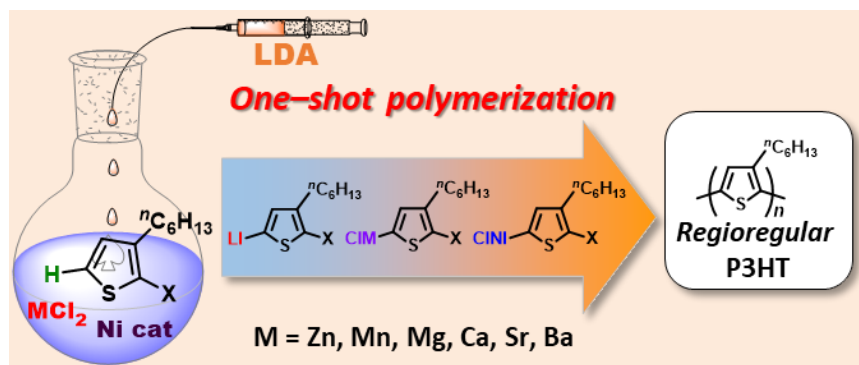
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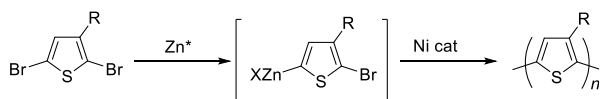
Abstract Effect of divalent metals was studied in the cross-coupling polymerization of thiophenes leading to head-to-tail-type poly-3-hexylthiophene. Deprotonation of the CH bond at the 5-position of 2-halo-3-hexylthiophene by LDA followed by metal exchange was carried out in one pot and following addition of nickel catalyst underwent polymerization. One-shot reaction involving deprotonation/transmetalation/cross coupling polymerization was also examined with manganese(II) chloride and nickel(II) catalyst.

Key words Deprotonative metalation; Poly(3-hexylthiophene), Group II metals; Nickel catalyst; One-shot reaction

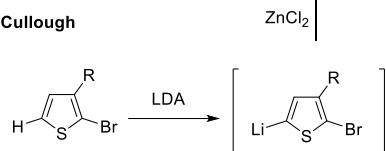
Polythiophenes attract much attention in materials science as potential utilities for organic photovoltaics, semiconductors, and conductive materials. Among those, the regioregular polythiophenes of the head-to-tail (HT) regularity show superior performances as materials.¹ Development of a facile and practical preparative method for the HT regioregular polythiophenes through the formation of metalated halothiophene via the cross-coupling polymerization is therefore an important issue in polymer synthesis as well as organometallic chemistry.^{2,3} The use of organomagnesium as a thiophene monomer species, which is recognized as GRIM (Grignard metathesis) method, has been served as a choice for the preparation of regioregular polythiophenes with a nickel complex as a catalyst for the polymerization.^{4,5} In contrast that use of thiophene–magnesium species has been extensively studied in polythiophene synthesis, less attention has been paid for the use of other metallic species.⁶ Rieke and co-workers reported in 1992 synthesis of HT-type regioregular polythiophenes employing an organozinc species of thiophene as a key intermediate, which was shown to be prepared by the reaction of an activated zinc species with 2,5-dihalo thiophene.⁷ McCullough also showed that the related thienylzinc can be obtained by the reaction of lithiated thiophene,

which was prepared by deprotonation of 2-halo thiophene, with a zinc salt through the metal exchange. Following nickel-catalyzed cross-coupling polymerization led to the HT-regioregular polythiophene.⁸ However, the reaction protocol involves an additional manipulation in the formation of organometallic species under inert conditions prior to the initiation of the polymerization by nickel catalysis. Since improved step efficiency has attracted recent concern in process chemistry of a wide range of fields, development concise reaction in polymer synthesis also of great interest. We thus envisaged that one-shot addition of the deprotonating agent lithium amide into the mixture of substrate thiophene in the presence of the corresponding metal salt. The process would lead to a facile preparative method of polythiophene compared with the successive lithiation/transmetalation protocol. Herein, we report that several group II and the related metals are available for the one-shot deprotonative metalation of thiophene derivative, which serves as an organometallic monomer for polythiophene synthesis.

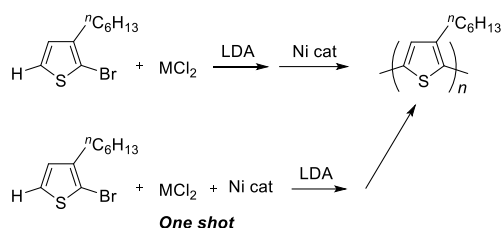
Rieke



McCullough



This work



Scheme 1. Polythiophene employing organozinc species as an in situ generated monomer

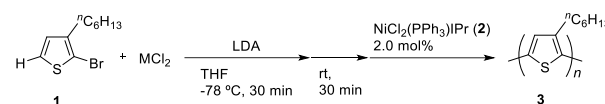
Preparation of thiophene–zinc species as an organometallic monomer has been reported to be carried out by the deprotonation of 2-halo-3-substituted thiophene **1** by LDA (Li^nPr_2) followed by the metal exchange to zinc by the addition of ZnCl_2 leading to thienyl–zinc species whereas the use of ZnCl_2 accompanies care for the hygroscopic characteristics of zinc halides. We first examined the direct reaction of the lithiated **1** with a nickel catalyst $\text{NiCl}_2(\text{IPr})\text{PPh}_3$ (**2**, 2.0 mol%; IPr = 1,3-bis(2,6-diisopropylphenyl)imidazole-1-ylidene) at room temperature for 24 h in THF. Little controlled polymerization was found to take place to result in broad polydispersity ($\text{PDI} = 3.98$) whereas polythiophene **3** was obtained.⁹

Next, we performed the deprotonative metalation with LDA in the presence of ZnCl_2 , by which in situ generation of organozinc species was considered to take place.¹⁰ A mixture of ZnCl_2 and 2-bromo-3-hexylthiophene (**1**) was treated with LDA at -78°C for 30 min. After the temperature of the resulting mixture was gradually raised to room temperature and kept for 30 min, nickel catalyst **2** was added. The color of the solution changed to dark orange suggesting the initiation of the polymerization. The reaction was continued at 60°C for 24 h to afford the corresponding polythiophene **3**. The number average molecular weight M_n and the polydispersity PDI showed 14900 and 1.77, respectively.¹¹

The effect of the chloride derivatives of several group II metals was also studied in a similar manner. As summarized in Table 1, magnesium, calcium, strontium, and barium chlorides underwent polymerization in 63–88% yields with M_n of ca. 10000–18000 after stirring at 60°C for 24 h whereas those PDI values were found to be slightly broader (1.98–2.72). The use of manganese(II) chloride was also found to undergo polymerization to afford polythiophene **3** with $M_n = 15400$ and $\text{PDI} = 1.44$, which molecular weight values were higher than that

based on the monomer/catalyst feed ratio (theoretical $M = 8300$). Lowering the reaction temperature to room temperature also resulted in giving the corresponding polythiophene **3**, when MgCl_2 , CaCl_2 ,¹² and ZnCl_2 were employed. In contrast, the use of SrCl_2 ,¹³ resulted in giving polymer **3** in a much lower yield and that of BaCl_2 ¹⁴ and MnCl_2 ¹⁵ did not afford the polymer at room temperature.

Table 1. Deprotonative metalation/polymerization of 2-bromo-3-hexylthiophene (**1**) in the presence of MCl_2 ^a



M	temp, °C	Yield (%) ^b	M_n^c	$\text{PDI}^{c,d}$
None	rt	65	20000	3.98
Zn	60	66	14900	1.77
	60	24 ^e	7900	1.55
	rt	44	14000	1.56
Mg	60	88	17200	2.72
	rt	59	8700	2.39
Ca	60	65	17100	2.29
	rt	>99	17600	2.68
Sr	60	63	10100	1.98
	rt	17	9800	1.70
Ba	60	75	18100	2.08
	rt	no polymerization		
Mn	60	84	15400	1.44
	rt	no polymerization		

^a Unless otherwise noted, the reaction was carried out with bromothiophene **1** (0.30 mmol), MCl_2 (1.1 eq), LDA (1.1 eq), and 2.0 mol% of Ni catalyst **2** in THF. Polymerization was carried out for 24 h. ^b Isolated yield. ^c Characterization of polythiophene **3** was performed by SEC analysis. The molecular weight was based on polystyrene standards. ^d PDI: Polydispersity index (M_w/M_n). ^e The reaction was carried out with cyclopentyl methyl ether (CPME) as a solvent.

Cooling of the mixture of 2-bromo-3-hexylthiophene **1** and divalent metal chloride at -78°C in THF resulted in forming the precipitate of the metal salt. The addition of LDA into the mixture, in which bromothiophene **1** was dissolved in THF, would undergo deprotonation at the 5-position of **1** to form a lithiated intermediate. The obtained organolithium then slowly reacts with a metal(II) salt to undergo the metal exchange reaction, during which the reaction was gradually raised to room temperature after stirring for 30 min at -78°C . Polymerization of the organometallic monomer of the divalent metal proceeds by the addition of nickel catalyst **2**. The reactivity of the in situ formed organometallic monomer of barium and manganese

would be much lower at room temperature and thus polymerization did not proceed.

Since relatively narrow PDI was achieved in the reaction with MnCl_2 , the relationship of the molecular weight toward the amount of the catalyst loading was studied as shown in Table 2. The obtained molecular weight of polythiophene **3** was found to increase as the amount of catalyst loading decreased whereas the M_n value was slightly high compared with exhibited reasonable values compared with the theoretical molecular weight in the range of the use of the nickel catalyst **2** with 1.0 to 3.0 mol%. The PDI values showed 1.32–1.60.

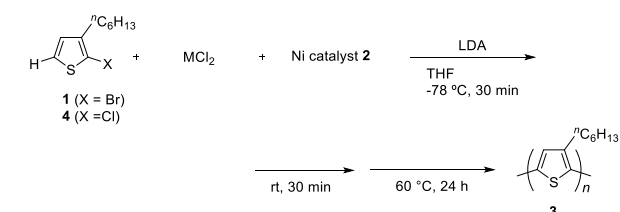
Table 2. Deprotonative metalation/polymerization with LDA in the presence of MnCl_2^a

2 (mol%)	Yield (%) ^b	theor M ^c	M_n^d	PDI ^d
1.0	67	16600	22300	1.60
1.5	55	11100	18300	1.53
2.0	84	8300	15400	1.44
3.0	>99	5500	11400	1.32

^a The reaction was carried out with bromothiophene **1**, MnCl_2 (1.1 eq), LDA (1.1 eq), in THF under similar manner performed in the reaction of Table 1. ^b Isolated yield. ^c The theoretical molecular weight (theor. M) based on the ratio of monomer amount/catalyst loading. ^d Measured by SEC analysis based on polystyrene standards.

It was also revealed that the one-shot polymerization, by which LDA the deprotonating agent is added into the mixture of bromothiophene **1**, metal(II) chloride, and nickel catalyst **2** altogether. Addition of LDA into such a mixture shown in Table 3 was performed at -78°C . After stirring the resulting mixture for 30 min, completion of the metal exchange would occur during gradually raising the reaction to room temperature. The polymerization would be initiated by the reaction with nickel **2** as a catalyst at 60°C . The polymerization was also shown to occur when the monomer is switched to chlorothiophene **4**.¹⁶ It was also found that the one-shot reaction also took place with other metal salts of calcium, strontium, and barium, however, the polydispersity of the obtained polymer **3** was much broader.

Table 3. One-shot polymerization of 2-halo-3-hexylthiophene with LDA, MCl_2 , and nickel catalyst **2**^a



Thiophene	MCl_2	Yield (%)	M_n^b	PDI ^b
1 (X=Br)	Mn	99	13000	1.40
4 (X=Cl)	Mn	66	6500	1.36

1	Ca	66	17300	2.46
1	Sr	42	14300	2.50
1	Ba	59	16900	3.03

^a The reaction was carried out with 2-halo-3-hexylthiophene MnCl_2 (1.1 eq), LDA (1.1 eq), and nickel catalyst **2** in THF. ^b The molecular weight of polythiophene **3** was measured by SEC analysis.

In summary, we have shown that one shot polymerization of 2-bromo-3-hexylthiophene **1** proceeds by the addition of LDA solution into the mixture of a metal(II) salt, thiophene monomer precursor **1**, and nickel catalyst **2**. The process undergoes metal exchange of lithium to some divalent metals, which allows smooth polymerization, avoids treatment of hygroscopic metal salts, and thus allows preparation of head-to-tail-type regioregular polythiophene from the deprotonation with LDA. Compared with McCullough's stepwise protocol, deprotonative metalation in the presence of polymerization catalyst as well as in situ metal exchange thereby improved pot economy of the reaction.¹⁷

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Procedures

Materials: Unless noted, chemicals were used as received. Group II metal chlorides, ZnCl_2 , and MnCl_2 were used after drying the solid heating at 100°C under reduced pressure in a Schlenk tube. Measurements of SEC (size exclusion chromatography) analyses were performed with a standard HPLC system equipped with a UV detector at 40°C using CHCl_3 as an eluent with Shodex HK-404L. Molecular weights and molecular weight distributions were estimated on the basis of the calibration curve obtained by 6 standard polystyrenes. PDI shows the ratio of number average molecular weight (M_n) and weight average molecular weight (M_w). THF (anhydrous grade) was purchased from Kanto Chemical. Co. Ltd. and passed through alumina and copper column (Nikko Hansen & Co. Ltd.) or distilled from sodium dispersion in a mineral oil/benzophenone ketyl prior to use.¹⁸

Poly(3-hexylthiophen-2,5-diyl) (3**) by one-shot polymerization of bromothiophene **1** with MnCl_2 :** In a 20 mL Schlenk tube equipped with a magnetic stirring bar $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ (65.3 mg, 0.33 mmol) was heated at 100°C under reduced pressure. After cooling to room temperature, argon was backfilled and $\text{NiCl}_2(\text{IPr})\text{PPh}_3$ (**2**, 4.7 mg, 0.006 mmol), THF (3 mL), and 2-bromo-3-hexylthiophene (**1**, 74.1 mg, 0.30 mmol) were added. The resulting mixture was cooled to -78°C and LDA (0.17 mL of 2.0 M THF/heptane/ethylbenzene solution, 0.33 mmol) was added dropwise. The temperature was kept at -78°C for 30 min and then, gradually raised to room temperature. After stirring was continued for further 30 min, the reaction mixture was heated at 60°C for 24 h. The reaction was quenched by the addition of methanol to form dark purple precipitates, which was filtered off. The residue was successively washed with methanol and hexanes repeatedly to afford 49.4 mg of polythiophene **3** (99% yield). The molecular weight was measured by SEC analysis based on polystyrene standards as $M_n = 13000$; PDI = 1.40. The spectroscopic properties and analytical data were found to be identical with those of the authentic sample.

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Supporting Information

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Primary Data

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