Macromolecules
Article
pubs.acs.org/Macromolecules

Scope and Regioselectivity of Iridium-Catalyzed C−H Borylation of Aromatic Main-Chain Polymers

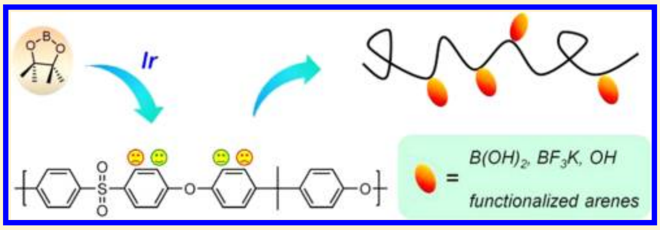
Ying Chang,[†,‡] Hanniel H. Lee,[‡] Se Hye Kim,[‡] Tae Soo Jo,[‡] and Chulsung Bae[†,‡,*]

[†]Department of Chemistry and Chemical Biology, New York State Center for Polymer Synthesis, Rensselaer Polytechnic Institute, 110 Eighth Street, Troy, New York 12180, United States

[‡]Department of Chemistry, University of Nevada Las Vegas, 4505 Maryland Parkway, Box 454003, Las Vegas, Nevada 89154−4003

Ⓢ *Supporting Information*

ABSTRACT: An efficient functionalization of aromatic main-chain polymers was established using a combination of iridium-catalyzed borylation of aromatic C−H bonds and the Suzuki−Miyaura coupling reaction. Comparative studies of various iridium catalysts and borylation reagents show that $[Ir(OMe)(COD)]_2$ is significantly more active than $[IrCl(COD)]_2$, and bis(pinacolato)diboron induces higher efficiency than pinacolborane. The regioselectivity of the borylation was investigated using model compounds that mimic the repeating unit structure of poly(arylene ether sulfone). The C−H bonds of the sulfone model compound were more reactive than those of the bisphenol model compound, and the borylation occurred preferentially at the meta position to the sulfone moiety owing to steric hindrance and electronic effects. The glass transition temperature of the borylated polymer increases with increasing concentration of pinacolboronic ester group. The pinacolboronic ester group could be conveniently converted to boronic acid $[B(OH)_2]$ and potassium trifluoroborate (BF_3K), which could also serve as versatile reactive sites for the synthesis of a wide range of functionalized polymers via Suzuki−Miyaura couplings.



INTRODUCTION

Aromatic main-chain polymers are important high-performance engineering plastics owing to excellent thermo-mechanical stability and chemical resistance. For example, Udel poly(arylene ether sulfone) (PSU) has been used extensively as a base material in membrane-based separation technology owing to its robust stability and semipermeable structure.[1,2] Incorporating specific functional groups into aromatic main-chain polymers such as PSU expands the properties and broadens the application of these polymers in material science.

Two approaches have been pursued to incorporate desired functional groups into PSU: (1) copolymerization with functionalized monomers, and (2) postfunctionalization. In the copolymerization method, nucleophilic functional groups, such as alcohol and amine, interfere with reactive sites during nucleophilic aromatic substitution polymerization and form undesired low-molecular-weight polymer products. In addition, because the polycondensation is generally conducted at high temperature (typically >150 °C), sensitive functional groups cannot survive during the polymerization.[3,4]

Postfunctionalization allows the introduction of a wide range of functional groups onto polymers, frequently that are not compatible with the original polymerization methods. Among postfunctionalization approaches, electrophilic aromatic substitutions (e.g., sulfonation,[5,6] bromination,[7,8] chloromethylation,[9−11] and amidoalkylation[12]) are the most commonly used strategies to introduce functional groups into the aromatic rings of PSU. Because a variety of polymers with different molecular weights can be used as starting materials, a controlled postfunctionalization could, in principle, create a broad range of functionalized PSUs with various molecular weights. However, electrophilic functionalization of PSU involves the formation of highly reactive carbocation intermediates and, as a result, frequently causes undesirable side reactions such as chain scission and gelation (i.e., extensive cross-linking of polymer chains). These side reactions can alter the molecular weights and physical properties of functionalized polymers. Thus, delicate control of the reaction conditions is essential to avoid or minimize undesirable side reactions along polymer chains. Postfunctionalization of PSU through lithiation followed by reaction with electrophiles has been investigated, but lithiation also requires well-controlled, low-temperature conditions owing to the extreme reactivity of lithiating reagents.[13−15]

Recently, functionalization of C−H bonds using transition metal catalysts has emerged as a new versatile strategy in organic synthesis[16−21] and polymer functionalization.[22−29] In contrast to traditional polymer functionalizations via reactive free radical or carbocation intermediates, which frequently cause undesired side reactions, this new method induces negligible changes in the molecular weights of functionalized polymers. Of special interest, iridium-catalyzed borylation of aromatic C−H bonds has afforded controlled functionalization

Received: December 17, 2012
Revised: February 8, 2013

© XXXX American Chemical Society

of commercial polystyrenes with various tacticities. The pinacolboronic ester (Bpin) group has been introduced into the aromatic rings of polymer chains without negatively affecting chain length or the tacticity of the starting polymer.[26,27] We have also discovered that aromatic main-chain polymers such as PSU can be functionalized in a controlled manner using an iridium-catalyzed C−H borylation. Bpin-functionalized PSU is a versatile precursor that can generate a variety of polymers containing specific functional groups with targeted concentrations.[28,29] This new transition metal-catalyzed synthetic method of functionalized aromatic polymers is unique in a sense that it can convert aromatic C−H bonds of polymers *directly* to a variety of functional groups (a) without requiring to have a precursor group in polymerization and (b) without restriction on the molecular weight of polymers. For example, Grignard metathesis polymerization (GRIM) has been a widely used synthetic method for conjugated aromatic polymers. However, due to incompatibility with Grignard reagents only a limited examples of functional groups (alkyl and alkoxy in most cases) can be attached to the aromatic main-chain polymers.[30] Although ruthenium-catalyzed ring-opening metathesis polymerization (ROMP) allows incorporation of more diverse ranges of functional groups into of polyolefins,[31] it cannot be applied for the synthesis of aromatic main-chain polymers. While both GRIM and ROMP require preinstallation of a functional (or precursor) group in monomer before the polymerization, the iridium-catalyzed C−H borylation of aromatic polymers does not.

Unless polymer substrate has a preferentially reactive C−H bond, the iridium-catalyzed C−H borylation of an aromatic polymer affords a mixture of randomly functionalized isomeric polymer products, which is a major difference in comparison with GRIM and ROMP. Thus, we investigated the scope and regioselectivity of the iridium-catalyzed C−H borylation using PSU as parent polymer in this study. The PSU repeating unit has four different aromatic C−H bonds that can be borylated, each with a different reactivity toward the borylation. Because the direct analysis of regioisomers of functionalized polymers was difficult, we examined the regioselectivity of the PSU borylation by studying the reaction of corresponding model compounds.

■ EXPERIMENTAL SECTION

General Comments. Udel poly(arylene ether sulfone) [PSU; M_n = 22.0 kg/mol, polydispersity index (PDI) = 1.65 measured from size exclusion chromatography (SEC) using THF as eluent] and pinacolborane (HBpin) were purchased from Sigma-Aldrich. 4,4′-Di-*tert*-butyl-2,2′-dipyridyl (d*t*bpy), di-*μ*-methoxobis(1,5-cyclooctadiene)-diiridium(I) ([Ir(OMe)(COD)]$_2$), and tetrakis(triphenylphosphine)-palladium(0) [Pd(PPh$_3$)$_4$] were obtained from Strem Chemicals Inc. and used as received. Hexane, methanol, and chloroform were reagent grade and used without further purification. Anhydrous tetrahydrofuran (THF) was obtained from Acros Organics and stored in a nitrogen-filled glovebox. Bis(pinacolato)diboron (B$_2$pin$_2$) and chloro-1,5-cyclooctadiene iridium(I) dimer ([IrCl(COD)]$_2$) were obtained from Frontier Scientific Co. and Sinocompound Technology Co., respectively, and used without further purification. Synthetic procedures of model compounds and their NMR spectra, including **S**, **B**, **P**, **S-*o*-Bpin**, **S-*m*-Bpin**, **B-*m*-Bpin**, **S-*o*-BF$_3$K**, **S-*m*-BF$_3$K**, and **B-*m*-BF$_3$K**, were given in the Supporting Information.

^{1}H, ^{13}C, ^{11}B, and ^{19}F NMR spectra were obtained at 400, 100, 128, and 376 MHz, respectively. ^{1}H and ^{13}C NMR chemical shifts were referenced to solvent residue peak, and ^{19}F NMR chemical shifts were referenced to CFCl$_3$. ^{11}B NMR chemical shifts were reported relative to an external reference of BF$_3$−Et$_2$O. The NMR samples were prepared by applying gentle heat to dissolve polymer in specific deuterated solvents. The mol % of Bpin in borylated polysulfone (PSU−Bpin) was estimated based on the relative intensity of resonances of −C(C*H*$_3$)$_2$− in the polymer main chain (at 1.6−1.7 ppm) and the four methyl groups of the Bpin (at 1.0−1.2 ppm).

Molecular weight measurement was performed using a VISCOTEK SEC equipped with three Jordi−HPLC Series columns and tetra detector array (UV/vis, low and right angle light scattering, refractive index, viscometer) at 40 °C. THF was the mobile phase and the flow rate was set at 0.3 mL/min. The instrument was calibrated using polystyrene standards.

Table 1. Iridium-Catalyzed Arene C−H Borylation of Poly(arylene ether sulfone) (PSU) with Bis(pinacolato)diboron (B$_2$pin$_2$).[a]

			PSU−Bpin			
entry	B$_2$pin$_2$ /PSU	cat.[b]	M_n[c]	PDI[c] (M_w/M_n)	Bpin (%)[d]	eff. (%)[e]
1	0.2	A	22.4	1.97	23	57
2	0.2	B	23.3	1.82	27	69
3	0.4	A	23.9	1.97	64	80
4	0.4	B	29.0	1.66	72	90
5	0.6	A	28.8	1.78	95	79
6	0.6	B	30.6	1.76	101	84
7	0.8	A	30.3	1.86	126	79
8	0.8	B	32.0	1.78	135	85
9	1.0	A	32.9	1.77	147	74
10	1.0	B	35.6	1.66	165	83
11[f]	1.0	A	22.3	1.83	26	13
12[f]	1.0	B	32.8	1.83	158	79
13	1.2	A	36.5	1.80	175	73
14	1.2	B	40.5	1.57	184	77
15	1.4	A	33.5	1.88	196	70
16	1.4	B	42.1	1.47	208	74
17	1.6	A	37.6	1.81	206	65
18	1.6	B	45.8	1.42	227	71

[a] Bpin = pinacolboronate ester. PSU (M_n = 22.0 kg/mol, PDI = 1.65). Unless otherwise specified, C−H borylation was conducted on 0.20 g of polymer with 3 mol % of iridium and 3 mol % of ligand relative to B$_2$pin$_2$ in 1 mL THF at 80 °C for 12 h. [b] A: [IrCl(COD)]$_2$. B: [Ir(OMe)(COD)]$_2$. [c] M_n in kg/mol and PDI were measured with size-exclusion chromatography using THF as the mobile phase at 40 °C relative to polystyrene standards. [d] Molar percentage of Bpin group per repeating unit of PSU calculated based on ^{1}H NMR spectrum. 100% indicates an average of 1.00 Bpin group is attached to the PSU repeating unit. [e] Efficiency of C−H borylation: amount of Bpin attached to the polymer divided by the number of boron atoms added. [f] C−H borylation was conducted at room temperature for 18 h.

Preparation of PSU−Bpin Using B$_2$pin$_2$ (Entry 1 of Table 1). In a nitrogen-filled glovebox, PSU (0.20 g, 0.45 mmol of polymer repeating unit), B$_2$pin$_2$ (23 mg, 0.09 mmol), [IrCl(COD)]$_2$ (0.9 mg, 1.5 mol % based on the amount of B$_2$pin$_2$), d*t*bpy (0.7 mg, 3 mol % based on the amount of B$_2$pin$_2$), THF (1 mL) and a magnetic stirring bar were placed into a vial and the vial was capped with a Teflon-lined septum. The vial was removed from the glovebox and stirred in an oil bath at 80 °C for 12 h. After cooling to room temperature, the reaction solution was diluted with chloroform and filtered through a short plug of silica gel to remove the catalyst. The filtrate was concentrated using a rotary evaporator and poured into hexane to precipitate polymer. The dissolution and precipitation process was repeated one more time to ensure complete removal of any impurities trapped in polymer. The borylated polymer was isolated as a white solid and was dried under vacuum at 60 °C for 12 h (0.20 g). ^{1}H NMR (CDCl$_3$): δ 8.26−8.34 (H_{arom}), 7.72−7.92 (H_{arom}), 7.14−7.30 (H_{arom}), 6.80−7.04 (H_{arom}), 1.60−1.74 [$C(CH_3)_2$ of PSU main chain], 1.22 and 1.01 [$BOCCH_3$]. ^{13}C NMR ($CDCl_3$): δ 165.4, 161.9, 154.7, 152.8, 147.3, 147.1, 145.9, 136.3, 135.6, 135.3, 131.0, 129.7, 129.5, 129.4, 128.4, 128.1, 119.8, 119.7, 118.7, 118.3, 117.6, 116.5, 113.3 (all from C_{arom}), 83.9 [$BOC(CH_3)$], 42.6 [$C(CH_3)_2$ of PSU main chain], 30.9 [$C(CH_3)_2$ of PSU main chain], 24.5 [$BOC(CH_3)$]. ^{11}B NMR ($CDCl_3$): δ 30.4 (broad).

Table 2. Iridium-Catalyzed Arene C−H Borylation of Poly(arylene ether sulfone) (PSU) with Pinacolborane (HBpin).[a]

			PSU−Bpin			
entry	HBpin/PSU	cat.[b]	M_n[c]	PDI[c] M_w/M_n	Bpin (%)[d]	eff. (%)[e]
1	0.6	A	22.8	1.96	33	55
2	0.6	B	25.2	1.82	39	65
3	1.0	A	29.8	1.81	55	55
4	1.0	B	28.9	1.73	66	66
5	1.4	A	29.8	1.75	66	47
6	1.4	B	31.8	1.68	93	66

[a] Bpin = pinacolboronate ester. PSU (M_n = 22.0 kg/mol; PDI = 1.65). Unless otherwise specified, C−H borylation was conducted on 0.20 g of polymer with 3 mol % of iridium and 3 mol % of ligand relative to HBpin in 1 mL THF at 80 °C for 24 h. [b] A: $[IrCl(COD)]_2$. B: $[Ir(OMe)(COD)]_2$. [c] M_n in kg/mol and PDI were measured with size-exclusion chromatography using THF as mobile phase at 40 °C relative to polystyrene standards. [d] Molar percentage of Bpin group per repeating unit of PSU calculated based on ^1H NMR spectrum. 100% indicates an average of 1.00 Bpin group is attached to the PSU repeating unit. [e] Efficiency of C−H borylation: amount of Bpin attached to the polymer divided by the number of boron atoms added.

Preparation of PSU−Bpin Using HBpin (Entry 1 of Table 2). In a nitrogen-filled glovebox, PSU (0.20 g, 0.45 mol of polymer repeating unit), HBpin (35 mg, 0.27 mmol), $[IrCl(COD)]_2$ (2.7 mg, 1.5 mol % based on the amount of HBpin), d*t*bpy (2.2 mg, 3 mol % based on the amount of HBpin), THF (1 mL) and a magnetic stirring bar were placed into a vial and the vial was capped with a Teflon-lined septum. The vial was removed from the glovebox and stirred in an oil bath at 80 °C for 24 h. After cooling to room temperature, the reaction solution was diluted with chloroform and filtered through a short plug of silica gel to remove the catalyst. The filtrate was concentrated using a rotary evaporator and poured into hexane to precipitate polymer. The dissolution and precipitation process was repeated one more time to ensure complete removal of any trapped impurities in the polymer. The polymer was isolated as a white solid and dried under vacuum at 60 °C for 12 h (0.21 g). NMR data (^1H, ^{13}C, ^{11}B) were identical to those prepared with B_2pin_2.

General Procedure for Preparation of PSU−FG via Suzuki−Miyaura Coupling Reaction of PSU−Bpin. In a nitrogen-filled glovebox, 46% PSU−Bpin (0.15 g, 0.14 mmol of Bpin), functionalized phenyl bromide (1.38 mmol, 10 equiv based on the amount of boryl group of PSU−Bpin), $Pd(PPh_3)_4$ (4.8 mg, 3 mol % based on the amount of boryl group of PSU−Bpin), K_2CO_3 (57 mg, 3 equiv based on the amount of boryl group of PSU−Bpin), THF (2 mL) and a magnetic stirring bar were placed into a 4 mL vial. The vial was capped with a Teflon-lined septum and was removed from the glovebox. Deionized water (0.2 mL) was added to the vial using a micro syringe, and the reaction mixture was stirred at 80 °C oil bath for 6 h. After cooling to room temperature, the reaction solution was diluted with chloroform and filtered through a short plug of silica gel, concentrated using a rotary evaporator and poured into hexane to precipitate polymer. The dissolution and precipitation process was repeated one more time. The filtered polymer was dried under vacuum at 80 °C for 12 h.

Preparation of PSU−OH. 46% PSU−Bpin (0.50 g, 0.46 mmol Bpin) was dissolved in dioxane (60 mL). Two M NaOH solution (3 mL) and 30% H_2O_2 (3 mL) were slowly added in sequence to the stirring polymer solution and the reaction mixture was stirred for 1 h at 50 °C. The polymer was precipitated as a white solid during the reaction due to the change of solubility. After removal of liquid from the solution residual polymer was washed with water and methanol, filtered and dried at 80 °C under vacuum for 12 h (0.31 g). ^1H NMR (DMSO-d_6): δ 7.60−7.90, 7.25, 6.80−7.10, 6.30−6.70 (all from H_{arom}), 1.40−1.70 [$C(CH_3)_2$].

Preparation of PSU−B(OH)$_2$. 46% PSU−Bpin (0.50 g, 0.46 mmol Bpin) was dissolved in dioxane (60 mL) and $NaIO_4$ (1.47 g, 6.89 mmol, 15 equiv) was added. Water (3 mL) was added dropwise to the polymer solution and the reaction mixture was stirred at 90 °C for 8 h. After evaporation of the solvent using a rotary evaporator, the residual polymer was washed with a mixture of methanol and water, filtered and dried at 80 °C under vacuum for 12 h (0.50 g). ^1H NMR (DMSO-d_6): δ 8.26, 7.80−8.05, 7.25, 6.70−7.10 (all from H_{arom}), 1.61 [$C(CH_3)_2$].

Preparation of PSU−BF$_3$K. 46% PSU−Bpin (0.50 g, 0.46 mmol Bpin) was dissolved in dioxane (60 mL). An aqueous solution of KHF_2 [0.54 g (6.89 mmol, 15 equiv) dissolved in 6 mL of water] was added dropwise to the polymer solution and the reaction mixture was stirred at 90 °C for 8 h. The reaction solution was concentrated using a rotary evaporator and poured into methanol to precipitate polymer. The obtained polymer was washed with water and methanol, filtered and dried at 80 °C under vacuum for 12 h (0.48 g). ^1H NMR (DMSO-d_6): δ 8.27, 7.80−8.05, 7.26, 6.70−7.12 (all from H_{arom}), 1.62 [$C(CH_3)_2$]. ^{19}F NMR (DMSO-d_6): δ −137.6 (BF_3K).

*Competitive C−H Borylation of Model Compounds **S** and **B**.* Model compounds **S** (53 mg, 0.19 mmol) and **B** (49 mg, 0.19 mmol), B_2pin_2 (77 mg, 0.3 mmol), $[IrCl(COD)]_2$ (3.0 mg, 1.5 mol % of B_2pin_2), d*t*bpy (2.5 mg, 3 mol % of B_2pin_2), THF (0.25 mL) and a magnetic stirring bar were added to a 4 mL vial which was capped with a Teflon-lined septum in a nitrogen-filled glovebox. The reaction mixture was stirred at 80 °C for 12 h. After cooling to room temperature, the reaction solution was diluted with ethyl acetate (30 mL), washed with water (15 mL × 3) and brine (15 mL), and dried with magnesium sulfate. Evaporation of volatile solvent using a rotary evaporator gave 0.16 g of borylated product as a brown syrup which was analyzed by ^1H NMR spectroscopy (DMSO-d_6): δ 8.08−8.10, 7.90−8.00, 7.80−7.86, 7.40−7.42, 7.06−7.24, 6.78−6.87 (all from H_{arom}), 3.81, 3.71, 1.57, 1.28, 1.24, 1.16.

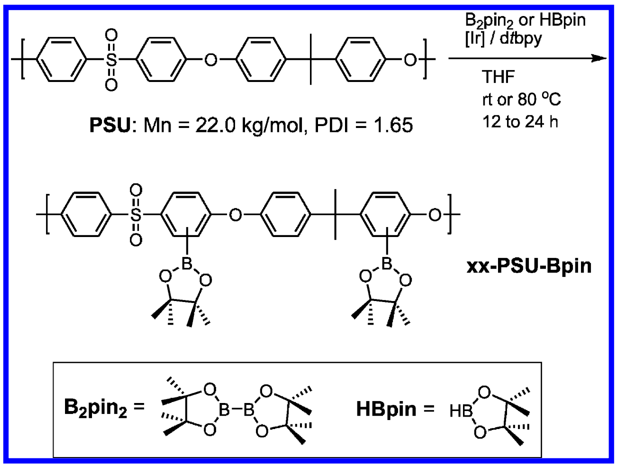
*Conversion of a Mixture of **S-Bpin** and **B-Bpin** to **S-BF$_3$K** and **B-BF$_3$K**.* The above crude product (a mixture of **S-Bpin** and **B-Bpin**, 0.16 g), KHF_2 (0.24 g, 3.04 mmol), THF (1.5 mL), water (0.5 mL) and a magnetic stirring bar were added to a 4 mL vial which was capped with a Teflon-lined septum. The reaction mixture was stirred for 12 h at room temperature. After evaporation of the solvent using a rotary evaporator, the residue was dissolved in acetone and filtered to remove insoluble solid. Evaporation of the filtrate using a rotary evaporator gave 92 mg of product which was analyzed by ^{19}F NMR spectroscopy (DMSO-d_6): δ −135.9, −137.5 (an integral ratio of 1:6).

*C−H Borylation of Model Compound **P**.* Model compound **P** (60 mg, 0.12 mmol), B_2pin_2 (24 mg, 0.09 mmol, 0.8 equiv), $[IrCl(COD)]_2$ (0.9 mg, 1.5 mol % of B_2pin_2), d*t*bpy (0.7 mg, 3 mol % of B_2pin_2), THF (0.2 mL) and a magnetic stirring bar were added to a 4 mL vial which was capped with a Teflon-lined septum in a glovebox. The reaction mixture was stirred at 80 °C for 12 h. After cooling to room temperature, the reaction solution was diluted with ethyl acetate (30 mL), washed with water (15 mL × 3) and brine (15 mL), and dried with magnesium sulfate. Evaporation of volatile solvent using a rotary evaporator gave borylated product as a brown syrup (76 mg). The borylated **P**, KHF_2 (73 mg, 0.93 mmol), THF (1.0 mL), water (0.3 mL), and a magnetic stirring bar were added to a 4 mL vial which was capped with a Teflon-lined septum. After stirring for 12 h at room temperature, the reaction solution was evaporated using a rotary evaporator. The residue was dissolved in acetone and filtered to remove insoluble solid. Evaporation of the filtrate gave 92 mg of yellowish solid which was analyzed by ^{19}F NMR spectroscopy (DMSO-d_6): δ −136.4, −137.6 (an integral ratio of 1:7).

RESULTS AND DISCUSSION

A. C−H Borylation of Poly(arylene ether sulfone). The iridium-catalyzed C−H borylation of PSU with various molar ratios of B_2pin_2 to polymer repeating unit in THF produced borylated polymers (PSU−Bpin) containing various concentrations of Bpin group (Scheme 1). PSU repeating unit contains one isopropylidene group and four aromatic rings with multiple C−H bonds that can be borylated. As shown in Figure 1, the ^{1}H NMR spectra of *xx*-PSU−Bpin (where xx indicates the molar percentage of Bpin group attached to the repeating unit) showed distinctive new resonances at 1.0−1.2 ppm from the methyl groups of Bpin attached to the polymer chain. Since the C−H bonds of sp^3 carbon is known to be unreactive in the iridium-catalyzed C−H borylation of arenes,[32,33] we selected the ^{1}H NMR resonance of the isopropylidene group as a reference and the mol % of attached Bpin group per PSU repeating unit was calculated by comparing the resonances intensities of $-C(CH_3)_2-$ in the polymer backbone (at 1.6−1.7 ppm) and the methyl groups of Bpin (at 1.0−1.2 ppm). These results are summarized in Table 1. The Bpin concentration could be controlled from 20 to 225 mol % by adjusting the ratio of B_2pin_2 relative to PSU repeating unit. The efficiency of C−H borylation, which is defined as the percentage of incorporated Bpin relative to added boron atoms, was consistently high (60−85% in most cases) when a precursor catalyst mixture composed of 1.5% $[IrCl(COD)]_2$ (COD = 1,5-cyclooctadiene) and 3% d*t*bpy was used. Thus, this approach allows convenient control of the degree of functionalization via stoichiometric tuning of the amount of added B_2pin_2. We also discovered that the quality of THF affects the efficiency of C−H borylation: anhydrous THF stored in a nitrogen-filled glovebox consistently demonstrated an efficiency 15−20% higher than that of ACS grade THF.

Scheme 1. Iridium-Catalyzed C−H Borylation of Poly(arylene ether sulfone)



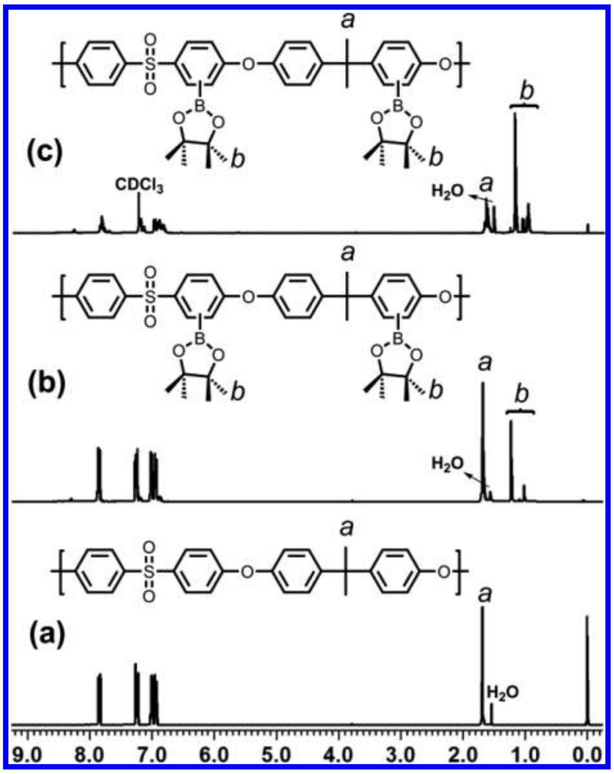


Figure 1. ^{1}H NMR spectra of (a) PSU, (b) 27-PSU−Bpin (Table 1, entry 2), and (c) 101-PSU−Bpin (Table 1, entry 6).

Since our initial report of the aromatic C−H borylation of PSU catalyzed by $[IrCl(COD)]_2$ and d*t*bpy,[28] we have investigated the scope of the catalyst system of the borylation. Miyaura and co-workers[32,33] have reported that the catalyst activity of arene C−H borylation depends on the basic strength of the anionic ligands of the iridium complex. Compared with $[IrCl(COD)]_2$, Ir(I) complexes with alkoxy ligands were reported to catalyze the C−H borylation of arenes at a faster rate owing to the more expeditious formation of (boryl)Ir^I intermediates. Thus, we compared activity of two iridium precursor catalysts, $[IrCl(COD)]_2$ and $[Ir(OMe)(COD)]_2$, in THF at 80 °C and room temperature (see Table 1 and Figure 2). Although both catalysts had comparable activity at 80 °C, the former was significantly less active at room temperature (see Table 1, entries 9 and 11). By contrast, $[Ir(OMe)(COD)]_2$ displayed a similar activity at both 80 °C and room temperature (see Table 1, entries 10 and 12). Both catalysts gave consistent results of borylation over a wide range of the ratios of B_2pin_2 and PSU (see Figures S28 and S29 of the Supporting Information).

C−H Borylation using HBpin as the borylating reagent was also investigated (Table 2). Because only one boron atom in HBpin participates in the reaction, the degrees of borylation in this reaction were significantly lower than those using B_2pin_2. However, the efficiency, defined as the ratio of incorporated boron atoms relative to added boron atoms, was only slightly lower than that with B_2pin_2. Again, between the two iridium catalysts, $[Ir(OMe)(COD)]_2$ displayed degrees of borylation and efficiency that were consistently higher than those of $[IrCl(COD)]_2$.

To investigate the possibility of side reactions affecting M_n and polydispersity index (PDI; M_w /M_n] during C−H borylation, we conducted SEC before and after the reaction (Figure S30 in the Supporting Information). The unfunctionalized PSU had a M_n of 22.0 kg/mol and a PDI of 1.65. As shown in Table 1, an increase in the ratio of B_2pin_2 to polymer repeating unit in the polymer functionalization reaction increased the M_n. A Different solubility of polymer after postfunctionalization may affect the size of hydrodynamic volume and average molecular weights of SEC measurement. However, since both PSU and borylated PSUs have a good solubility in THF, we attributed the increase of molecular

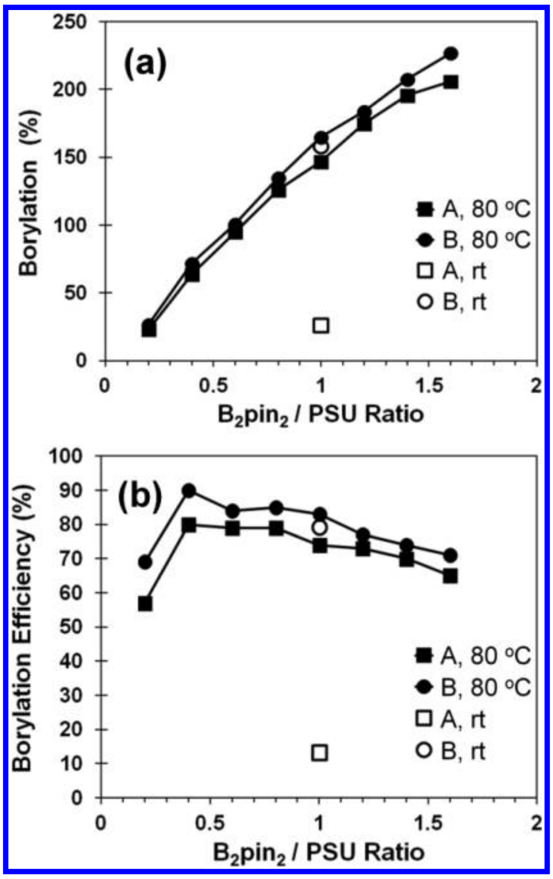


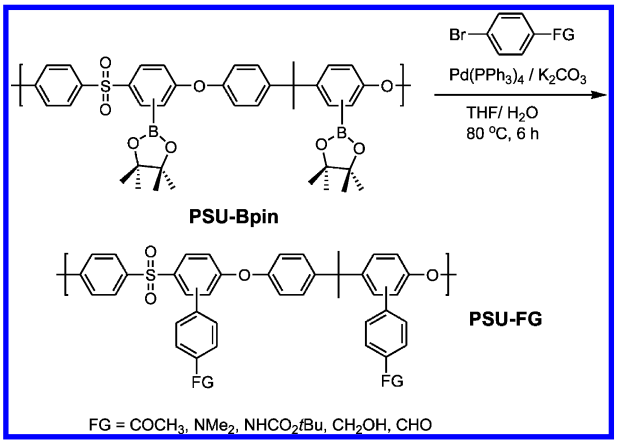
Figure 2. (a) Mol % of pinacolboronic ester (Bpin) in the poly(arylene ether sulfone) (PSU) repeating unit, and (b) efficiency of C−H borylation: (A) $[IrCl(COD)]_2$; (B) $[Ir(OMe)(COD)]_2$.

weights of PSU−Bpin to the incorporation of Bpin group into the polymer chain and the corresponding increase in hydrodynamic volume rather than solubility difference. PDI values always stayed within the range of 1.6−1.9. Similar results were obtained from borylation with HBpin: the M_n of the borylated PSU gradually increased with increasing amounts of HBpin, and PDIs consistently ranged from 1.7 to 2.0 (see Table 2). These results clearly indicate that the iridium-catalyzed borylation of the aromatic C−H bonds of PSU induces no deleterious side reactions (i.e., chain degradation or cross-linking reactions) on the polymer chains.

B. Transformation of Bpin in PSU to Other Functional Groups via Suzuki−Miyaura Cross-Coupling Reactions.

Palladium-catalyzed cross-coupling of aryl halide and aryl boron (the Suzuki−Miyaura reaction) is widely used to construct biaryl C−C bonds in organic synthesis because of its excellent tolerance for a broad range of functional groups.[34−37] Accordingly, Bpin group in an aromatic polymer can be converted to various functional groups via Suzuki−Miyaura reactions with functionalized aryl halides. To investigate this possibility, we selected 46-PSU−Bpin as a precursor polymer and conducted the Suzuki reaction with phenyl bromides that contained a ketone, an amine, a *tert*-butyl carbamate- (Boc-) protected amine, an alcohol, and an aldehyde (Scheme 2). As shown in Figure 3, the coupling reactions of 46-PSU−Bpin afforded the corresponding functionalized PSUs (PSU−FG, where FG is $COCH_3$ for ketone, NMe_2 for amine, NHBoc for Boc-protected amine, CH_2OH for benzyl alcohol, and CHO for aldehyde) with almost identical functional degrees. Molecular weight analysis using SEC revealed no detectable polymer chain scission or cross-linking.

Scheme 2. Suzuki−Miyaura Cross-Coupling Reactions with PSU−Bpin



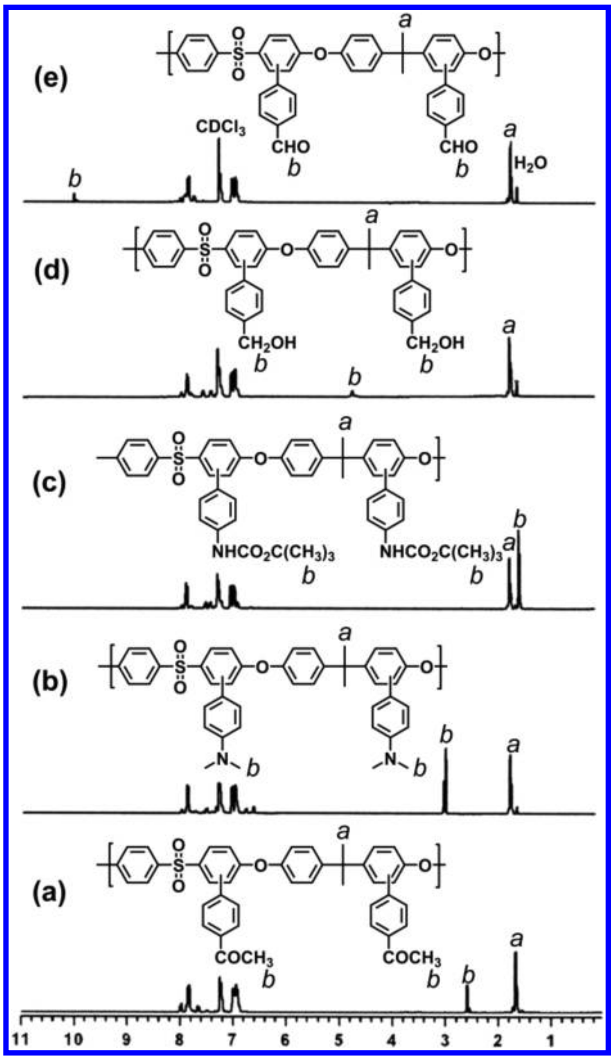


Figure 3. ^1H NMR spectra of functionalized poly(arylene ether sulfone)s from Suzuki−Miyaura cross-coupling reactions: (a) 47% PSU−$COCH_3$, (b) 48% PSU−NMe_2, (c) 46% PSU−NHBoc, (d) 46% PSU−CH_2OH, and (e) 47% PSU−CHO.

The thermal properties of PSU, PSU−Bpin, and PSU−FG were investigated using differential scanning calorimetry. As shown in Figure 4, the glass transition temperature (T_g) of PSU−Bpin was higher than that of PSU, and it increased with increasing degrees of borylation owing to restricted polymer chain mobility with the bulky Bpin group. The functionalized PSUs containing ketone, amine, Boc-protected amine, benzyl alcohol, and aldehyde showed T_gs ranging from 190 to 206 °C (Figure 5). Under identical concentrations of functional groups, the polymer functionalized with the bulky group (i.e., PSU−NHBoc) showed the highest T_g (206 °C; Figure 5c).

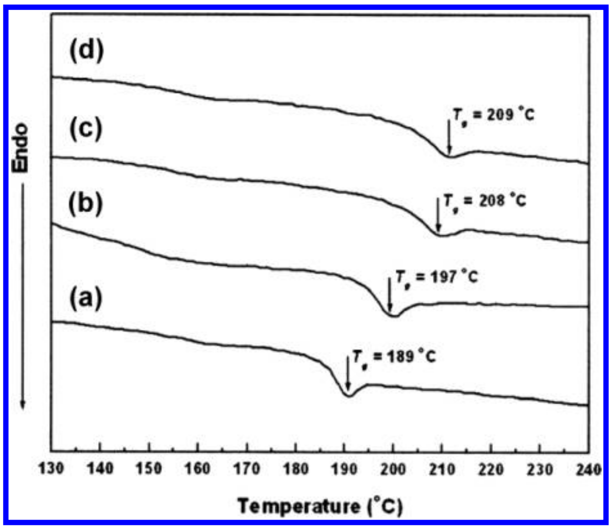


Figure 4. Differential scanning calorimetry scans of (a) PSU, (b) 46-PSU−Bpin, (c) 138-PSU−Bpin, and (d) 176-PSU−Bpin.

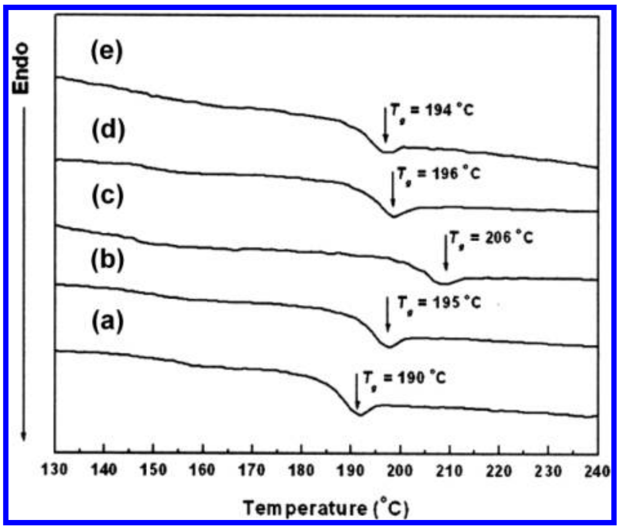


Figure 5. Differential scanning calorimetry scans of (a) 47% PSU−$COCH_3$, (b) 48% PSU−NMe_2, (c) 46% PSU−NHBoc, (d) 46% PSU−CH_2OH, and (e) 47% PSU−CHO.

In addition to conversion via Suzuki coupling, Bpin group can be converted into a variety of polar functional groups including hydroxyl,[38] boronic acid,[39−42] and potassium trifluoroborate.[43,44] The oxidation of boronic ester to hydroxyl group using hydrogen peroxide in the presence of a base is one of the most widely used transformations of organoboranes. We prepared hydroxyl-functionalized poly(arylene ether sulfone) (PSU−OH) by treating PSU−Bpin with sodium hydroxide and hydrogen peroxide in aqueous dioxane (Scheme 3). Upon oxidation, the resulting polymer (PSU−OH) became insoluble in $CHCl_3$ and THF but soluble in polar aprotic solvents such as dimethyl sulfoxide and dimethylacetamide. This dramatic solubility change is due to the transformation of the less polar Bpin group to the more polar hydroxyl group. The Bpin resonances disappeared in the ^1H NMR spectrum of PSU−OH (Figure 6b), and a strong O−H stretching band around 3400 cm^{-1} appeared in the FT-IR spectrum (Figure S26 of Supporting Information).

We also converted the Bpin moiety of PSU−Bpin to boronic acid [PSU−$B(OH)_2$] and potassium trifluoroborate (PSU−BF_3K) using $NaIO_4$ and KHF_2, respectively (Scheme 3). These new boron functional groups induced significantly higher polarity in the resulting polymers and made them poorly soluble in chloroform and THF but readily soluble in dimethyl sulfoxide. The disappearance of methyl resonances at 1.0−1.3 ppm in the ^1H NMR spectrum (Figure 6c) and the appearance of a broad O−H stretching band around 3500 cm^{-1} in the FT-IR spectrum confirmed the conversion of Bpin to $B(OH)_2$ in the polymer (see Figure S26). Transformation of PSU−Bpin to PSU−BF_3K was also confirmed by a characteristic resonance at −137.6 ppm in the ^{19}F NMR spectrum (Figure S27).

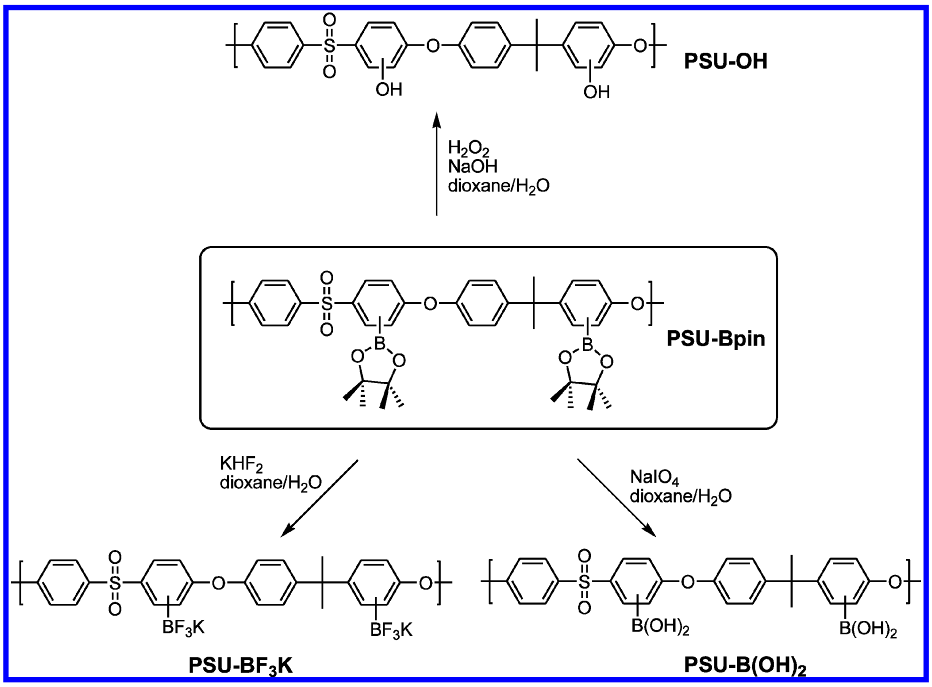
Aryl boronic acid and aryl potassium trifluoroborate are commonly used boron substrates in Suzuki−Miyaura coupling reactions.[45] To confirm that the transformations of Bpin to the new boryl groups caused no deborylation in the polymer, we conducted Suzuki−Miyaura reactions of 46-PSU−$B(OH)_2$ and 46-PSU−BF_3K with 4′-bromoacetophenone (Scheme 4). The resulting polymer, PSU−$COCH_3$, maintained a similar functional degree, demonstrating that both PSU−$B(OH)_2$ and PSU−BF_3K kept the same level of boryl group as the parent 46-PSU−Bpin.

The present functionalization method allows an efficient introduction a broad range of functional groups, including boronic ester, boronic acid, potassium trifluoroborate, and functionalized arenes, to the aromatic polymer chains without negative impact on the polymer chain length. Since aromatic C−H bonds are abundant in polymer materials, the present functionalization method involving the C−H borylation and Suzuki−Miyaura coupling is highly versatile and offers a viable alternative approach to polymer functionalization by electrophilic aromatic substitutions. However, considering the cost of metal catalysts (iridium and palladium) this method is more suitable for functionalization processes of commodity plastics targeting relatively a low degree of functionalization. For preparation of functionalized specialty polymers, the issue of catalyst cost could be considerably alleviated. This is of particular importance for the preparation of those key polymer materials with critical applications, which are synthetically challenging to approach by other routes.[27,29]

C. Regioselectivity Study of C−H Borylation via Model Compounds.

Four types of aromatic C−H bonds in the PSU repeating unit can undergo borylation: two in the sulfone unit and two in the bisphenol unit. Owing to unfavorable steric hindrance,[46,47] the C−H bond at the ortho position to the isopropylidene would be unreactive in the borylation. The ^1H NMR spectrum of PSU−Bpin with borylation levels up to 100% showed two relatively clean proton resonances of Bpin group at 1.22 and 1.01 ppm (see Figure 1), indicating the formation of two regioisomers. Unfortunately, identifying the regioisomers of PSU−Bpin directly with NMR spectroscopy was difficult owing to their structural similarities. Therefore, model compounds that closely mimic the chemical structures of

Scheme 3. Transformations of PSU−Bpin



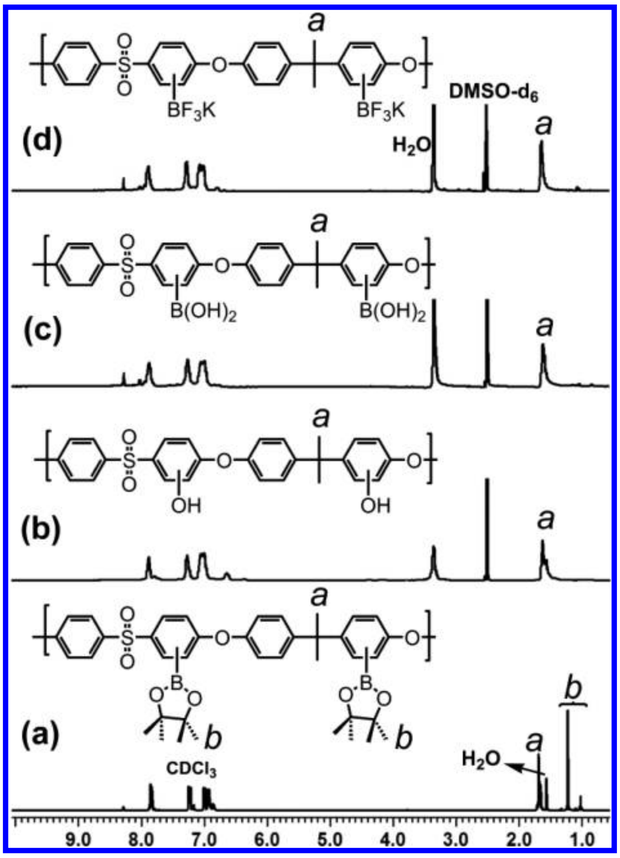
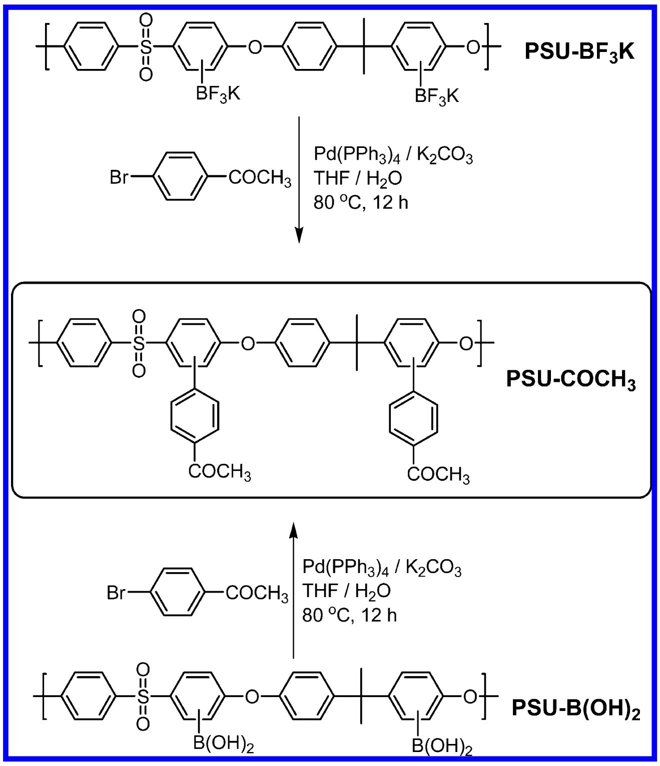


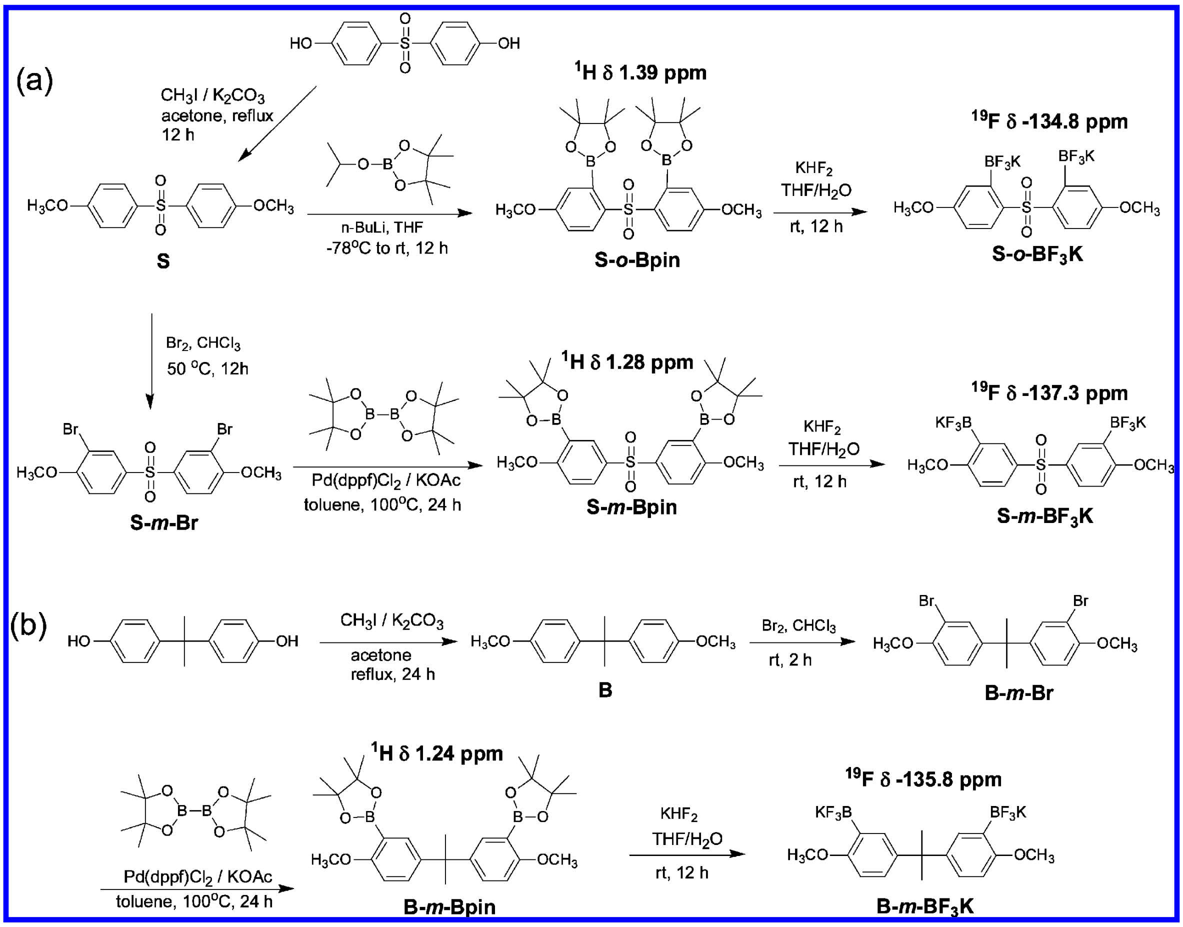
Figure 6. ^{1}H NMR spectra of (a) 46-PSU−Bpin, (b) 46-PSU−OH, (c) 46-PSU−$B(OH)_2$, and (d) 46-PSU−BF_3K.

the PSU repeating unit and their borylated reference compounds were prepared and studied instead: sulfone unit model compound (**S**) and bisphenol unit model compound (**B**). Their Bpin-functionalized reference products (**S-*o*-Bpin**, **S-*m*-Bpin**, and **B-*m*-Bpin**) and potassium trifluoroborate counterparts (**S-*o*-BF_3K**, **S-*m*-BF_3K**, and **B-*m*-BF_3K**) were prepared via the independent synthetic routes shown in Scheme 5 and fully characterized using NMR spectroscopies (see Supporting Information). A regioselectivity study was then conducted via a competitive C−H borylation reaction with a 1:1 mixture of **S** and **B** (Scheme 6). The resulting product mixtures containing **S-Bpin** and **B-Bpin** were converted to the potassium trifluoroborate counterparts via treatment with

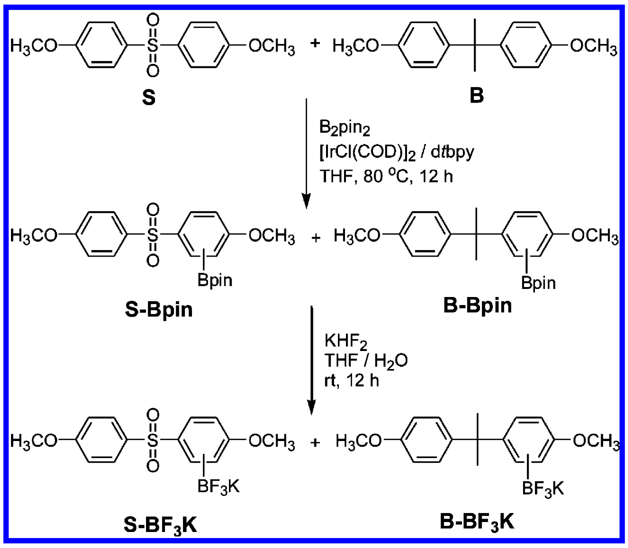
Scheme 4. Suzuki−Miyaura Cross-Coupling Reactions with PSU−$B(OH)_2$ and PSU−BF_3K



Scheme 5. Preparation of Borylated Reference Model Compounds



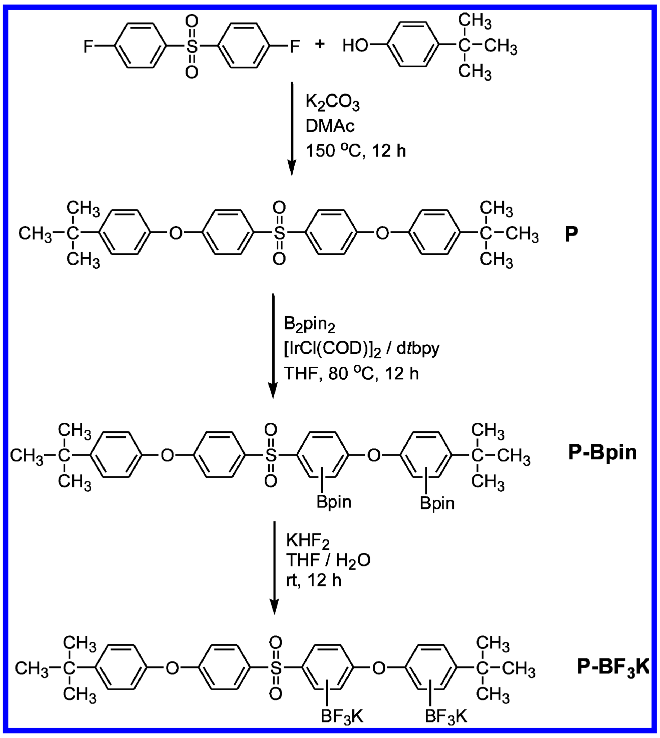
Scheme 6. Competitive C−H Borylation of Model Compounds (S and B) with B_2pin_2



KHF$_2$. We also prepared a third model compound, **P**, that resembles the repeating unit of PSU and incorporated the Bpin and BF$_3$K groups using a similar synthetic method (**P-Bpin** and **P-BF$_3$K** in Scheme 7).

GC/MS analysis of the product mixture of **S-Bpin** and **B-Bpin** revealed only monoborylated products and unreacted starting materials. The structures of the monoborylated

Scheme 7. Preparation of Model Compound P and its C−H Borylation with B_2pin_2



products were then investigated using NMR spectroscopy. As shown in Figure 7d, the ^{1}H NMR spectrum of the crude mixture of **S-Bpin** and **B-Bpin** showed two proton resonances of the Bpin groups at 1.28 (major) and 1.24 (minor) ppm in a ratio of 7:1 in addition to the methyl peak of remaining B_2pin_2 (1.16 ppm). Comparing these results with the chemical shifts of the borylated reference model compounds prepared using the independent routes shown in Scheme 5 (Figure 7a–c), we tentatively concluded that **S-*o*-Bpin**—predicted to have a resonance around 1.39 ppm—was not formed in the borylation. Accordingly, this result indicates that the C–H bond at the ortho position to the sulfone group of **S** is unreactive under these conditions. Owing to the proximity of the two proton resonances of **S-*m*-Bpin** and **B-*m*-Bpin**, the distinction of two isomers with ^{1}H NMR data alone was inconclusive.

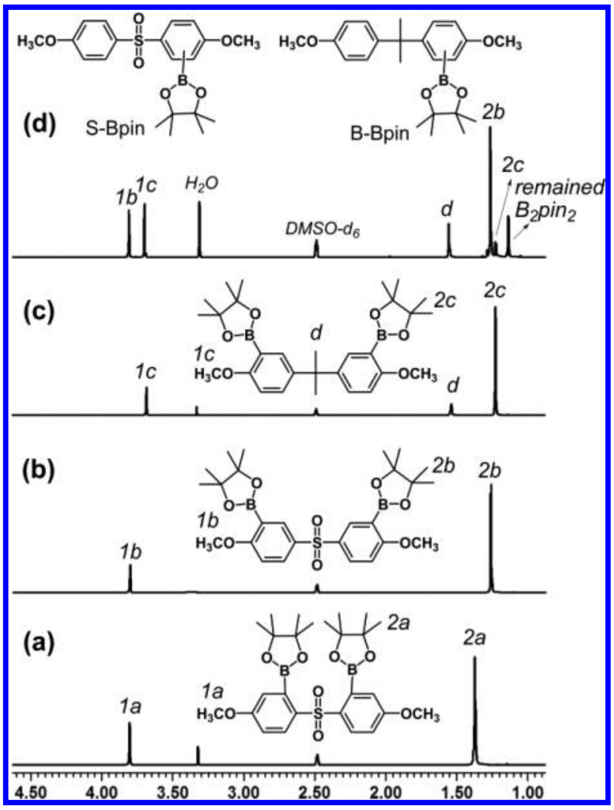


Figure 7. ^{1}H NMR spectra of (a) **S-*o*-Bpin**, (b) **S-*m*-Bpin**, (c) **B-*m*-Bpin**, and (d) crude mixture of **S-Bpin** and **B-Bpin** from Scheme 6.

Thus, we converted the Bpin group of the model compounds to the BF_3K group and compared their ^{19}F NMR resonances. The potassium trifluoroborate groups of the reference model compounds appeared as distinct peaks at −134.8, −137.3, and −135.8 ppm for **S-*o*-BF$_3$K**, **S-*m*-BF$_3$K**, and **B-*m*-BF$_3$K**, respectively (Figure 8a–c). The product mixture from the C–H borylation of equimolar amounts of **S** and **B** showed two ^{19}F NMR resonances that match well with those of **S-*m*-BF$_3$K** and **B-*m*-BF$_3$K**, and their integral ratio was 6:1. Similar to the conclusion drawn from ^{1}H NMR analysis, no ^{19}F NMR resonance that matched **S-*o*-BF$_3$K** was observed. The ^{19}F NMR spectrum of **P-BF$_3$K** also displayed two peaks (−137.6 and −136.4 ppm) with an integral ratio of 7:1, and the proximity of their chemical shifts allowed us to assign them to the meta position to sulfone (−137.6 ppm) and the meta position to *tert*-butyl (−136.4 ppm). Thus, data obtained from ^{1}H and ^{19}F NMR analyses suggested that (1) the C–H bond ortho to the sulfone group is unreactive (i.e., no formation of **S-*o*-Bpin**), and (2) the C–H bond meta to the sulfone group in **S** is more reactive than the C–H bond meta to the isopropylidene group in **B** under these borylation conditions. These results are consistent with those of previous kinetic studies of the C–H borylation of monosubstituted benzenes: while an electron-withdrawing group activates the aromatic C–H bond in the borylation, an electro-donating group deactivates it.[33,47,48]

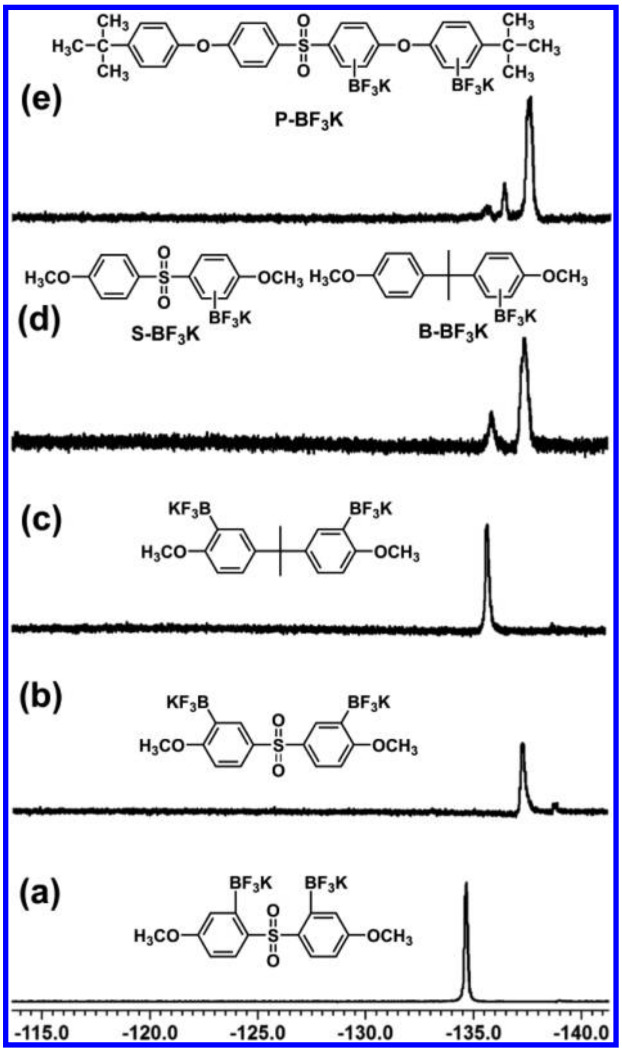


Figure 8. ^{19}F NMR spectra of (a) **S-*o*-BF$_3$K**, (b) **S-*m*-BF$_3$K**, (c) **B-*m*-BF$_3$K**, (d) crude mixture of **S-BF$_3$K** and **B-BF$_3$K** from Scheme 6, and (e) **P-BF$_3$K** of Scheme 7.

Given the NMR results from the model compounds study, we believe that the aromatic C–H bonds of the sulfone segment are more reactive than those of the bisphenol segment in the PSU repeating unit. Thus, the two proton resonances of 27-PSU–Bpin at 1.22 and 1.01 ppm (see Figure 1b) correspond to the two borylated polymer isomers at which C–H borylation occurs meta to the sulfone (major isomer) and meta to the isopropylidene (minor isomer) groups, respectively.

■ CONCLUSIONS

We studied the catalyst activity, scope, and regioselectivity of the iridium-catalyzed C–H borylation of aromatic PSU. B_2pin_2

displayed a borylation efficiency higher than that of HBpin under comparable conditions. Comparison of the catalysts showed that although similar borylation reactivity could be achieved at elevated temperature, $[Ir(OMe)(COD)]_2$ afforded a significantly higher activity than $[IrCl(COD)]_2$ at room temperature. Regioselectivity of the borylation of PSU was studied using model compounds, and the results suggest that (a) the aromatic C−H bonds of the sulfone unit are more reactive than those of the bisphenol unit and (b) the borylation takes place preferentially at the meta position of the sulfone than at the meta position of the isopropylidene group. The incorporation of functional groups and their concentrations affects the glass transition temperature of the resulting polymer. Bpin group along the polymer chain could be conveniently transformed to more polar boronic acid and potassium trifluoroborate forms, all of which are versatile precursors for the synthesis of a wide variety of functionalized PSUs via Suzuki−Miyaura coupling reactions. All chemical conversion processes described herein proceeded efficiently without causing polymer chain degradation or cross-linking reactions, which are common side reactions in conventional polymer functionalizations. Our results are of great importance in the design and synthesis of functionalized aromatic main-chain polymers and may broaden their potential applications.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Supplementary experimental details of the synthesis and NMR characterization of model compounds, FT-IR spectra of 46-PSU−Bpin, 46-PSU−OH and 46-PSU−$B(OH)_2$, degree of C−H borylation and borylation efficiency with error bars, and size exclusion chromatography of PSU and PSU−Bpin.This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: baec@rpi.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

C.B. thanks the NSF for generous support (CAREER DMR-0747667). The gifts of B_2pin_2 from Frontier Scientific Co. and $[IrCl(COD)]_2$ from Sinocompound Technology Co. are acknowledged. The authors thank Dr. Jongwon Park for his help in the SEC measurements and Dr. James Selsser at the University of Nevada Las Vegas for allowing access to his instrument.

■ REFERENCES

(1) Wang, S.; McGrath, J. E.; In *Step Polymerization*; Rogers, M.; Long, T. E., Eds.; Wiley: New York, 2002.

(2) Guiver, M. D.; Robertson, G. P.; Yoshikawa, M.; Tam, C. M. In *Membrane Formation and Modification*; Pinnau, I., Freeman, B., Eds.; ACS Symposium Series 744; American Chemical Society: Washington, DC, 1999; Chapter *10*, pp 137−161.

(3) Bottino, F. A.; Mamo, A.; Recca, A.; Brady, J.; Street, A. C.; McGrail, P. T. *Polymer* **1993**, *34*, 2901−2902.

(4) Pak, S. J.; Lyle, G. D.; Mercier, R.; McGrath, J. E. *Polym. Bull.* **1992**, *29*, 477−484.

(5) Iojoiu, C.; Maréchal, M.; Chabert, F.; Sanchez, J.-Y. *Fuel Cells* **2005**, *5*, 344−354.

(6) Johnson, B. C.; Yilgör, İ.; Tran, C.; Iqbal, M.; Wightman, J. P.; Lloyd, D. R.; McGrath, J. E. *J. Polym. Sci., Part A: Polym. Chem.* **1984**, *22*, 721−737.

(7) Guiver, M. D.; Kutowy, O.; ApSimon, J. W. *Polymer* **1989**, *30*, 1137−1142.

(8) Jakoby, K.; Peinemann, K. V.; Nunes, S. P. *Macromol. Chem. Phys.* **2003**, *204*, 61−67.

(9) Warshawsky, A.; Kahana, N.; Deshe, A.; Gottlieb, H. E.; Arad-Yellin, R. *J. Polym. Sci., Part A: Polym. Chem.* **1990**, *28*, 2885−2905.

(10) Wang, G.; Weng, Y.; Chu, D.; Chen, R.; Xie, D. *J. Membr. Sci.* **2009**, *332*, 63−68.

(11) Pan, J.; Lu, S.; Li, Y.; Huang, A.; Zhuang, L.; Lu, J. *Adv. Funct. Mater.* **2010**, *20*, 312−319.

(12) Kahana, N.; Arad-Yellin, R.; Deshe, A.; Warshawsky, A. *J. Polym. Sci., Part A: Polym. Chem.* **1990**, *28*, 3303−3315.

(13) Karlsson, L. E.; Jannasch, P. *J. Membr. Sci.* **2004**, *230*, 61−70.

(14) Kerres, J.; Cui, W.; Reichle, S. *J. Polym. Sci., Part A: Polym. Chem.* **1996**, *34*, 2421−2438.

(15) Jutemar, E. P.; Jannasch, P. *J. Membr. Sci.* **2010**, *351*, 87−95.

(16) Chen, H.; Schlecht, S.; Semple, T. C.; Hartwig, J. F. *Science* **2000**, *287*, 1995−1997.

(17) Frey, G. D.; Rentzsch, C. F.; Preysing, D. V.; Scherg, T.; Mühlhofer, M.; Herdtweck, E.; Herrmann, W. A. *J. Organomet. Chem.* **2006**, *691*, 5725−5738.

(18) Iverson, C. N.; Simth, M. R., III. *J. Am. Chem. Soc.* **1999**, *121*, 7696−7697.

(19) Cho, J.−Y.; Iverson, C. N.; Simth, M. R., III. *J. Am. Chem. Soc.* **2000**, *122*, 12868−12869.

(20) Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 14263−14278.

(21) Murphy, J. M.; Lawrence, J. D.; Kawamura, K.; Incarvito, C.; Hartwig, J. F. *J. Am. Chem. Soc.* **2006**, *128*, 13684−13685.

(22) Díaz-Requejo, M.; Wehrmann, P.; Leatherman, M. D.; Trofimenko, S.; Mecking, S.; Brookhart, M.; Pérez, P. J. *Macromolecules* **2005**, *38*, 4966−4969.

(23) Bae, C.; Hartwig, J. F.; Harris, N. K. B.; Long, R. O.; Anderson, K. S.; Hillmyer, M. A. *J. Am. Chem. Soc.* **2005**, *127*, 767−776.

(24) Boaen, N. K.; Hillmyer, M. A. *Macromolecules* **2003**, *36*, 7027−7034.

(25) Bae, C.; Hartwig, J. F.; Chung, H.; Harris, N. K.; Switek, K. A.; Hillmyer, M. A. *Angew. Chem., Int. Ed.* **2005**, *44*, 6410−6413.

(26) Shin, J.; Jensen, S. M.; Ju, J.; Lee, S.; Xue, Z.; Noh, S. K.; Bae, C. *Macromolecules* **2007**, *40*, 8600−8608.

(27) Chang, Y.; Brunello, G. F.; Fuller, J.; Hawley, M.; Kim, Y. S.; Disabb-Miller, M.; Hickner, M. A.; Jang, S. S.; Bae, C. *Macromolecules* **2011**, *44*, 8458−8469.

(28) Jo, T. S.; Kim, S. H.; Shin, J.; Bae, C. *J. Am. Chem. Soc.* **2009**, *131*, 1656−1657.

(29) Chang, Y.; Brunello, G. F.; Fuller, J.; Disabb-Miller, M. L.; Hawley, M. E.; Kim, Y. S.; Hickner, M. A.; Jang, S. S.; Bae, C. *Polym. Chem.* **2013**, *4*, 272−281.

(30) Yokozawa, T.; Yokoyama, A. *Chem. Rev.* **2009**, *109*, 5595−5619.

(31) Trnka, T. M.; Crubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18−19.

(32) Ishiyama, T.; Takagi, J.; Hartwig, J. F.; Miyaura, N. *Angew. Chem., Int. Ed.* **2002**, *41*, 3056−3058.

(33) Ishiyama, T.; Nobuta, Y.; Hartwig, J. F.; Miyaura, N. *Chem. Commun.* **2003**, 2924−2925.

(34) Suzuki, A. In *Metal-Catalyzed Cross-Coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: New York, 1988, 49−97.

(35) Miyaura, N.; Yamada, K.; Suginome, H.; Suzuki, A. *J. Am. Chem. Soc.* **1985**, *107*, 972−980.

(36) Miyaura, N.; Ishiyama, T.; Ishikawa, M.; Suzuki, A. *Tetrahedron Lett.* **1986**, *27*, 6369−6372.

(37) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457−2483.

(38) Pelter, A.; Smith, K.; Brown, H. C. *Borane Reagents*; Academic Press: New York, 1988.

(39) Murphy, J. M.; Tzschucke, C. C.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 757−760.

(40) Tzschucke, C. C.; Murphy, J. M.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 761−764.

(41) Pennington, T. E.; Kardiman, C.; Hutton, C. *Tetrahedron Lett.* **2004**, *45*, 6657−6660.

(42) Yuen, A. K. L.; Hutton, C. A. *Tetrahedron Lett.* **2005**, *46*, 7899−7903.

(43) Darses, S.; Michaud, G.; Genêt, J.−P. *Eur. J. Org. Chem.* **1999**, 1875−1883.

(44) Molander, G. A.; Yun, C.−S.; Ribagorda, M.; Biolatto, B. *J. Org. Chem.* **2003**, *68*, 5534−5539.

(45) Darses, S.; Genet, J.−P. *Eur. J. Org. Chem.* **2003**, 4313−4327.

(46) Takagi, J.; Sato, K.; Hartwig, J. F.; Ishiyama, T.; Miyaura, N. *Tetrahedron Lett.* **2002**, *43*, 5649−5651.

(47) Ishiyama, T.; Takagi, J.; Ishida, K.; Miyaura, N. *J. Am. Chem. Soc.* **2002**, *124*, 390−391.

(48) Chotana, G. A.; Rak, M. A.; Smith, M. R., III. *J. Am. Chem. Soc.* **2005**, *127*, 10539−10544.