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Thioether-Directed *Peri*-Selective C−H Arylation under Rhodium Catalysis: Synthesis of Arene-Fused Thioxanthenes

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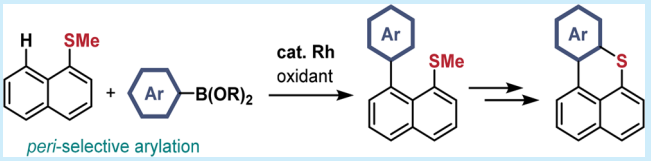
Supporting Information

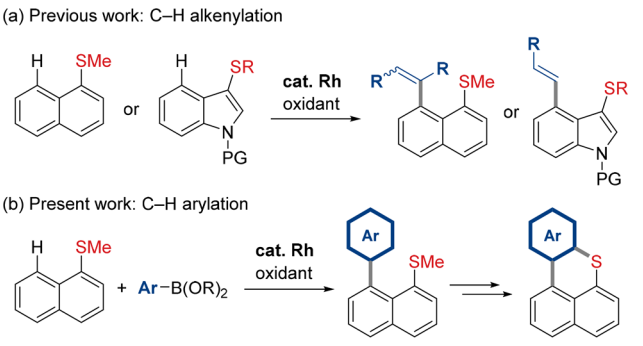
ABSTRACT: A rhodium-catalyzed direct C−H arylation of naphthalene and anthracene was developed with the assistance of a thioether directing group. The reaction proceeded with exclusive *peri*-selectivity, and the series of coupling products were readily transformed into the corresponding sulfur-containing polyaromatics. Charge-transport properties of the provided dithiapyrenes were evaluated by computational studies.



Sulfur-containing fused aromatic compounds have received tremendous attention because of their vital use in organic electronic materials such as field-effect transistors (OFETs), light-emitting diodes (OLEDs), and photovoltaics (OPVs).[1] To meet the increasing demand in this field, development of efficient synthetic methods for these compounds has been a substantial topic over the past decades.[2]

Recently, considerable research efforts have been focusing on the direct functionalization of aromatic C−H bonds[3] with the assistance of thioether directing groups.[4] A potential advantage of the reaction systems is that the directing groups can be easily converted into various other functional groups through sulfur−lithium exchange reactions[5] or transition-metal catalyses.[6] Our group has also been investigating the Rh-catalyzed direct functionalization of aromatic compounds using sulfur-containing directing groups[7] and recently disclosed the intriguing site-selectivity of the C−H alkenylation reactions for the acene *peri*-positions[7e] as well as the indole C4 positions[7f] (Scheme 1a). As a consequence of our interest in this area, we herein describe a rhodium-catalyzed[8] *peri*-selective C−H arylation of naphthalene and anthracene using boronic acid esters as arylating reagents (Scheme 1b). For the synthesis of sulfur-containing polyaromatic compounds, the acid-mediated cyclization of aromatic methyl sulfoxides has been one of the most promising methods.[9] Accordingly, the present catalytic reaction would provide valuable synthetic precursors of the thia-heterocycles by installing various aromatic units nearby the thiomethyl functionality. In fact, a series of coupling products readily underwent the cyclization to provide novel thioxanthene and dithiapyrene derivatives, which are key motifs in biologically active compounds[10] and optoelectronic materials.[11] Additionally, we evaluated the photo- and electrochemical properties of the provided thia-heterocycles.

Scheme 1. Sulfur-Directed Direct C−H Functionalization



We started our investigation with an optimization study for the direct C−H arylation using 1-(methylthio)naphthalene (**1**) and a boronic ester PhB(neo) (**2a**: neo = neopentyl glycolato) as representative substrates (Table 1). Initially, the corresponding coupling product **3a** was obtained in 15% yield in the presence of $[Cp^*Rh(CH_3CN)_3][SbF_6]_2$ catalyst along with Ag_2O oxidant in $PhCF_3$ (entry1). Solvent screening was then carried out, and the yield was improved up to 67% using *t*-AmOH (entries 2−4). Addition of any bases significantly retarded the reaction (entries 5 and 6). Ag_2CO_3 was less effective than Ag_2O in the present reaction system (entry 7), and no coupling product was obtained with $Cu(OAc)_2{\cdot}H_2O$ oxidant (entry 8). Replacement of the cationic Rh catalyst with a chloride complex $[Cp^*RhCl_2]_2$ resulted in a negligible outcome (entry 9). Further improvement was achieved with the increased amounts of the boron reagent and Ag_2O to furnish the desired compound in 90% isolated yield with exclusive *peri*-selectivity (entry 10). This reaction could be carried out on a subgram scale (entry 11). Although we tested other boron reagents, PhB(OH)$_2$ and PhB(pin) (pin = pinacolato), they gave lower yields (entries 12 and 13). A $[Cp^*RhCl_2]_2/AgSbF_6$ catalyst gave a lower yield (entry 14).

We next investigated the substrate scope with respect to the boronates under the optimized conditions (Table 1, entry 10),

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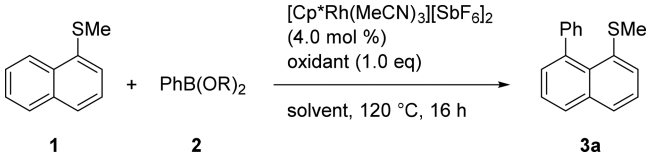
Table 1. Optimization Study for the Direct Arylation[a]



1 2 3a

entry	$PhB(OR)_2$	oxidant, additive	solvent	yield[b] (%)
1	PhB(neo)	Ag_2O	$PhCF_3$	15
2	PhB(neo)	Ag_2O	dioxane	21
3	PhB(neo)	Ag_2O	diglyme	41
4	PhB(neo)	Ag_2O	^{t}AmOH	67
5	PhB(neo)	Ag_2O, K_2CO_3 (1.0 equiv)	^{t}AmOH	11
6	PhB(neo)	Ag_2O, K_3PO_4 (1.0 equiv)	^{t}AmOH	5
7	PhB(neo)	Ag_2CO_3	^{t}AmOH	34
8	PhB(neo)	$Cu(OAc)_2·H_2O$ (2.0 equiv)	^{t}AmOH	nd
9[c]	PhB(neo)	Ag_2O	^{t}AmOH	trace
10[d]	PhB(neo)	Ag_2O (1.5 equiv)	^{t}AmOH	(90)
11[e]	PhB(neo)	Ag_2O (1.5 equiv)	^{t}AmOH	(71)
12[d]	$PhB(OH)_2$	Ag_2O (1.5 equiv)	^{t}AmOH	57
13[d]	PhB(pin)	Ag_2O (1.5 equiv)	^{t}AmOH	65
14[d,f]	PhB(neo)	Ag_2O (1.5 equiv)	^{t}AmOH	60

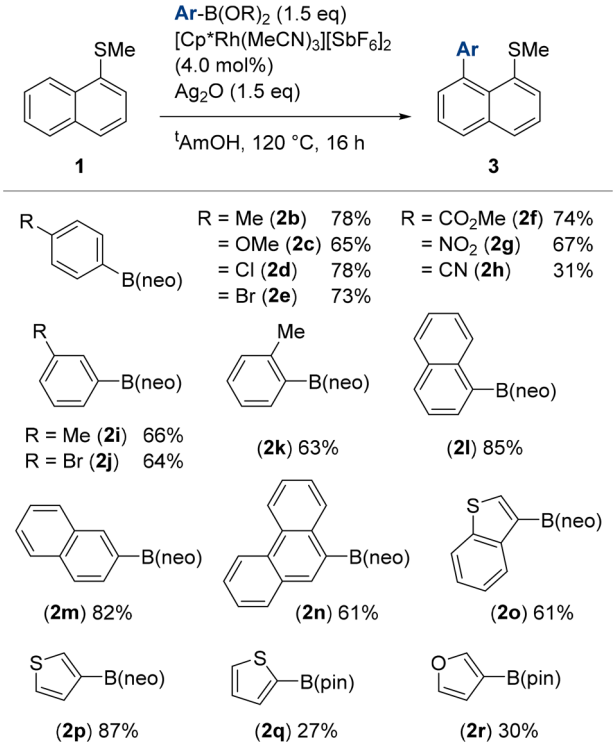
[a]Reaction conditions: **1** (0.1 mmol), $PhB(OR)_2$ (0.1 mmol), $[Cp^*Rh(MeCN)_3][SbF_6]_2$ (4.0 mol %), and oxidant (0.1 mmol) in solvent (1.0 mL). [b]Yield was determined by GC analysis. Isolated yield is in parentheses. [c]$[Cp^*RhCl_2]_2$ (2.0 mol %) was used instead of $[Cp^*Rh(MeCN)_3][SbF_6]_2$. [d]0.2 mmol scale: 1.5 equiv of $PhB(OR)_2$ was used. [e]2.0 mmol scale: 1.5 equiv of PhB(neo) was used, and the reaction time was for 24 h. [f]$[Cp^*RhCl_2]_2$ (2.5 mol %) and $AgSbF_6$ (10 mol %) were used instead of $[Cp^*Rh(MeCN)_3][SbF_6]_2$.

and the results are summarized in Scheme 2. Aryl boronic esters bearing various functional groups at the *para* position, involving alkyl (**2b**), alkoxy (**2c**), halogen (**2d** and **2e**), ester (**2f**), nitro (**2g**), and cyano (**2h**), were well tolerated under the present catalytic conditions to afford the corresponding *peri*-arylated products. The *meta* and *ortho* substituents did not largely decrease the reaction efficiency (**2i–k**). Naphthyl and phenanthryl groups were also successfully installed to give **3l–n** in good to high yields. Importantly, heteroaromatic substrates were also applicable to the current transformation. Benzo[*b*]thiophene-3-yl (**2o**) and thiophene-3-yl (**2p**) boronates reacted smoothly. However, a significant drop of the product yield was observed with either thiophene-2-yl boronate (**2r**) or furan-3-yl boronate (**2s**). This is probably due to their instability under the catalytic conditions, and the pinacol esters gave higher yields for these substrates. Pyridine-4-yl boronate was not a suitable substrate for the present system (not shown).

Subsequently, double C–H arylation was tested (Scheme 3).[12] Two aryl groups could be introduced to 9-(methylthio)-anthracene (**4**) to give the corresponding products **5a** and **5b**, although the yields were low to moderate. Both of the *peri* positions were successfully arylated in case two SMe directing groups present on the periphery of naphthalene ring (**6** and **8**), producing the 1,4,5,8-tetrasubstituted naphthalenes with different molecular connectivity (**7** and **9**).

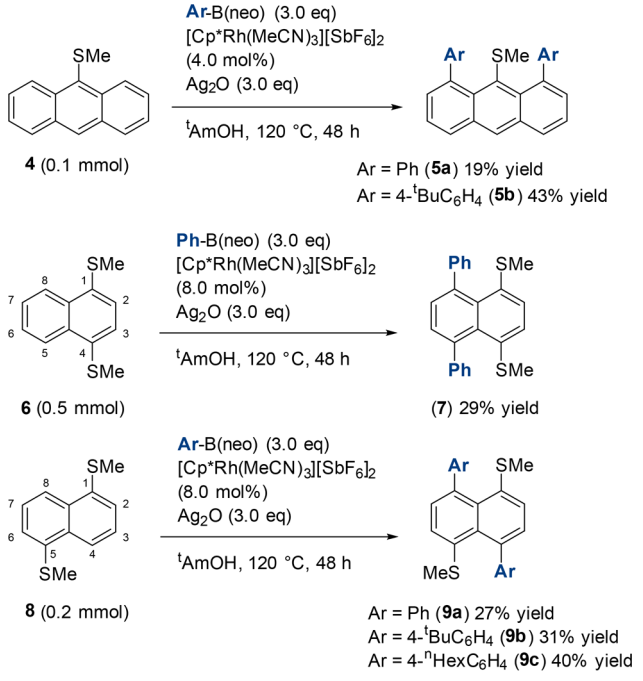
With the series of coupling products in hand, we turned our attention to the construction of various fused thia-heterocycles through acid-mediated annulation (Scheme 4). The thioether group was oxidized by reaction with *m*-CPBA, and the resulting sulfoxides were sequentially treated with TfOH (Tf

Scheme 2. Substrate Scope for the Boron Reagents[a]



[a]Reaction conditions: **1** (0.2 mmol), **2** (0.3 mmol), Ag_2O (0.3 mmol), and $[Cp^*Rh(MeCN)_3][SbF_6]_2$ (4.0 mol %) in ^{t}AmOH (2.0 mL). nd = not detected.

Scheme 3. Double C–H Arylation



= trifluoromethanesulfonyl) and pyridine. Cyclization incorporating the installed aryl fragments proceeded smoothly to afford the corresponding benzo[*kl*]thioxanthenes **10–12** in high yields. This method could also be applied to the construction of benzo-fused dithiapyrene derivatives **13** and **14** via the 2-fold C–S annulation. In the cyclic voltammetry

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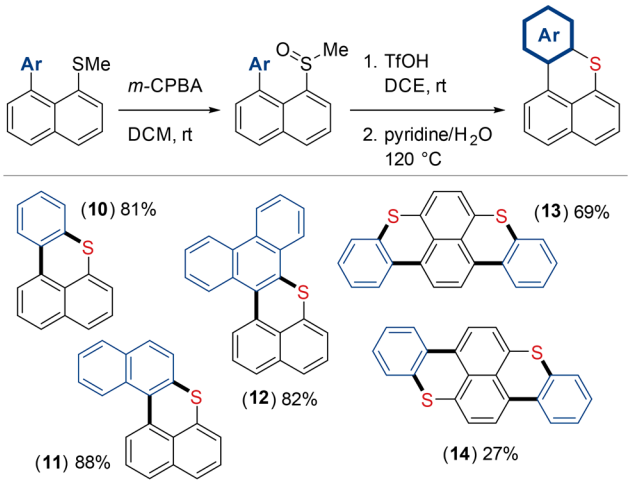
Scheme 4. Acid-Mediated Cyclization of Sulfoxides[a]



[a]Isolated yields over two steps are shown.

measurement of the doubly cyclized compounds **13** and **14**, both of them exhibited two oxidation peaks as expected,[11a] and the HOMO levels were estimated to be −4.76 and −4.72 eV, respectively (for details, see the Supporting Information).

Considering the potential application of dithiapyrene derivatives as semiconductor materials,[13] we also investigated the solid-state structure of **13** and **14** by X-ray crystallography. The 1,4-isomer **13** has a nonplanar shape where one sulfur atom (S1 in Figure 1) is pointing in an out-of-plane direction

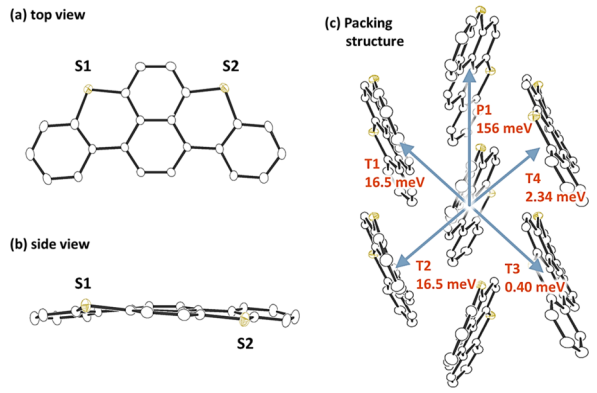


Figure 1. Solid-state structure of **13** drawn with 30% thermal probability. Hydrogen atoms are omitted for clarity. The values indicate the transfer integral for each direction.

with a torsion angle of 18.6° from the hydrocarbon body. Weak $\pi-\pi$ stacking (3.33−3.36 Å) and CH/π interactions are presumably responsible for its packing structure (Figure 1c). On the other hand, the 1,5-isomer **14** has a planar structure and crystallizes into the well-ordered herringbone packing mode (Figure 2). There exist two independent S···H short interstack contacts whose distances are, respectively, 2.98 and 2.99 Å; however, no significant $\pi-\pi$ or CH/π interactions are observed. To estimate the charge-transport properties of these compounds, we carried out computational studies using the ADF (Amsterdam Density Functional package)[14,15] program for the atom coordinates obtained by the X-ray analyses. The compound **13** showed a large transfer integral along the π-stacking direction (P: 156 meV), whereas those of the

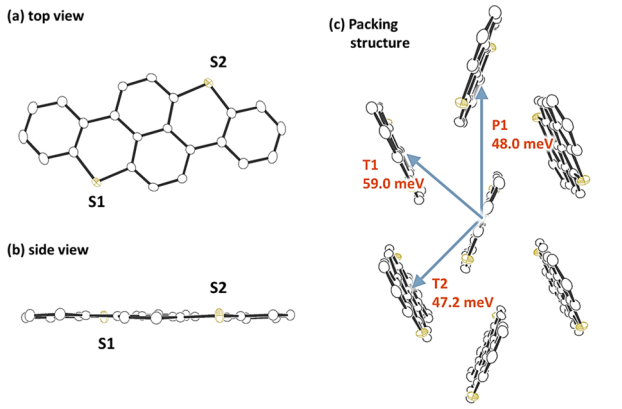
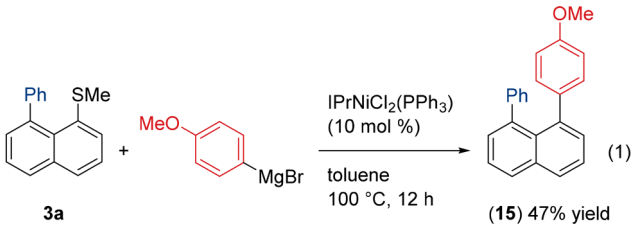


Figure 2. Solid-state structure of **14** drawn with 40% thermal probability. Hydrogen atoms are omitted for clarity. The values indicate the transfer integral for each direction.

transverse directions were rather small (T1−T4: 0.40−16.5 meV). In sharp contrast to the highly anisotropic nature of **13**, relatively large transfer integrals both in the stacking (P: 48.0 meV) and transverse directions (T1: 59.0 meV, T2: 47.2 meV) were calculated for **14**. Moreover, a relatively small reorganization energy (λ: 185 meV) was given to **14**.

As another example for the synthetic application of the thioether directing group, we examined a catalytic transformation of the SMe group on **3a** (eq 1). Applying a nickel-catalyzed cross-coupling reaction with Grignard reagent,[16] the 4-methoxyphenyl group was introduced onto the naphthalene ring to give an asymmetrically substituted 1,8-diarylnaphthalene **15** in 47% yield. This type of compound has been used for evaluating the through-space aromatic interaction.[17]



In conclusion, we have developed a rhodium-catalyzed direct C−H arylation of naphthalene and anthracene derivatives using a thioether directing group. The reaction system exhibited broad functional group compatibility and exclusive *peri*-selectivity. The coupling products were readily transformed into the corresponding sulfur-containing poly aromatics. Preliminary structural and computational studies on the obtained dithiapyrene derivatives implied the unique relationship between molecular connectivity and isotropic/anisotropic charge-transport characteristics of them.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.8b03675.

Detailed experimental procedures and computational methods, product identification data, optical and electrochemical measurements, ORTEP drawings, and NMR spectra (PDF)

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Accession Codes

CCDC 1877717 and 1877720−1877721 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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(12) Considerable amounts of monoarylated products (14−47%, GC−MS) were also formed in these reactions.

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