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COMMUNICATION

Highly Efficient C-C Cross-Coupling for Installing Thiophene Rings into π -Conjugated Systems

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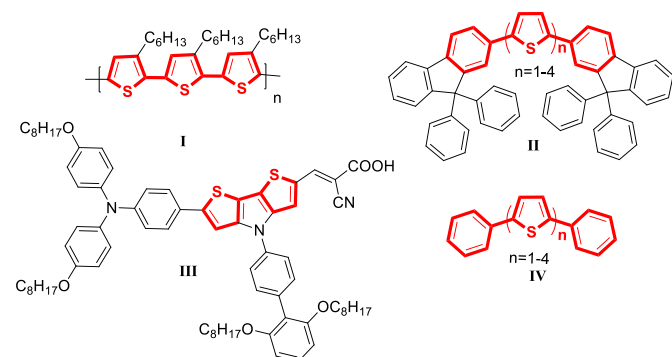
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Thiophene as one of the most common structural unit in functional organic materials, was efficiently installed into π -conjugated systems via a simple, ligand-free Suzuki coupling. The reaction proceeded with high efficiency and good functional-group compatibility while requiring 0.02 mol% of palladium catalyst.

Thiophene and its derivatives represent an important class of five-membered heterocyclic compounds in both organic synthesis and material science.¹ During the last few years, thiophene-based π -conjugated compounds have become a highly interdisciplinary field of research. Thousands of papers which related to the field of material science have been published. Various functionalized thiophenes have been extensively used for OPVs, DSSCs, OLEDs, and OFETs *etc.*²⁻⁴ The reason why these compounds are attractive is due to their characteristic properties such as stable oxidation states, unique electronic, optical, redox properties, excellent charge transport properties and so on,^{2a, 5} which make them one of the most crucial assets for applications in material science.

Scheme 1. Selected Examples of Molecules Material Containing Thiophene-arene Frameworks



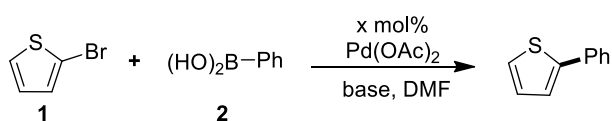
Selected examples of molecules material containing thiophene-arene frameworks are listed in Scheme 1. P3HT (I), a commercially

available material, was the most commonly used donor for OPVs.⁶ For FTn (II), it has been reported that their color of the emissions can be controlled by varying the conjugation length of the oligothiophene core.⁷ C251 (III) was described as one of the most efficient materials for DSSCs which presented a power conversion efficiency 9.3% at the 100 mW cm⁻² and simulated AM 1.5 conditions.⁸ Besides, the phenyl-capped oligothiophenes a-PnT (IV) have also been widely investigated.⁹ All these materials shared two common characteristics: they were π -conjugated systems and containing thiophene units. Thus, developing highly efficient C-C bond formations for installing thiophene rings into π -conjugated systems of molecules material is appealing and important.

The most exploited reaction for the preparation of thiophene-based π -conjugated compounds is the coupling of halogenated thienyls with metalated counterparts.¹⁰ Among these coupling reactions, palladium-catalyzed Suzuki reaction is more preferable owing to the generality and ability to tolerate a wide range of important organic functional groups. It offers an abundance of possibilities to transfer aryl groups into π -conjugated systems. Using Suzuki couplings, many thiophene-based materials have been synthesized.¹¹ Herein, we disclosed an effective synthetic approach for the preparation of thiophene-base π -conjugated molecules via a simple, ligand-free Suzuki couplings with a low catalyst loading (0.02 mol%).

Our initial investigation was focused on the condition screening of the reaction between 2-bromothiophene and phenylboronic acid. Detailed information was listed in Table 1. Initial base screening revealed that K₃PO₄·3H₂O, Na₂CO₃ and KOAc were less effective compared with K₂CO₃ in the presence of 2 mol% catalyst in 2 mL DMF at 80 °C for 12 h (Table 1, entries 1-4). Then we try to decrease the catalyst loading, and surprisingly found that lower catalyst loading also exhibited excellent reactivity in this transformation, among which 0.02 mol% Pd(OAc)₂ gave the best result (Table 1, entries 5-8).

Table 1. Optimization of the reaction conditions^a



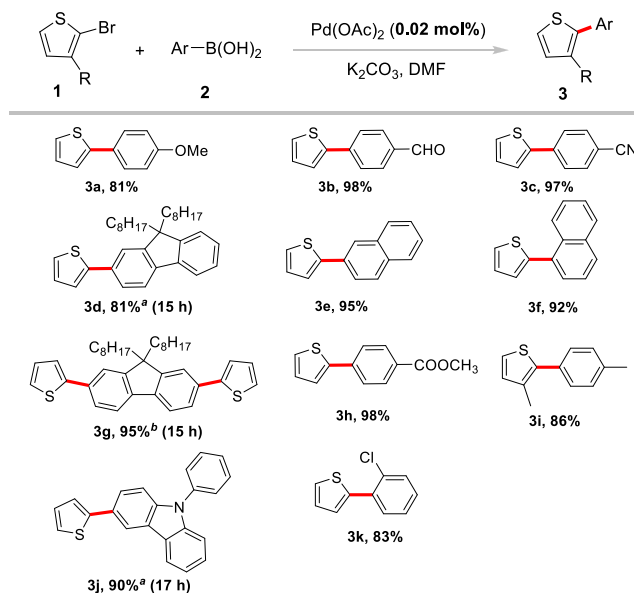
Entry	Pd (mol %)	Base	Yield(%) ^b
1 ^c	2	K ₃ PO ₄ ·3H ₂ O	68
2 ^c	2	Na ₂ CO ₃	74
3 ^c	2	KOAc	60
4 ^c	2	K ₂ CO ₃	87
5	0.2	K ₂ CO ₃	92
6 ^d	0.02	K ₂ CO ₃	99(92 ^e)
7	0.01	K ₂ CO ₃	89
8	0.005	K ₂ CO ₃	88
9 ^f	—	K ₂ CO ₃	N.D

^a Unless otherwise noted, the reaction was carried out with **1** (0.5 mmol), **2** (0.6 mmol), base (1.0 mmol), solvent (2 mL), 120 °C, 12 h. ^b The yield was determined by GC analysis with naphthalene as the internal standard. ^c 80 °C. ^d 1 mL DMF. ^e Isolated yield. ^f No catalyst was added.

Notably, the catalyst loading could be lowered to 0.005 mol%, along with a good yield of the desired product (Table 1, entry 8). However, no product was detected in the absence of Pd(OAc)₂ (Table 1, entry 9). Herein, the combination of reaction condition including 0.02 mol% of Pd(OAc)₂, 1.0 equiv of 2-bromothiophene, 1.2 equiv of arylboronic acid, 2.0 equiv of K₂CO₃ in DMF at 120 °C for 12 h was determined to be optimal conditions.

Subsequently, 2-bromothiophene was initially applied to introduce thiophene ring into *p*-conjugated systems with various aryl boronic acids. The results in Scheme 2 demonstrated that this reaction had a high degree of functional group tolerance. A variety of arylboronic acids proceeded efficiently to afford desired products in excellent yields. Arylboronic acids bearing electron-withdrawing groups including -CHO, -CN, -COOMe were well tolerated and gave excellent yields (**3b**, **3c**, **3h**). Electron-donating group such as methoxyl led to a good yield of the coupling product **3a**. Coupling of naphthalene boronic acids also occurred in excellent yields of 95% and 92% respectively (**3e**, **3f**). Steric hindrance on arylboronic acid or bromothiophene was reasonable tolerated in the reaction. For example, ortho-substituted phenylboronic acid coupled with 2-bromothiophene in a good yield (**3k**). 3-methyl-2-bromothiophene also reacted smoothly with 4-methyl-phenylboronic acid under the standard conditions in a high yield (86%, **3i**). Notably, Fluorene and carbazole borate which were often selected as building blocks in organic optoelectronic materials¹² showed excellent reactivity and gave the corresponding products in high yields (**3d**, **3g**, **3j**).

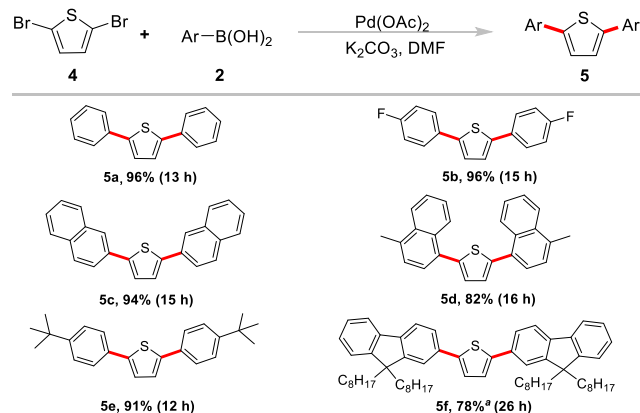
Scheme 2. Suzuki Coupling of 2-Bromothiophenes



Reaction conditions: 0.50 mmol of **1** (1.0 equiv), **2** (1.2 equiv), Pd(OAc)₂ (0.02 mol%), K₂CO₃ (2.0 equiv), DMF (1.0 mL), 12 h, 120 °C. ^a 0.25 mmol of **1** was used. ^b **1** (0.25 mmol), **2** (0.15 mmol). Isolated yield.

As a kind of active components, thiophene-based oligomers and polymers are pervasive in electronic devices and fluorescent materials. In order to elucidate the potential synthetic utility of our methodology in the field of materials science, we extended our studies on the double arylation of 2,5-bibromothiophene under the optimized conditions (Scheme 3). We were delighted to observe that high yields were generally obtained. Phenylboronic acid showed good reactivity and gave the desired products **5a** in 90% yield. Reaction of cyano-substituted phenyl boronic acid occurred in excellent yield of 96% (**5b**). Naphthalen-2-yl boronic acid and (4-methyl naphthalen-1-yl) boronic acid also coupled with 2,5-bibromothiophene smoothly and gave the corresponding products **5c** and **5d** in 94% and 82% yields, respectively.

Scheme 3. Suzuki Coupling of 2,5-Dibromothiophene

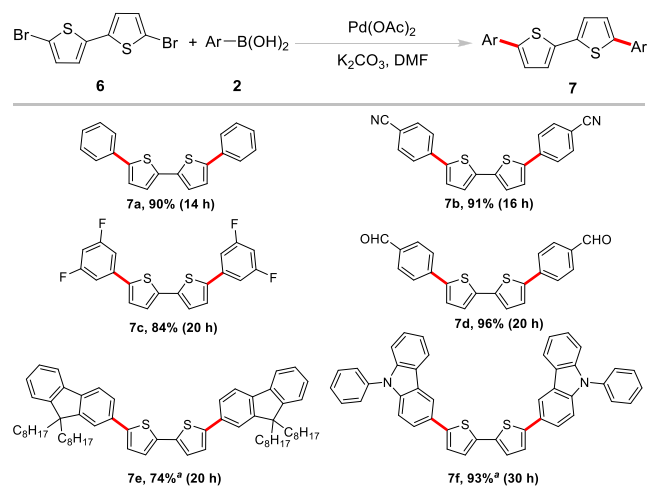


Reaction conditions: 0.25 mmol of **4** (1.0 equiv), **2** (2.4 equiv), Pd(OAc)₂ (0.04 mol%), K₂CO₃ (4.0 equiv), DMF (1.0 mL), 120 °C, 12 h. ^a 0.125 mmol of **4** was used. Isolated yield.

Tert-butyl functional group has been reported playing a potent effect on photoelectric properties. It helps to enhance the solubility

of materials, increase of steric hindrance to avoid congregating of molecules and so on.¹³ Therefore, 4-*t*-Bu-phenyl boronic acid was selected to couple with 2,5-dibromothiophene and the corresponding coupling product **5e** was obtained in 91% yield. Furthermore, another important unit in functional organic materials of 9,9-Bioctyl-fluorene was also introduced into the thiophene-based π -conjugated system. The corresponding borate of 9,9-bioctyl-fluorene was employed to react with 2,5-dibromothiophene and gave the product **5f** in 78% yield.

Scheme 4. Suzuki Coupling of 5,5'-Dibromo-2,2'-bithiophene



Reaction conditions: 0.25 mmol of **6** (1.0equiv), **2** (2.4 equiv), Pd(OAc)₂ (0.04 mol%), K₂CO₃ (4.0 equiv), DMF (1.0 mL), 120 °C, 12 h. ^a 0.125 mmol of **6** was used. Isolated yield.

Those promising results paved the way for the sequential investigations of employing 5,5'-dibromo-2,2'-bithiophene as substrate. Bithiophene is another active unit in organic semiconductor materials.¹⁴ However, in most of bithiophene-based coupling reactions, without some special ligands or poisonous tin reagents to help facilitate the reaction, it is difficult to get satisfactory results.¹⁵ Therefore, it is still a challenge to efficiently construct phenyl-capped oligo-thiophenes by Suzuki coupling. Under established optimized reaction conditions, a variety of arylboronic acids were examined to couple with 5,5'-dibromo-2,2'-bithiophene for the feasibility of this methodology as shown in Scheme 4. As expected, Phenylboronic acid proceeded well and afforded the coupling product **7a** in 90% yield. C-F bonds and -CN, -CHO groups were well tolerated to afford the coupling product in excellent yields (**7b-7d**). 9,9-Bioctyl-2-fluorene borate and 9-phenyl-3-carbazole boronic acid were also found to be reasonable coupling partners in this reaction (**7e-f**). Obviously, these transformations provided a straightforward access to the synthesis of biaryl-substituted bithiophene derivatives from readily available and inexpensive dibrominated bithiophene. Among these products, **7a** was one of the members of **IV** (n=2), its terminal phenyl groups evidently produced additional extension of the π -system.¹⁶ It has been reported that the crystal structure of **7b** displayed a high close packing. Its HOMO/LUMO levels and film orientation suggested the promising use of this compound as an active layer in FET devices.¹⁷ The existence of formyl functional group in **7d** offered the

opportunity for further utility in DSSCs.¹⁸ Moreover, fluoro-substituted aryl groups usually were beneficial for improving fluorescence quantum efficiency in luminescent materials which allow to **7c** as a candidate in material field.¹⁹

Conclusions

In summary, we have developed an efficient ligandless Suzuki coupling for installing thiophene and bithiophene units into π -conjugated systems. The reaction proceeded with high yields and good functional group compatibility while requiring only 0.02 mol% of palladium catalyst. The simplicity of the reaction procedure coupled with the possibility of obtaining a wide variety of aryl-thiophenes and oligo-thiophenes. Herein, this method will certainly attract the attention of material investigators interested in this class of compounds. Studies about further application of this methodology in organic photoelectric materials are currently in progress.

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