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Synthesis of (*Z*)-1-Thio- and (*Z*)-2-Thio-1-alkenyl Boronates via Copper-Catalyzed Regiodivergent Hydroboration of Thioacetylenes: An Experimental and Theoretical Study

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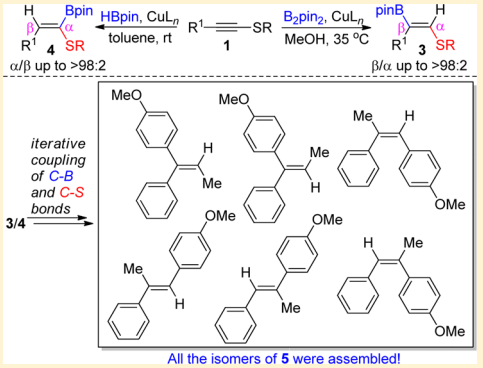
Supporting Information

ABSTRACT: A Cu-catalyzed divergent hydroboration of thioacetylenes has been achieved, providing (*Z*)-1-thio- or (*Z*)-2-thio-1-alkenyl boronates in moderate to high yields with excellent regio- and stereoselectivity, by using pinacolborane or bis(pinacolato)diboron as the hydroborating reagents, respectively. DFT calculations indicate that the sulfur atom plays a key role in determining the regioselectivity through polarizing the C−C triple bonds and participating in the HOMO orbitals. Moreover, the SR group can serve as a good leaving group, resulting in the concise synthesis of six regio- and stereoisomers of trisubstituted alkenes **5** via the iterative cross-coupling of C−B and C−S bonds. Clearly, it will be valuable for assembling stereochemically diverse trisubstituted olefins in organic synthesis.



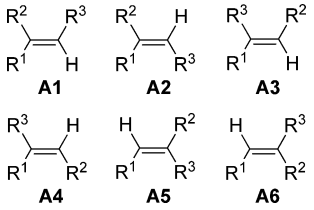
INTRODUCTION

Alkenylboronates are a class of fundamentally important building blocks in organic synthesis because they are exploited in a number of chemical transformations, including the Miyaura−Suzuki coupling reaction.[1] As such, the development of a general and stereocontrolled method for the preparation of these motifs has fascinated chemists for decades. In particular, the acetylenic hydroboration reaction[2−4] proves to be one of the most efficient and straightforward approaches to access vinylic boronates. Noteworthy, to develop a synthetic useful alkyne hydroboration reaction, the control of regioselectivity is an essential issue. Although good regioselectivity and yields were achieved for terminal alkynes,[2−4] the hydroboration of unsymmetrical internal alkynes only achieved limited success.[5] For example, pioneering work in the Ni-catalyzed β-selective borylation of thioacetylenes was achieved by Miyaura and Suzuki[5b] with the use of moisture-sensitive catecholborane as the hydroboration reagent. However, the regioselective α-borylation of thioalkynes has not been reported.

Recently, Yun and co-workers[6a] developed a Cu-catalyzed regioselective borylation of α,β-acetylenic esters using air- and moisture-stable bis(pinacolato)diboron (B_2pin_2) as the hydroborating reagent. Later, they,[6b,c] Tsuji,[7] and Ma[8] successfully extended the regiocontrolled hydroboration reaction into 1-aryl-1-alkynes. In 2011, Ito[9] disclosed an elegant copper-catalyzed regioselective borylation of 1,3-enyne for the divergent synthesis of 1,3-dienylboronates and 3-alkynylboronates, in which the regioselectivity was found to be controlled by the substrate structure or ligand of choice. Quite recently, the groups of Carretero[10] and McQuade[11] independently achieved the regiocontrolled Cu-catalyzed borylation of propargylic-substituted internal alkynes. Despite these significant advances,[5−11] the regiodivergent hydroboration of internal unsymmetrical acetylenes still remains both challenging and of great importance.[7,11]

On the other hand, trisubstituted alkenes are ubiquitous motifs that occur in many natural products, pharmacologically active compounds, or organic emitter materials, and they have been found to be important starting materials or synthetic intermediates for a myriad of chemical transformations.[12] In principle, trisubstituted olefins **A** have six types of regio- and stereoisomers **A1**−**6** (Scheme 1). Although a manifold of synthetic approaches[13] have been devised for the assembly of stereodefined trisubstituted alkenes, most of them can only afford one or two of the six possible isomers. In contrast, there is no method enabling the synthesis of all of the isomers **A1**−**6** so far.

Scheme 1. All Possible Regio- and Stereoisomers of Trisubstituted Alkenes A



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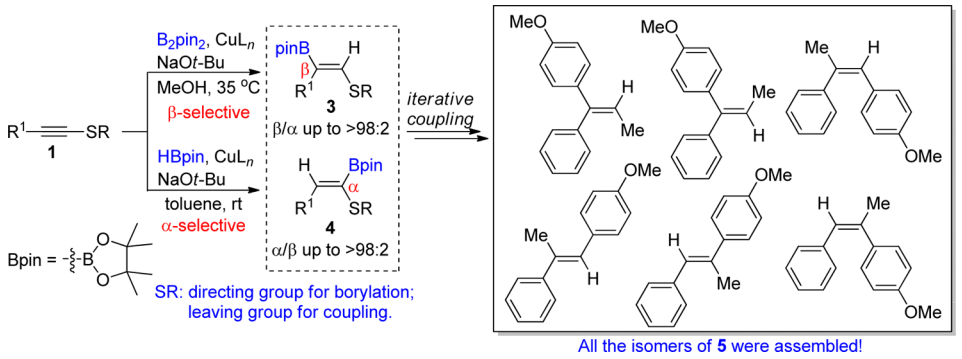
Scheme 2. Summary of This Work



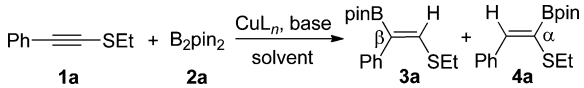
As part of our ongoing program geared toward the development of regio- and stereoselective reactions of heteroatom-substituted alkynes,[14] we have learned that heteroatoms might be able to control the regioselectivity of addition reactions through the polarization of C−C triple bonds. Hence, the regioselectivity issue associated with hydroboration of nonterminal alkynes could be resolved with the use of heteroatoms as directing groups. More importantly, the easy participation of carbon−heteroatom bonds into organic reactions, especially the transition-metal-catalyzed coupling reactions, may provide a good platform to elaborate more complex molecules. As such, we report herein a Cu-catalyzed regiodivergent borylation[15] of thioacetylenes by altering the catalytic species, providing (*Z*)-1-thio- or (*Z*)-2-thio-1-alkenyl boronates via the α- or β-selective borylation, respectively. Noteworthy, from the vinylic boronates thus obtained, we have succeeded in developing a rapid and divergent method for preparing all the possible regio- and stereoisomers of trisubstituted alkenes **5** by employing the iterative cross-coupling strategy[16] (Scheme 2). Fundamentally, it can find significant utility in the construction of other stereochemically diverse trisubstituted olefins **A1**−**6**.

RESULTS AND DISCCUSION

To explore the Cu-catalyzed β-borylation reaction, thioalkyne **1a** was chosen as a representative substrate for the initial screening. As a result, treating **1a** with 10 mol % of CuCl, 10 mol % of bis(2-diphenylphosphinophenyl)ether (DPEphos), 15 mol % of NaO*t*-Bu, and 1.1 equiv of B_2pin_2 (**2a**) in toluene with the addition of 2 equiv of MeOH at room temperature for 12 h led to a good conversion and regioselectivity (β/α = 85:15) (Table 1, entry 1). In contrast, running the reaction in MeOH at 35 °C for 12 h resulted in a full conversion of **1a**, and more importantly, **3a** was obtained in 88% yield with >98% β-selectivity as a (*Z*)-isomer (Table 1, entry 4). Notably, the reaction could be performed under an air atmosphere without significant loss of the yield.

The control experiments indicated that both CuCl and DPEphos were essential for the high yields and site selectivity (Table 1, entries 5 and 6). However, excellent regioselectivity (91% of β) was still observed in the absence of DPEphos, demonstrating that the ligand is not the primary reason for this β-borylation reaction. Further investigations revealed that other copper sources and ligands resulted in inferior results, although 9,9-dimethyl-4,5-bis(diphenylphosphino)xanthene (Xantphos) also proved to be a good choice (Table 1, entries 7−14). Hence, the optimized reaction conditions for β-borylation consisted of 10 mol % of CuCl, 10 mol % of DPEphos, 15 mol % of NaO*t*-Bu, and 1.1 equiv of B_2pin_2 (**2a**) in MeOH at 35 °C for 12 h. The structure of **3a** was determined by single X-ray diffraction analysis (see the Supporting Information).

Table 1. Optimization of the Reaction Conditions for Cu-Catalyzed β-Borylation[a]



entry	CuX_n	ligand	solvent	conv (%)[b]	β/α[b]
1[c]	CuCl	DPEphos	toluene[d]	73	85:15
2[c]	CuCl	DPEphos	THF[d]	74	92:8
3[c]	CuCl	DPEphos	MeOH	78	>98:2
4	CuCl	DPEphos	MeOH	>98 (88)[e] (85)[f]	>98:2
5	–	DPEphos	MeOH	<5	n.d.
6	CuCl	–	MeOH	51	91:9
7[g]	CuCl	DPEphos	MeOH	96	>98:2
8	$CuCl_2$	DPEphos	MeOH	67	>98:2
9	CuBr	DPEphos	MeOH	92	>98:2
10	CuI	DPEphos	MeOH	97	92:8
11	CuCl	PCy_3[h]	MeOH	>98	38:62
12	CuCl	PPh_3	MeOH	95	89:11
13	CuCl	dppe	MeOH	96	91:9
14	CuCl	Xantphos	MeOH	>98	97:3

[a]Reaction conditions: **1a** (0.5 mmol), **2a** (0.55 mmol), CuX_n (0.05 mmol), ligand (0.05 mmol), NaO*t*-Bu (0.075 mmol), 35 °C, under N_2, 12 h. [b]Determined by GC. [c]The reaction was performed at room temperature. [d]2 equiv of MeOH weres added. [e]Isolated yield. [f]Under air. [g]KO*t*-Bu was used instead of NaO*t*-Bu. [h]Generated in situ by treating PCy_3·HBF_4 with NaO*t*-Bu. n.d. = not detected.

Then, the scope and limitations of this β-selective borylation reaction were investigated, and the results were summarized in Table 2. In general, the reaction proceeded well to provide the desired vinylic boronates **3** in moderate to excellent yields with high regioselectivity. An assortment of aromatic thioacetylenes **1a**−**h** bearing either electron-withdrawing or -donating groups on the benzene ring afforded alkenylboronates **3a**−**h** in good to excellent yields (Table 2, entries **3a**−**h**). It should be noted that, in the case of 4-chlorophenylethynyl thioether (**1c**), cleavage of the alkynyl C−S bond occurred to a significant extent (>40%) under the standard conditions. Luckily, this side reaction could be successfully suppressed by replacing DPEphos with 1 equiv of Me_2S, leading to 91% of **3c**; in contrast, 2-chlorophenylethynyl thioether (**1d**) led to **3d** with slightly decreased regioselectivity (β/α = 92:8) under the modified reaction conditions (Table 2, **3c** and **3d**), indicating the steric effect had little influence on the regioselectivity. However, this effect seemed to be negligible for alkyl substrates

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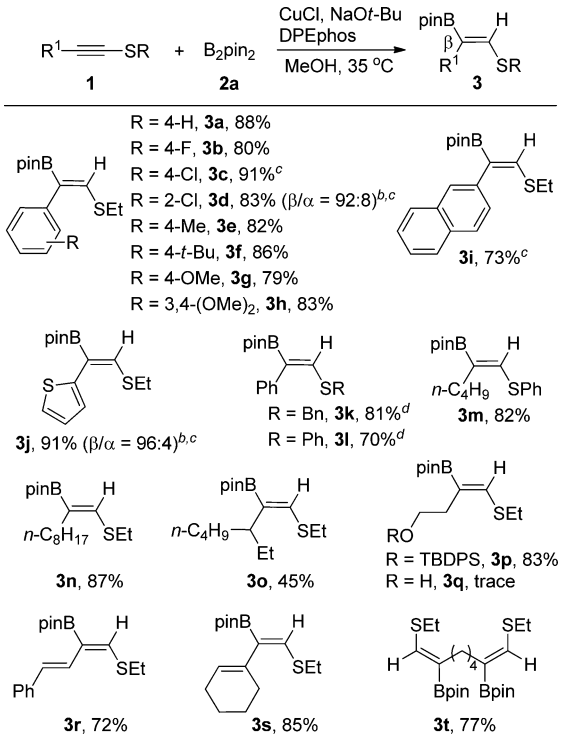
Table 2. Scope of the Cu-Catalyzed β-Borylation[a]



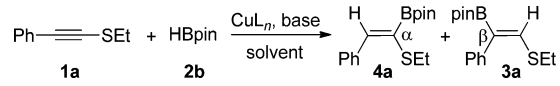
[a]Reaction conditions: **1** (0.5 mmol), **2a** (0.55 mmol), CuCl (0.05 mmol), DPEphos (0.05 mmol), NaO*t*-Bu (0.075 mmol), MeOH, 35 °C, 12 h. Unless otherwise noted, the desired products **3** were obtained with β/α > 98:2 selectivity. [b]Determined by GC. [c]DPEphos was replaced with 1 equiv of Me_2S. [d]50 °C.

because either primary alkyl-substituted thioalkynes **1m** and **1n** or the sterically demanding equivalent **1o** exclusively resulted in the β-borylation products, although the steric hindrance did affect the yields (Table 2, **3m**–**o**).

The influence of the substituents on the sulfur atom was also briefly investigated. As for benzyl and phenyl thioethers **1k** and **1l**, the reaction delivered expected products in satisfactory yields, albeit at an enhanced reaction temperature (50 °C). Borylation of TBDPS-protected ethynylthioether **1p** occurred smoothly to provide **3p** in 83% yield; surprisingly, its parent substrate **1q** was almost unreactive even at reflux (Table 2, **3p** and **3q**). In addition, when alkenyl substrates **1r** and **1s** were subjected to the optimized reaction conditions, we isolated the corresponding 1,3-dienylboronates in satisfactory yields (Table 2, **3r** and **3s**). Remarkably, the double hydroboration of **1t** proceeded successfully furnishing **3t** in 77% yield (Table 2, **3t**). As such, we have developed a Cu-catalyzed highly β-selective borylation of thioacetylenes[5b] with air- and moisture-stable B_2pin_2 as the hydroboration reagent. Clearly, the scope and synthetic utility of this method would be significantly enhanced if the α-version could be realized. Then, we paid attention to exploring the α-borylation reaction.

Indeed, as shown in Table 1, α-borylation was found to take place selectively in the presence of PCy_3, and consequently, we first focused on varying the ligands to explore the α-selective hydroboration. Unfortunately, synthetically useful α-selectivity could not be realized in the presence of B_2pin_2, even after a number of efforts. Finally, the utilization of CuH catalytic species[17] was found to be helpful. Conducting the reaction with 10 mol % of CuCl, 10 mol % of PPh_3, 20 mol % NaO*t*-Bu, and 2 equiv of neat pinacolborane (HBpin) in toluene at room temperature for 12 h resulted in 92% conversion of **1a** and 97% α-selectivity; however, the protodeboronation of **4a** occurred with noticeable amounts (>15%) (Table 3, entry 1).

Table 3. Optimization of the Reaction Conditions for Cu-Catalyzed α-Borylation[a]



entry	ligand	CuX_n	solvent	conv (%)[b]	α/β[b]
1	PPh_3	CuCl	toluene	92[c]	97:3
2	$P(2\text{-tol})_3$	CuCl	toluene	<5	–
3	$P(t\text{-Bu})_3$[d]	CuCl	toluene	91	94:6
4	PCy_3[d]	CuCl	toluene	82	80:20
5	Xphos	CuCl	toluene	<5	–
6	BDP	CuCl	toluene	76	95:5
7	IPr^{Cl}	CuCl	toluene	14	75:25
8	dppe	CuCl	toluene	61	95:5
9	dppf	CuCl	toluene	35	91:9
10	DPEphos	CuCl	toluene	41	91:9
11	Xantphos	CuCl	toluene	>97 (85)[e]	>98:2
12	Xantphos	CuCl	THF	94	>98:2
13	Xantphos	CuBr	toluene	65	96:4
14	Xantphos	CuI	toluene	48	96:4

[a]Reaction conditions: **1a** (0.5 mmol), **2b** (1.0 mmol), CuCl (0.05 mmol), ligand (0.05 mmol), and NaO*t*-Bu (0.1 mmol), rt, 12 h. [b]Determined by GC. [c]Protonolysis of the C–B bond of **4a** occurred to some extent (>15%). [d]Generated in situ by treating $P(t\text{-Bu})_3\cdot HBF_4$ or $PCy_3\cdot HBF_4$ with NaO*t*-Bu. [e]Isolated yield.

We envisioned that the utilization of sterically demanding ligands might be able to inhibit the side reaction, and as such, a wide range of ligands were screened. In particular, the use of Xantphos not only successfully inhibited the protonolysis of C–B bond but also provided the highest regioselectivity (>98:2) (Table 3, entry 11). In contrast, other ligands appeared to be less effective (Table 3, entries 2–10). It should be noted that the use of 1 equiv of HBpin led to relatively lower conversions even after a prolonged reaction time (24 h). Thus, the best reaction conditions for α-borylation of thioacetylenes were finally identified as follows: 10 mol % of CuCl, 10 mol % of Xantphos, 20 mol % of NaO*t*-Bu, and 2 equiv of neat HBpin in toluene at room temperature for 12 h, delivering the α-borylation product **4a** as a single (*Z*)-isomer in 85% yield.

As shown in Table 4, the Cu-catalyzed α-borylation of thioacetylenes proved to be quite general. Except for the substrate possessing a free hydroxyl group, a wide selection of functional groups including F, Cl, OMe, OTBDPS, alkyl, (hetero)aryl, and alkenyl groups were found to be well compatible with this new Cu-catalyzed α-borylation reaction, giving (*Z*)-1-thio-1-alkenyl boronates in good yields with excellent regioselectivity ($\alpha/\beta \geq 92/8$). For example, 4-fluorophenyl ethynylthioether **1b** generated 85% of **4b** with excellent regioselectivity; in contrast, the reaction of 4-chlorophenyl and 2-chlorophenyl substrates **1c** and **1d** furnished the desired products with slightly reduced regioselectivity (Table 4, **4b**–**d**). Notably, the substrate **1n** with a primary alkyl chain produced **4n** in 83% yield, while the sterically hindered equivalent **1o** gave rise to **4o** in 75% yield with perfect regiocontrol (Table 4, **4n** and **4o**), again implying that the steric effects had no significant correlation with the

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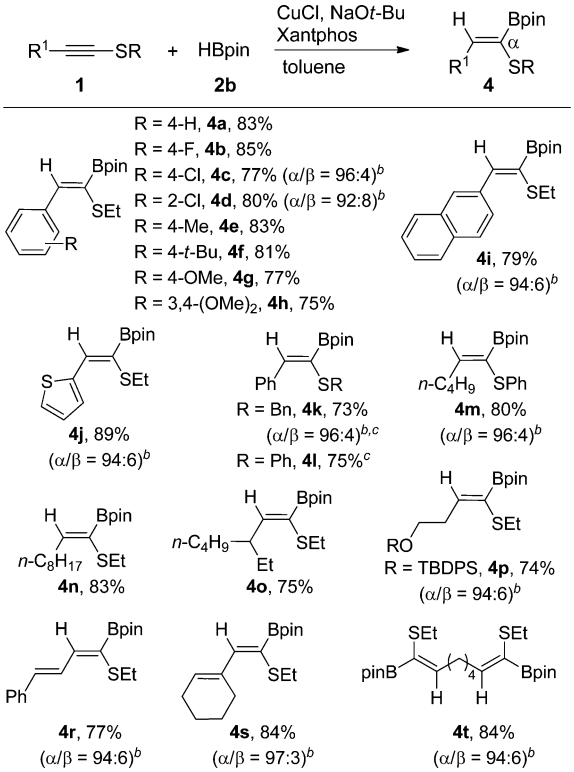
Table 4. Scope of the Cu-Catalyzed α-Borylation[a]



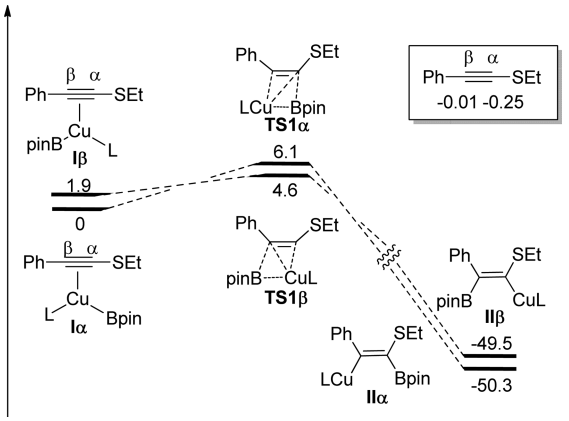
[a]Reaction conditions: **1** (0.5 mmol), **2b** (1.0 mmol), CuCl (0.05 mmol), Xantphos (0.05 mmol), NaO*t*-Bu (0.10 mmol), toluene, rt, 12 h. Unless otherwise noted, the desired products **4** were obtained with α/β > 98:2 selectivity. [b]Determined by GC. [c]18 h.

regioselectivity. Gratifyingly, this transformation was amenable to substrates with an alkenyl chain, as demonstrated by the production of stereodefined dienyl boronates **4r** and **4s** (Table 4, **4r** and **4s**). Likewise, the double borylation of **1t** occurred uneventfully providing **4t** in 84% yield with excellent α-selectivity (Table 4, **4t**). The regio- and stereochemistry of this Cu-catalyzed α-borylation reaction was identified by single X-ray diffraction analysis of **4l** (see the Supporting Information).

To gain insights into this Cu-catalyzed regiodivergent borylation reaction, related DFT calculations were carried out, by using the CPCM model with consideration of the complete phosphine ligand structure. Following the widely accepted mechanism[1e] for the Cu-catalyzed borylation of alkynes with B_2pin_2, the β-borylation of **1a** was first investigated. Coordination of **1a** to the actual catalyst Bpin-Cu-L[1e] can produce two different geometrical regioisomers **I*β*** and **I*α***, with **I*α*** 1.9 kcal/mol below **I*β*** (Scheme 3). Specifically, the Cu−C(α) and Cu−C(β) distances in **I*β*** are 2.084 and 2.051 Å, while the Cu−C(α) bond in **I*α*** is obviously shorter than the Cu−C(β) bond (2.076 vs 2.390 Å). Attack of the boron atom onto its neighboring acetylenic carbon atoms in **I*α*** and **I*β*** results in two four-membered transition states **TS1*α*** and **TS1*β***, as shown in Figure 1. The energy of **TS1*β*** is lower by 1.5 kcal/mol than that of **TS1*α***. Taken together, it constitutes a typical kinetic scenario that fits the Curtin−Hammett principle;[18] as such, the calculated ratio for [**II*β***]/[**II*α***] is determined to be 92:8, supporting the observed β-selectivity under the conditions described in Table 2.

To further illustrate the origin of β-selectivity, NBO analysis was conducted. As demonstrated in Scheme 3, the C−C triple

Scheme 3. Energy Profile for the β-Borylation of 1a Using DPEphos as the Ligand[a]



[a]Optimized structures in (M06/6-31G(d) (C,H,S,O,P) LANL2DZ-(Cu) CPCM model. Relative *G* values at 298 K (kcal/mol). $\Delta G^{\ddagger}(\alpha)$ = 6.1 kcal/mol, $\Delta G^{\ddagger}(\beta)$ = 2.7 kcal/mol.

bond of thioacetylene **1a** is found to be polarized obviously, and specifically, the carbon atom α to the SEt group is relatively electron-rich, implying that the inductive effect of the S atom should be predominant over the resonance effect in this substrate. Either the π-complexes **I** or transition states **TS1** possess a similar charge distribution. Consequently, α-cupration (or β-borylation) of **1a** appears to be favorable due to the natural charge population.[19] Similar α-cupration has been documented in the carbocupration of thioaceylenes.[20] On the other hand, the sulfur atom orbitals are found to significantly contribute to the HOMO orbitals of **TS1*β*** and **I*β***, while these orbital interactions are much smaller in **TS1*α*** and **I*α*** (see the Supporting Information), thereby leading to the energy difference for α- and β-borylation. As such, we believe that the excellent regioselectivity demonstrated in this reaction is mainly directed by the sulfur atom, through polarizing the C−C triple bonds and participating in the HOMO orbitals.

On the other hand, DFT calculations for α-selective borylation of **1a** were also performed. According to the accepted mechanism[7,17] involving hydrocupration of alkynes with CuH species followed by transmetalation with HBpin, the precursor complexes **III** (**III*α*** and **III*β***, with a different alkyne orientation) can be generated by the coordination of the alkyne with the HCuL species (Scheme 4). The Cu−C(α) and Cu−C(β) distances in **III*α*** are 2.153 and 2.164 Å, while those in **III*β*** are 2.225 and 2.455 Å, respectively. **III*β*** is 7.4 kcal/mol more stable than **III*α***. Transition states **TS2** were further located by hydrocupration of the C−C triple bonds (Figure 2). Compared with the starting complexes **III**, the Cu−C(α) and Cu−C(β) bonds in transition states **TS2** are more advanced, along with the partial formation of C−H bonds. The energy gaps for α- and β-borylation are 9.0 and 12.8 kcal/mol, respectively, which are well consistent with the preference of α-selectivity under the conditions depicted in Table 4. Similar with the β-borylation, the natural charge analysis indicates that the α carbon atoms in **III** and **TS2** are always more nucleophilic than the β ones toward cupration. Furthermore, the S atom orbitals are found to obviously participate in the HOMO orbitals of **III*α*** and **TS2*α***, while these contributions are smaller in **III*β*** and **TS2*β*** (see the Supporting Information). Therefore, the orbital interactions as well as polarization of C−

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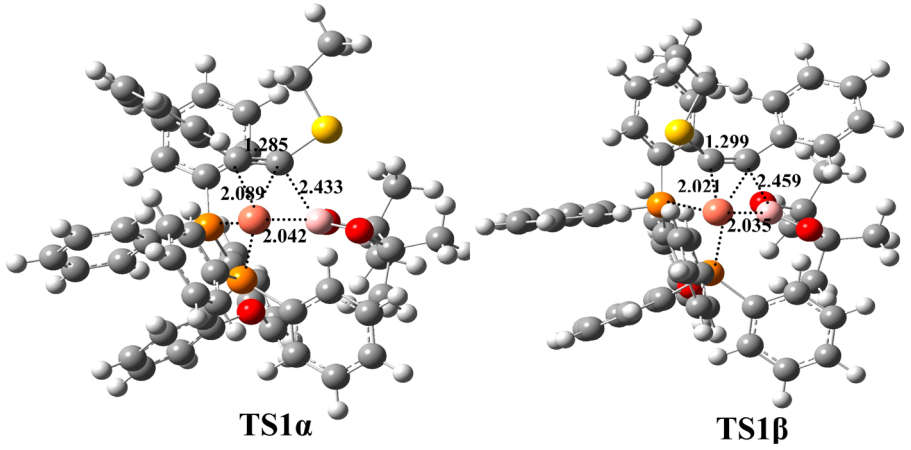
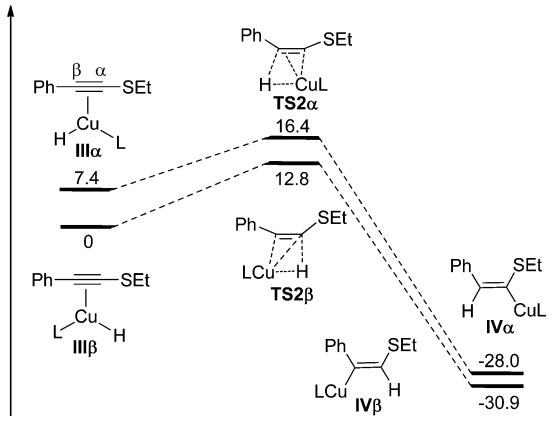


Figure 1. Molecular structure of transition states **TS1**. Selected bond distances (Å) are provided.

Scheme 4. Energy Profile for the α-Borylation of 1a Using Xantphos as the Ligand[a]



[a]Optimized structures in (M06/6-31G(d) (C,H,S,O,P) LANL2DZ-(Cu) CPCM model. Relative *G* values at 298 K (kcal/mol). $\Delta G^{\ddagger}(\alpha)$ = 9.0 kcal/mol, $\Delta G^{\ddagger}(\beta)$ = 12.8 kcal/mol.

C triple bonds, both caused by the S atom,[21] again account for the α-selective borylation.

As mentioned above, the efficient construction of stereodefined (*Z*)- or (*E*)-trisubstituted alkenes **A1−6** remains an unmet goal. To address this issue, the iterative cross-coupling of resulting (*Z*)-1-thio- and (*Z*)-2-thio-1-alkenyl boronates was performed. Suzuki−Miyaura coupling[1a] of the C−B bond of **3a** with 1.2 equiv of 4-OMe-C_6H_4I, conducted with 5 mol % of $Pd(dba)_2$, 10 mol % of PPh_3, and 1.5 equiv of K_3PO_4 in DMF at 80 °C for 6 h, followed by Ni(dppe)Cl_2-catalyzed coupling of the C−S bond[22] with MeMgCl produced **5a** as a single isomer in 82% yield over 2 steps (Scheme 5). Likewise, the sequential Suzuki−Miyaura/Kumada-type coupling of **4a** provided **5b**, a regioisomer of **5a**, in 70% yield (2 steps). In addition, the Suzuki−Miyaura coupling of **3g** with PhI followed by a subsequent C−S bond coupling with MeMgCl produced **5c** in 83% yield, while the same sequence of **4g** furnished **5d** in 72% yield. Then, we turned our attention to the synthesis of more challenging (*Z*)-trisubstituted olefins **5e** and **5f**. After some trials, the Suzuki−Miyaura coupling of **3a** with MeI[23] followed by Ni-catalyzed coupling with 4-OMe-C_6H_4MgBr gave **5e** with excellent stereoselectivity, albeit in a moderate yield. The stepwise cross-coupling strategy was also suitable for the construction of (*Z*)-trisubstituted alkene **5f**. As such, all the possible regio- and stereoisomers of **5** have been successfully established from (*Z*)-1-thio- or (*Z*)-2-thio-1-alkenyl boronates

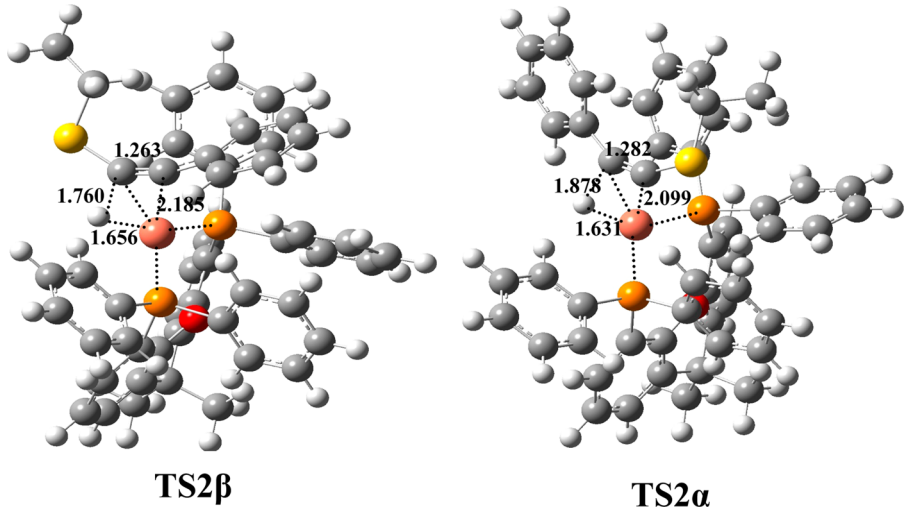


Figure 2. Molecular structure of transition states **TS2**. Selected bond distances (Å) are provided.

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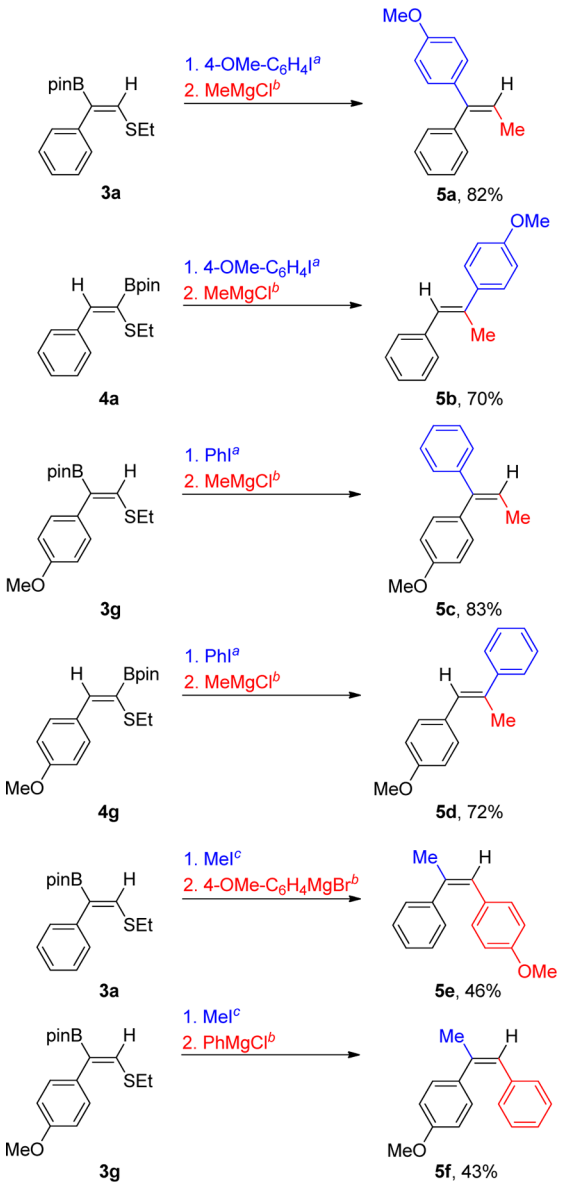
Scheme 5. Synthesis of Stereochemically Diverse Trisubstituted Alkenes 5[a]



[a]Reaction conditions: $Pd(dba)_2$ (5 mol %), PPh_3 (10 mol %), K_3PO_4 (2 equiv), DMF, 80 °C, 6 h. Yields are referred to as overall yields for 2 steps. [b]$Ni(dppe)Cl_2$ (10 mol %), THF, rt to reflux, overnight. [c]$Pd(dba)_2$ (5 mol %), P(2-tol)$_3$ (10 mol %), K_2CO_3 (2 equiv), DMF/H_2O (9:1), 60 °C, 12 h.

via the Suzuki–Miyaura/Kumada-type coupling sequence. Fundamentally, it can be applied to the divergent synthesis of different types of trisubstituted alkenes **A1–6**.

CONCLUSION

In conclusion, we have developed a Cu-catalyzed, highly selective α- and β-borylation of thioacetylenes for the first time, allowing a facile access to (*Z*)-1-thio- and (*Z*)-2-thio-1-alkenyl boronates in good yields with excellent regio- and stereoselectivity. The reaction operates under mild reaction conditions and tolerates a wide range of functional groups. DFT caculations suggest that the regioselectivity arises from the polarization of the C–C triple bonds and orbital interactions both caused by the S atom. The unique effects derived from heteroatoms may be useful for the development of new regiocontrolled acetylenic addition reactions. Moreover, the SR group serves as a good leaving group, thus resulting in a short approach to the elaboration of six regio- and stereoisomers of trisubstituted alkenes **5** via the Suzuki–Miyaura/C–S bond coupling sequence. It represents a first method which is capable of generating all possible regio- and stereoisomers of trisubstituted alkenes such as **5**. Clearly, it will be of value for elaborating stereochemically diverse molecules in organic synthesis.

EXPERIMENTAL SECTION

General. Toluene, THF, and dioxane were distilled from sodium prior to use. Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Commercially available neat pinacolborane (HBpin) was employed as the hydroborating reagent. ^1H, ^{13}C, and ^{19}F NMR spectra were measured on a 400 or 600 MHz NMR spectrometer using $CDCl_3$ as the solvent with tetramethylsilane (TMS) as the internal standard. Chemical shifts were given in δ relative to TMS, and the coupling constants were given in Hz. Column chromatography was performed using silica gel (300–400 mesh). High-resolution mass spectra (HRMS) analyses were carried out using a TOF MS instrument with an EI or ESI source.

General Procedure for Cu-Catalyzed β-Borylation of Thioacetylenes. To a mixture of CuCl (5.0 mg, 0.05 mmol), DPEphos (27.0 mg, 0.05 mmol), NaO*t*-Bu (7.2 mg, 0.075 mmol), and B_2pin_2 (**2a**) (69.9 mg, 0.55 mmol) was added a solution of **1a** (81 mg, 0.5 mmol) in 2 mL of MeOH under a nitrogen atmosphere. After stirring at 35 °C for 12 h, the reaction mixture was concentrated and purified by column chromatography (petroleum ether/EtOAc = 20:1) on silica gel to give 128 mg (yield: 88%) of **3a** as a white solid, mp: 76–78 °C; R_f = 0.37 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 600 MHz): δ 1.27 (s, 12H), 1.31 (t, *J* = 7.4 Hz, 3H), 2.79 (q, *J* = 7.4 Hz, 2H), 7.20–7.24 (m, 1H), 7.27 (s, 1H), 7.32–7.40 (m, 4H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.4, 24.7, 28.8, 83.5, 126.4, 127.8, 128.7, 139.6, 145.0; MS (EI, *m*/*z*): 290 (M^+, 17), 289 (4), 229 (2), 163 (8), 102 (100); HRMS (EI) calcd for $C_{16}H_{23}BO_2S$ (M^+) 290.1512, found 290.1511.

Crystal data for **3a** ($C_{16}H_{23}BO_2S$, 290.21): monoclinic, space group *P*2(1)/*c*, *a* = 17.3504(16) Å, *b* = 6.1246(7) Å, *c* = 17.8836(17) Å, *U* = 1691.6(3) Å^3, *Z* = 4, *T* = 296(2) K, absorption coefficient 0.190 mm^{-1}, reflections collected 13 822, independent reflections 3861 [*R*(int) = 0.0406], refinement by full-matrix least-squares on F^2, data/restraints/parameters 3861/0/181, goodness-of-fit on F^2 = 1.013, final *R* indices [$I > 2\sigma(I)$] R1 = 0.0498, wR2 = 0.1464, *R* indices (all data) R1 = 0.0962, wR2 = 0.1828, largest diff peak and hole 0.174 and −0.206 e·Å^{-3}. Crystallographic data for the structure **3a** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 960848.

Compound ***3b***. 80% yield (123 mg); white solid, mp: 83–85 °C; R_f = 0.38 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.27 (s, 12H), 1.31 (t, *J* = 7.4 Hz, 3H), 2.79 (q, *J* = 7.4 Hz, 2H), 7.01–7.08 (m, 2H), 7.27 (s, 1H), 7.33–7.39 (m, 2H); ^{19}F NMR ($CDCl_3$, 565 MHz): δ −116.1; ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 24.6, 28.7, 83.5, 114.6 (d, *J* = 21.0 Hz), 130.3 (d, *J* = 7.8 Hz), 135.4 (d, *J* = 3.3 Hz), 145.2, 161.2 (d, *J* = 243.5 Hz); MS (EI, *m*/*z*): 308 (M^+, 21), 307 (7), 279 (11), 180 (11), 120 (100); HRMS (EI) calcd for $C_{16}H_{22}BFO_2S$ (M^+) 308.1418, found 308.1422.

Compound ***3c***. 91% yield (148 mg); white solid, mp: 104–106 °C; R_f = 0.29 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 600 MHz): δ 1.26 (s, 12H), 1.30 (t, *J* = 7.4 Hz, 3H), 2.79 (q, *J* = 7.4 Hz, 2H), 7.33–7.38 (m, 5H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.4, 24.6, 28.8, 83.6, 127.9, 130.0, 131.9, 138.0, 145.7; MS (EI, *m*/*z*): 326 (31), 324 (M^+, 100), 309 (2), 196 (5); HRMS (EI) calcd for $C_{16}H_{22}BClO_2S$ (M^+) 324.1122, found 324.1127.

Compound ***3d***. 83% yield (135 mg); white solid, mp: 90–92 °C, β/α = 92:8; R_f = 0.27 (petroleum ether/EtOAc = 20:1); ^1H NMR

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($CDCl_3$, 400 MHz): δ 1.25 (s, 12H), 1.30 (t, J = 7.6 Hz, 3H), 2.76 (q, J = 7.4 Hz, 2H), 7.16−7.29 (m, 3H), 7.31 (s, 1H), 7.35−7.39 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 24.6, 28.1, 83.4, 126.4, 128.0, 129.3, 130.2, 132.6, 138.7, 146.2; MS (EI, m/z): 326 (2), 324 (M^+, 6), 289 (54), 263 (2), 197 (12); HRMS (EI) calcd for $C_{16}H_{22}BClO_2S$ (M^+) 324.1122, found 324.1120.

Compound ***3e***. 82% yield (125 mg); white solid, mp: 99−101 °C; R_f = 0.34 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.26 (s, 12H), 1.30 (t, J = 7.6 Hz, 3H), 2.31 (s, 3H), 2.77 (q, J = 7.4 Hz, 2H), 7.10−7.16 (m, 2H), 7.21−7.27 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 21.2, 24.6, 28.7, 83.4, 128.4, 128.5, 135.8, 136.6, 144.4; MS (EI, m/z): 304 (M^+, 3), 303 (2), 176 (9), 162 (3), 116 (100); HRMS (EI) calcd for $C_{17}H_{25}BO_2S$ (M^+) 304.1668, found 304.1663.

Compound ***3f***. 86% yield (149 mg); white solid, mp: 85−87 °C; R_f = 0.35 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 600 MHz): δ 1.26−1.34 (m, 24H), 2.79 (q, J = 7.4 Hz, 2H), 7.24 (s, 1H), 7.33 (q, J = 7.4 Hz, 4H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.4, 24.7, 28.9, 31.3, 34.4, 83.4, 124.7, 128.3, 136.4, 144.3, 148.8; MS (EI, m/z): 346 (M^+, 100), 331 (96), 218 (2), 158 (7); HRMS (EI) calcd for $C_{20}H_{31}BO_2S$ (M^+) 346.2138, found 346.2134.

Compound ***3g***. 79% yield (126 mg); white solid, mp: 71−73 °C; R_f = 0.31 (petroleum ether/EtOAc = 10:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.27 (s, 12H), 1.30 (t, J = 7.4 Hz, 3H), 2.78 (q, J = 7.4 Hz, 2H), 3.77 (s, 3H), 6.84−6.90 (m, 2H), 7.20 (s, 1H), 7.28−7.33 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 24.6, 28.7, 55.0, 83.4, 113.2, 129.8, 131.9, 143.8, 157.9; MS (EI, m/z): 320 (M^+, 3), 192 (6), 291 (2), 132 (100); HRMS (EI) calcd for $C_{17}H_{25}BO_3S$ (M^+) 320.1617, found 320.1615.

Compound ***3h***. 83% yield (145 mg); white solid, mp: 75−77 °C; R_f = 0.18 (petroleum ether/EtOAc = 10:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.28 (s, 12H), 1.32 (t, J = 7.4 Hz, 3H), 2.80 (q, J = 7.4 Hz, 2H), 3.86 (s, 3H), 3.87 (s, 3H), 6.83−6.97 (m, 1H), 6.93−7.00 (m, 2H), 7.22 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.3, 24.5, 28.7, 55.4, 55.5, 83.3, 110.4, 112.0, 121.0, 132.0, 143.8, 147.2, 147.8; MS (EI, m/z): 350 (M^+, 24), 289 (1), 222 (2), 162 (100); HRMS (EI) calcd for $C_{18}H_{27}BO_4S$ (M^+) 350.1723, found 350.1722.

Compound ***3i***. 73% yield (124 mg); white solid, mp: 98−100 °C; R_f = 0.30 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.29 (s, 12H), 1.32 (t, J = 7.4 Hz, 3H), 2.81 (q, J = 7.4 Hz, 2H), 7.36 (s, 1H), 7.38−7.44 (m, 2H), 7.47−7.52 (m, 1H), 7.76−7.82 (m, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.5, 24.7, 28.8, 83.6, 125.4, 125.6, 127.30, 127.34, 127.5, 128.0, 132.2, 133.3, 137.3, 145.6; MS (EI, m/z): 340 (M^+, 4), 212 (7), 184 (29), 152 (100); HRMS (EI) calcd for $C_{20}H_{25}BO_2S$ (M^+) 340.1668, found 340.1668.

Compound ***3j***. 91% yield (135 mg); colorless oil, β/α = 96:4; R_f = 0.40 (petroleum ether/EtOAc = 30:1); ^1H NMR ($CDCl_3$, 600 MHz): δ 1.30 (s, 12H), 1.37 (t, J = 7.4 Hz, 3H), 2.91 (q, J = 7.4 Hz, 2H), 7.03 (t, J = 4.7 Hz, 1H), 7.21 (s, 1H), 7.27 (d, J = 5.1 Hz, 1H), 7.50 (d, J = 3.6 Hz, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.5, 24.6, 29.9, 83.6, 124.5, 126.4, 127.3, 142.1, 142.2; HRMS (ESI) calcd for $C_{14}H_{22}BO_2S_2$ $(M + H)^+$ 297.1154, found 297.1156.

Compound ***3k***. 81% yield (143 mg); white solid, mp: 117−119 °C; R_f = 0.32 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.27 (s, 12H), 4.02 (s, 2H), 7.15−7.36 (m, 11H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 24.7, 39.3, 83.6, 126.5, 127.3, 127.9, 128.6, 128.7, 128.9, 137.3, 139.4, 144.2; MS (EI, m/z): 352 (M^+, 74), 261 (7), 229 (1), 224 (2); HRMS (EI) calcd for $C_{21}H_{25}BO_2S$ (M^+) 352.1668, found 352.1665.

Compound ***3l***. 70% yield (118 mg); white solid, mp: 111−113 °C; R_f = 0.30 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.27 (s, 12H), 7.23−7.42 (m, 8H), 7.44 (s, 1H), 7.43−7.49 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 24.7, 83.6, 126.7, 127.4, 128.0, 128.7, 129.1, 130.9, 135.4, 139.2, 143.8; MS (EI, m/z): 338 (M^+, 3), 229 (2), 210 (9), 102 (46); HRMS (EI) calcd for $C_{20}H_{23}BO_2S$ (M^+) 338.1512, found 338.1509.

Compound ***3m***. 82% yield (130 mg); colorless oil; R_f = 0.45 (petroleum ether/EtOAc = 30:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 0.94 (t, J = 7.2 Hz, 3H), 1.23 (s, 12H), 1.36−1.55 (m, 4H), 2.30 (t, J = 7.6 Hz, 2H), 7.10 (s, 1H), 7.24−7.29 (m, 1H), 7.31−7.37 (m, 2H), 7.45−7.49 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 14.1, 22.6, 24.6, 30.7, 31.0, 83.2, 127.0, 129.0, 130.6, 135.4, 140.6; MS (EI, m/z): 318 (M^+, 78), 261 (3), 209 (15), 191 (48); HRMS (EI) calcd for $C_{18}H_{27}BO_2S$ (M^+) 318.1825, found 318.1825.

Compound ***3n***. 87% yield (142 mg); colorless oil; R_f = 0.44 (petroleum ether/EtOAc = 30:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 0.87 (t, J = 7.0 Hz, 3H), 1.22−1.44 (m, 27H), 2.17 (t, J = 7.6 Hz, 2H), 2.77 (q, J = 7.4 Hz, 2H), 6.91 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 14.1, 15.7, 22.6, 24.6, 27.8, 28.6, 29.3, 29.5, 29.6, 30.8, 31.9, 83.0, 142.1; MS (EI, m/z): 326 (M^+, 19), 297 (12), 199 (26), 265 (3); HRMS (EI) calcd for $C_{18}H_{35}BO_2S$ (M^+) 326.2451, found 326.2450.

Compound ***3o***. 45% yield (70 mg); colorless oil; R_f = 0.47 (petroleum ether/EtOAc = 30:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 0.79−0.89 (m, 6H), 1.16−1.28 (m, 16H), 1.31 (t, J = 7.4 Hz, 3H), 1.37−1.61 (m, 4H), 2.25−2.33 (m, 1H), 2.76 (q, J = 7.4 Hz, 2H), 6.94 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 12.4, 14.1, 15.6, 22.9, 24.5, 24.7, 27.5, 28.0, 30.0, 33.8, 44.2, 82.6, 142.7; MS (EI, m/z): 312 (M^+, 20), 283 (75), 251 (2), 182 (18); HRMS (EI) calcd for $C_{17}H_{33}BO_2S$ (M^+) 312.2294, found 312.2297.

Compound ***3p***. 83% yield (205 mg); colorless oil; R_f = 0.35 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.12 (s, 9H), 1.13 (s, 12H), 1.34 (t, J = 7.4 Hz, 3H), 2.63 (t, J = 7.4 Hz, 2H), 2.79 (q, J = 7.4 Hz, 2H), 3.79 (t, J = 7.4 Hz, 2H), 7.07 (s, 1H), 7.39−7.47 (m, 6H), 7.74−7.80 (m, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.7, 19.2, 24.6, 26.9, 27.8, 34.3, 62.4, 83.0, 127.4, 129.3, 134.2, 135.6, 144.8; HRMS (ESI) calcd for $C_{28}H_{42}BO_3SSi$ $(M+H)^+$ 497.2717, found 497.2723.

Compound ***3r***. 72% yield (114 mg); colorless oil; R_f = 0.33 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 600 MHz): δ 1.23 (s, 12H), 1.28 (t, J = 7.4 Hz, 3H), 2.78 (q, J = 7.4 Hz, 2H), 6.94−7.00 (m, 2H), 7.05−7.13 (m, 2H), 7.19−7.23 (m, 2H), 7.36−7.40 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.7, 24.8, 28.6, 83.3, 126.4, 126.7, 127.0, 128.3, 131.8, 138.4, 144.8; MS (EI, m/z): 316 (M^+, 80), 315 (10), 301 (2), 287 (100), 189 (3); HRMS (EI) calcd for $C_{18}H_{25}BO_2S$ (M^+) 316.1668, found 316.1662.

Compound ***3s***. 85% yield (125 mg); colorless oil; R_f = 0.32 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.25 (s, 12H), 1.31 (t, J = 7.4 Hz, 3H), 1.57−1.71 (m, 4H), 2.11 (br, 4H), 2.74 (t, J = 7.4 Hz, 2H), 5.55 (br, 1H), 6.91 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 22.1, 22.9, 24.6, 25.1, 28.1, 28.4, 83.0, 125.0, 137.5, 142.0; MS (EI, m/z): 294 (M^+, 1), 265 (100), 221 (45), 165 (18), 136 (5); HRMS (EI) calcd for $C_{16}H_{27}BO_2S$ (M^+) 294.1825, found 294.1826.

Compound ***3t***. 77% yield (186 mg); white solid, mp: 104−106 °C; R_f = 0.18 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.24 (s, 24H), 1.31 (t, J = 7.4 Hz, 6H), 1.41 (br, 4H), 2.17 (br, 4H), 2.76 (q, J = 7.4 Hz, 4H), 6.89 (s, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.7, 24.6, 27.7, 28.7, 30.9, 82.8, 141.9; HRMS (ESI) calcd for $C_{24}H_{45}B_2O_4S_2$ $(M + H)^+$ 483.2945, found 483.2947.

General Procedure for Cu-Catalyzed α-Borylation of Thioacetylenes. To a mixture of CuCl (5.0 mg, 0.05 mmol), Xantphos (28.8 mg, 0.05 mmol), and NaO*t*-Bu (9.6 mg, 0.1 mmol) in 0.5 mL of toluene was added neat HBpin (150 μL, 1.0 mmol) under a nitrogen atmosphere. After stirring at 0 °C for 15 min, **1a** (0.5 mmol) was added at 0 °C, followed by stirring at 25 °C for 12 h (determined by GC). The reaction mixture was concentrated and purified by column chromatography (petroleum ether/EtOAc = 20:1) on silica gel to give 120 mg (yield: 83%) of **4a** as a colorless oil; R_f = 0.35 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.22 (t, J = 7.4 Hz, 3H), 1.34 (s, 12H), 2.95 (q, J = 7.4 Hz, 2H), 7.23−7.28 (m, 1H), 7.30 (s, 1H), 7.33−7.38 (m, 2H), 7.64 (d, J = 7.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 24.7, 27.6, 84.1, 127.7, 127.9, 130.1, 137.0, 141.0; MS (EI, m/z): 290 (M^+, 100), 275 (3), 229 (1), 163 (4); HRMS (EI) calcd for $C_{16}H_{23}BO_2S$ (M^+) 290.1512, found 290.1507.

Compound ***4b***. 85% yield (131 mg); colorless oil; R_f = 0.36 (petroleum ether/EtOAc = 20:1); ^1H NMR ($CDCl_3$, 400 MHz): δ 1.22 (t, J = 7.4 Hz, 3H), 1.33 (s, 12H), 2.96 (q, J = 7.4 Hz, 2H), 7.00−7.06 (m, 2H), 7.25 (s, 1H), 7.62−7.67 (m, 2H); ^{19}F NMR ($CDCl_3$, 565 MHz): δ −113.1; ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.3, 24.6, 27.5, 84.0, 114.7 (d, J = 21.0 Hz), 131.8 (d, J = 8.0 Hz), 133.2 (d, J =

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2.5 Hz), 139.8, 161.8 (d, J = 246.9 Hz); MS (EI, m/z): 308 (M^+, 100), 293 (3), 289 (2), 161 (23); HRMS (EI) calcd for $C_{16}H_{22}BFO_2S$ (M^+) 308.1418, found 308.1412.

Compound ***4c***. 77% yield (125 mg); colorless oil, α/β = 96:4; R_f = 0.30 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.22 (t, J = 7.4 Hz, 3H), 1.33 (s, 12H), 2.97 (q, J = 7.4 Hz, 2H), 7.22 (s, 1H), 7.30−7.33 (m, 2H), 7.57−7.61 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.4, 24.6, 27.5, 84.1, 128.0, 131.3, 133.2, 135.5, 139.3; MS (EI, m/z): 326 (37), 324 (M^+, 100), 311 (4), 309 (4), 263 (1); HRMS (EI) calcd for $C_{16}H_{22}BClO_2S$ (M^+) 324.1122, found 324.1124.

Compound ***4d***. 80% yield (130 mg); colorless oil, α/β = 92:8; R_f = 0.26 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.20 (t, J = 7.6 Hz, 3H), 1.34 (s, 12H), 2.90 (q, J = 7.4 Hz, 2H), 7.18−7.22 (m, 1H), 7.23−7.27 (m, 1H), 7.36−7.39 (m, 1H), 7.45 (s, 1H), 7.69−7.72 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.3, 24.7, 27.3, 84.2, 125.9, 128.8, 129.2, 131.0, 133.5, 135.0, 137.7; MS (EI, m/z): 326 (4), 324 (M^+, 11), 289 (88), 263 (1); HRMS (EI) calcd for $C_{16}H_{22}BClO_2S$ (M^+) 324.1122, found 324.1120.

Compound ***4e***. 83% yield (126 mg); colorless oil; R_f = 0.34 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.21 (t, J = 7.6 Hz, 3H), 1.32 (s, 12H), 2.33 (s, 3H), 2.94 (q, J = 7.4 Hz, 2H), 7.15 (d, J = 8.0 Hz, 2H), 7.29 (s, 1H), 7.56 (d, J = 8.2 Hz, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.3, 21.2, 24.6, 27.5, 83.8, 128.5, 130.0, 134.2, 137.5, 141.2; MS (EI, m/z): 304 (M^+, 100), 289 (5), 243 (2), 176 (8); HRMS (EI) calcd for $C_{17}H_{25}BO_2S$ (M^+) 304.1668, found 304.1663.

Compound ***4f***. 81% yield (140 mg); colorless oil; R_f = 0.33 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.22 (t, J = 7.4 Hz, 3H), 1.31 (s, 9H), 1.33 (s, 12H), 2.95 (q, J = 7.4 Hz, 2H), 7.28 (s, 1H), 7.38 (d, J = 8.4 Hz, 2H), 7.60 (d, J = 8.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.3, 24.7, 27.6, 31.2, 34.6, 83.9, 124.8, 129.9, 134.2, 141.2, 150.7; MS (EI, m/z): 346 (M^+, 100), 331 (89), 218 (5), 289 (1); HRMS (EI) calcd for $C_{20}H_{31}BO_2S$ (M^+) 346.2138, found 346.2134.

Compound ***4g***. 77% yield (123 mg); colorless oil; R_f = 0.30 (petroleum ether/EtOAc = 10:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.22 (t, J = 7.4 Hz, 3H), 1.33 (s, 12H), 2.94 (q, J = 7.4 Hz, 2H), 3.82 (s, 3H), 6.88−6.91 (m, 2H), 7.28 (s, 1H), 7.63−7.67 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.3, 24.7, 27.7, 55.2, 83.9, 113.3, 129.9, 131.8, 141.3, 159.1; MS (EI, m/z): 320 (M^+, 100), 305 (4), 292 (7), 132 (18); HRMS (EI) calcd for $C_{17}H_{25}BO_3S$ (M^+) 320.1617, found 320.1624.

Compound ***4h***. 75% yield (131 mg); colorless oil; R_f = 0.15 (petroleum ether/EtOAc = 10:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.24 (t, J = 7.4 Hz, 3H), 1.34 (s, 12H), 2.96 (q, J = 7.4 Hz, 2H), 3.89 (s, 3H), 3.90 (s, 3H), 6.85−6.89 (m, 1H), 7.25−7.28 (m, 2H), 7.37−7.39 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.4, 24.6, 27.6, 55.71, 55.72, 83.9, 110.4, 113.1, 123.6, 130.1, 141.3, 148.1, 148.6; MS (EI, m/z): 350 (M^+, 100), 335 (12), 321 (2), 306 (48); HRMS (EI) calcd for $C_{18}H_{27}BO_4S$ (M^+) 350.1723, found 350.1722.

Compound ***4i***. 79% yield (134 mg); colorless oil, α/β = 94:6; R_f = 0.31 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.24 (t, J = 7.4 Hz, 3H), 1.35 (s, 12H), 2.99 (q, J = 7.4 Hz, 2H), 7.43−7.46 (m, 3H), 7.77−7.81 (m, 3H), 7.84−7.87 (m, 1H), 8.14 (s, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.4, 24.6, 27.6, 84.0, 125.9, 126.1, 127.2, 127.4, 127.8, 128.4, 129.5, 132.6, 133.0, 134.5, 140.9; MS (EI, m/z): 340 (M^+, 57), 311 (8), 213 (3), 212 (9); HRMS (EI) calcd for $C_{20}H_{25}BO_2S$ (M^+) 340.1668, found 340.1671.

Compound ***4j***. 89% yield (132 mg); colorless oil, α/β = 94:6; R_f = 0.39 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.26 (t, J = 7.4 Hz, 3H), 1.31 (s, 12H), 3.00 (q, J = 7.4 Hz, 2H), 7.02 (dd, J = 5.0, 3.7 Hz, 1H), 7.29 (d, J = 3.5 Hz, 1H), 7.38 (d, J = 5.1 Hz, 1H), 7.60 (s, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.5, 24.6, 27.9, 83.8, 126.1, 128.3, 131.2, 136.4, 140.7; HRMS (ESI) calcd for $C_{14}H_{21}BO_2S_2$ (M^+) 296.1076, found 296.1074.

Compound ***4k***. 73% yield (129 mg); white solid, mp: 110−112 °C, α/β = 96:4; R_f = 0.32 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.32 (s, 12H), 4.20 (s, 2H), 7.16−7.21 (m, 1H), 7.22−7.27 (m, 3H), 7.28−7.34 (m, 5H), 7.58−7.62 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 24.7, 38.2, 84.1, 126.8, 127.7, 127.9, 128.3, 128.9, 130.1, 136.8, 138.1, 141.8; MS (EI, m/z): 352 (M^+, 48), 261 (12), 224 (1), 134 (17); HRMS (EI) calcd for $C_{21}H_{25}BO_2S$ (M^+) 352.1668, found 352.1668.

Compound ***4l***. 75% yield (127 mg); white solid, mp: 105−107 °C; R_f = 0.31 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.06 (s, 12H), 7.14−7.18 (m, 1H), 7.22−7.26 (m, 2H), 7.28−7.32 (m, 1H), 7.36−7.40 (m, 4H), 7.45 (s, 1H), 7.64−7.67 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 24.4, 84.1, 126.3, 128.0, 128.2, 128.6, 129.9, 130.2, 136.5, 137.6, 143.0; MS (EI, m/z): 338 (M^+, 100), 229 (2), 210 (34), 184 (3); HRMS (EI) calcd for $C_{20}H_{23}BO_2S$ (M^+) 338.1512, found 338.1509.

Crystal data for **4l** ($C_{20}H_{23}BO_2S$, 338.25): monoclinic, space group $P2(1)/n$, a = 10.4509(2) Å, b = 12.8373(2) Å, c = 14.3242(3) Å, U = 1913.91(6) Å^3, Z = 4, T = 296(2) K, absorption coefficient 0.070 mm^{-1}, reflections collected 28 764, independent reflections 4404 [R(int) = 0.0328], refinement by full-matrix least-squares on F^2, data/restraints/parameters 4404/0/217, goodness-of-fit on F^2 = 1.039, final R indices [$I > 2\sigma(I)$] R1 = 0.0595, wR2 = 0.1613, R indices (all data) R1 = 0.0703, wR2 = 0.1750, largest diff peak and hole 0.478 and −0.495 e·Å^{-3}. Crystallographic data for the structure **4l** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC 960847.

Compound ***4m***. 80% yield (127 mg); colorless oil, α/β = 96:4; R_f = 0.40 (petroleum ether/EtOAc = 30:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 0.90 (t, J = 7.3 Hz, 3H), 1.07 (s, 12H), 1.33−1.40 (m, 2H), 1.42−1.48 (m, 2H), 2.44 (q, J = 7.4 Hz, 2H), 6.77 (t, J = 7.1 Hz, 1H), 7.09−7.13 (m, 1H), 7.20−7.24 (m, 2H), 7.26−7.29 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 13.9, 22.4, 24.4, 30.4, 30.8, 83.8, 125.4, 128.5, 128.9, 138.0, 152.3; MS (EI, m/z): 318 (M^+, 100), 241 (2), 209 (16), 191 (19); HRMS (EI) calcd for $C_{18}H_{27}BO_2S$ (M^+) 318.1825, found 318.1825.

Compound ***4n***. 83% yield (135 mg); colorless oil; R_f = 0.41 (petroleum ether/EtOAc = 30:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 0.88 (t, J = 7.0 Hz, 3H), 1.19 (t, J = 7.4 Hz, 3H), 1.25−1.30 (m, 22H), 1.38−1.45 (m, 2H), 2.33 (dd, J = 14.8, 7.2 Hz, 2H), 2.81 (q, J = 7.4 Hz, 2H), 6.58 (t, J = 6.9 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 14.1, 15.5, 22.6, 24.6, 26.9, 28.6, 29.2, 29.4, 30.5, 31.8, 83.6, 150.0; MS (EI, m/z): 326 (M^+, 60), 311 (6), 297 (100), 199 (40); HRMS (EI) calcd for $C_{18}H_{35}BO_2S$ (M^+) 326.2451, found 326.2450.

Compound ***4o***. 75% yield (117 mg); colorless oil; R_f = 0.49 (petroleum ether/EtOAc = 30:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 0.86 (q, J = 7.2 Hz, 6H), 1.19 (t, J = 7.4 Hz, 3H), 1.21−1.27 (m, 6H), 1.29 (s, 12H), 1.36−1.51 (m, 3H), 2.79 (q, J = 7.4 Hz, 2H), 6.32 (d, J = 9.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 11.8, 14.0, 15.5, 22.9, 24.6, 24.7, 27.0, 27.7, 29.5, 34.3, 41.6, 83.6, 155.2; MS (EI, m/z): 312 (M^+, 45), 311 (17), 297 (5), 283 (100), 251 (4); HRMS (EI) calcd for $C_{17}H_{33}BO_2S$ (M^+) 312.2294, found 312.2291.

Compound ***4p***. 74% yield (184 mg); colorless oil, α/β = 94:6; R_f = 0.35 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.09 (s, 9H), 1.22 (t, J = 7.4 Hz, 3H), 1.32 (s, 12H), 2.70 (q, J = 7.0 Hz, 2H), 2.85 (q, J = 7.4 Hz, 2H), 3.78 (t, J = 7.0 Hz, 2H), 6.68 (t, J = 7.0 Hz, 1H), 7.39−7.47 (m, 6H), 7.70−7.74 (m, 4H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.5, 19.2, 24.6, 26.79, 26.82, 33.9, 62.7, 83.7, 127.5, 129.5, 133.9, 135.5, 145.5; HRMS (ESI) calcd for $C_{28}H_{42}BO_3SSi$ $(M + H)^+$ 497.2717, found 497.2719.

Compound ***4r***. 77% yield (122 mg); colorless oil, α/β = 94:6; R_f = 0.31 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.17 (t, J = 7.4 Hz, 3H), 1.24 (s, 12H), 2.84 (q, J = 7.4 Hz, 2H), 6.68 (d, J = 15.6 Hz, 1H), 7.10 (d, J = 10.8 Hz, 1H), 7.13−7.26 (m, 3H), 7.33−7.44 (m, 3H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.5, 24.7, 27.4, 83.9, 125.3, 127.0, 128.1, 128.6, 136.6, 137.1, 145.0; MS (EI, m/z): 316 (M^+, 44), 315 (16), 301 (2), 287 (100), 189 (4); HRMS (EI) calcd for $C_{18}H_{25}BO_2S$ (M^+) 316.1668, found 316.1665.

Compound ***4s***. 84% yield (124 mg); colorless oil, α/β = 97:3; R_f = 0.32 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.21 (t, J = 7.4 Hz, 3H), 1.29 (s, 12H), 1.55−1.67 (m, 4H), 2.19 (br, 2H), 2.35 (br, 2H), 2.87 (q, J = 7.4 Hz, 2H), 6.01 (br, 1H), 6.69 (s, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.2, 21.8, 22.8, 24.6, 25.9, 27.7, 29.1, 83.7, 133.0, 135.9, 144.6; MS (EI, m/z): 295 (M^+, 2), 265 (100),

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280 (2), 167 (3); HRMS (EI) calcd for $C_{16}H_{27}BO_2S$ (M^+) 295.1903, found 295.1901.

Compound ***4t***. 84% yield (202 mg); white solid, mp: 99−101 °C, α/β = 94:6; R_f = 0.19 (petroleum ether/EtOAc = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 1.19 (t, J = 7.4 Hz, 6H), 1.29 (s, 24H), 1.45−1.49 (m, 4H), 2.32−2.38 (m, 4H), 2.81 (q, J = 7.4 Hz, 4H), 6.57 (t, J = 6.9 Hz, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 15.4, 24.6, 26.8, 28.3, 30.3, 83.6, 149.5; HRMS (ESI) calcd for $C_{24}H_{45}B_2O_4S_2$ $(M+H)^+$ 483.2945, found 483.2947.

General Procedure for the Synthesis of Trisubstituted Alkenes 5 via the Suzuki−Miyaura/Kumada-type Coupling Sequence. To a mixture of $Pd(dba)_2$ (14.4 mg, 0.025 mmol), PPh_3 (13.1 mg, 0.05 mmol), K_3PO_4 (212 mg, 1.0 mmol), and **3a** (145 mg, 0.5 mmol) in 2 mL of DMF was added 4-$OMeC_6H_4I$ (129 mg, 0.55 mmol). After stirring at 80 °C for 6 h, the reaction mixture was quenched with water, extracted with ethyl acetate, washed with brine, dried over Na_2SO_4, and concentrated. Column chromatography (petroleum ether/EtOAc = 30:1) on silica gave 129 mg (yield: 96%) of the Suzuki coupling product as a colorless oil. To a mixture of Suzuki coupling product obtained thus (67.5 mg, 0.25 mmol) and $Ni(dppe)Cl_2$ (13.2 mg, 0.025 mmol) in 1 mL of THF was added MeMgCl as a 3.0 M solution in THF (0.25 mL, 0.75 mmol) under a nitrogen atmosphere. After stirring at reflux overnight, the reaction mixture was quenched with water, extracted with ethyl acetate, washed with brine, dried over Na_2SO_4, and concentrated. Column chromatography (petroleum ether/CH_2Cl_2 = 20:1) on silica gave 48 mg (yield: 85%) of **5a**[24] as a white solid, mp: 49−51 °C; R_f = 0.50 (petroleum ether/CH_2Cl_2 = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.73 (d, J = 6.8 Hz, 3H), 3.77 (s, 3H), 6.08 (q, J = 6.8 Hz, 1H), 6.79 (d, J = 8.0 Hz, 2H), 7.10−7.19 (m, 4H), 7.25−7.31 (m, 1H), 7.32−7.39 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.6, 55.2, 113.4, 122.4, 126.7, 128.1, 128.2, 130.0, 135.7, 140.2, 141.8, 158.5; MS (EI, m/z): 224 (M^+, 24), 209 (11), 193 (35), 178 (32).

Compound ***5b***:[25] 70% yield (45 mg) over 2 steps; white solid, mp: 95−96 °C; R_f = 0.51 (petroleum ether/CH_2Cl_2 = 20:1); ^{1}H NMR ($CDCl_3$, 600 MHz): δ 2.26 (s, 3H), 3.84 (s, 3H), 6.78 (s, 1H), 6.89−6.94 (m, 2H), 7.21−7.25 (m, 1H), 7.34−7.39 (m, 4H), 7.46−7.49 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 17.4, 55.3, 113.7, 126.22, 126.24, 127.0, 128.1, 129.1, 136.4, 136.8, 138.5, 158.9; MS (EI, m/z): 224 (M^+, 36), 209 (15), 193 (44), 178 (30).

Compound ***5c***:[24] 83% yield (48 mg) over 2 steps; white solid, mp: 47−49 °C; R_f = 0.47 (petroleum ether/CH_2Cl_2 = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.77 (d, J = 7.0 Hz, 3H), 3.82 (s, 3H), 6.11 (q, J = 7.0 Hz, 1H), 6.88−6.93 (m, 2H), 7.08−7.13 (m, 2H), 7.17−7.27 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 15.8, 55.1, 113.4, 123.8, 126.6, 127.2, 128.0, 131.2, 132.2, 141.9, 143.3, 158.3; MS (EI, m/z): 224 (M^+, 100), 209 (10), 193 (34), 178 (21).

Compound ***5d***:[25] 72% yield (45 mg) over 2 steps; white solid, mp: 85−86 °C; R_f = 0.49 (petroleum ether/CH_2Cl_2 = 20:1); ^{1}H NMR ($CDCl_3$, 400 MHz): δ 2.28 (s, 3H), 3.83 (s, 3H), 6.78 (s, 1H), 6.89−6.95 (m, 2H), 7.24−7.40 (m, 5H), 7.48−7.54 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 17.4, 55.3, 113.6, 125.9, 126.9, 127.2, 128.3, 130.3, 130.9, 135.9, 144.2, 158.1.

Compound ***5e***. The title compound was prepared according to Suzuki's procedure,[23] described as follows: To a mixture of $Pd(dba)_2$ (14.4 mg, 0.025 mmol), P(*o*-tolyl)$_3$ (15.2 mg, 0.05 mmol), K_2CO_3 (138 mg, 1.0 mmol), and **3a** (145 mg, 0.50 mmol) in 0.9 mL of DMF and 0.1 mL of H_2O was added MeI (213 mg, 1.5 mmol). After stirring at 60 °C for 12 h, the reaction mixture was quenched with water, extracted with ethyl acetate, washed with brine, dried over Na_2SO_4, and concentrated. Column chromatography (petroleum ether/EtOAc = 10:1) on silica gave 49 mg (yield: 55%) of the Suzuki coupling product as a colorless oil. To a mixture of Suzuki coupling product obtained thus (44.5 mg, 0.25 mmol) and $Ni(dppe)Cl_2$ (13.2 mg, 0.025 mmol) in 1 mL of THF was added MeMgCl (0.75 mmol) under a nitrogen atmosphere. After stirring at reflux overnight, the reaction mixture was quenched with water, extracted with ethyl acetate, washed with brine, dried over Na_2SO_4, and concentrated. Column chromatography on silica gave 47 mg (yield: 84%) of **5e** as a white solid, mp: 44−46 °C; R_f = 0.48 (petroleum ether/CH_2Cl_2 = 20:1); The stereochemistry of this compound was determined by the NOE measurements. ^{1}H NMR ($CDCl_3$, 600 MHz): δ 2.10 (s, 3H), 3.63 (s, 3H), 6.32 (s, 1H), 6.52−6.57 (m, 2H), 6.76−6.80 (m, 2H), 7.08−7.22 (m, 5H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 27.0, 55.1, 113.3, 125.9, 126.7, 128.2, 128.5, 130.0, 130.2, 136.8, 142.4, 157.8; MS (EI, m/z): 224 (M^+, 100), 209 (27), 194 (15), 178 (19); HRMS (EI) calcd for $C_{16}H_{16}O$ (M^+) 224.1201, found 224.1200.

Compound ***5f***. 43% yield (46 mg) over 2 steps; colorless oil; R_f = 0.32 (petroleum ether/CH_2Cl_2 = 30:1); The stereochemistry of this compound was determined by the NOE measurements. ^{1}H NMR ($CDCl_3$, 600 MHz): δ 2.09 (s, 3H), 3.70 (s, 3H), 6.34 (s, 1H), 6.70−6.74 (m, 2H), 6.87−6.91 (m, 2H), 6.94−6.99 (m, 1H), 7.00−7.05 (m, 4H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ 27.0, 55.1, 113.8, 125.9, 126.1, 127.8, 128.9, 129.3, 134.1, 137.9, 138.1, 158.5; MS (EI, m/z): 224 (M^+, 100), 209 (35), 194 (24), 178 (23); HRMS (EI) calcd for $C_{16}H_{16}O$ (M^+) 224.1201, found 224.1197.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Spectroscopic data of compounds **3**−**5** and computational data. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For selected reviews, see: (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457. (b) *Metal-Catalyzed Cross-Coupling Reactions*, Vol. *1*; de Meijere, A., Diederich, F., Eds.; Wiley-VCH: Weinheim, 2004. (c) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829. (d) Beletskaya, I.; Moberg, C. *Chem. Rev.* **2006**, *106*, 2320. (e) Miyaura, N. *Bull. Chem. Soc. Jpn.* **2008**, *81*, 1535 and references therein.

(2) For selected reviews, see: (a) Brown, H. C.; Campbell, J. B., Jr. *Aldrichimica Acta* **1981**, *14*, 3. (b) Trost, B. M.; Ball, Z. T. *Synthesis* **2005**, 853. (c) Yun, J. *Asian J. Org. Chem.* **2013**, *2*, 1016 and references therein.

(3) For selected reports on the hydroboration of alkynes using boranes, see: (a) Brown, H. C.; Gupta, S. K. *J. Am. Chem. Soc.* **1975**, *97*, 5249. (b) Tucker, C. E.; Davidson, J.; Knochel, P. *J. Org. Chem.* **1992**, *57*, 3482. (c) Pereira, S.; Srebnik, M. *Organometallics* **1995**, *14*, 3127. (d) Ohmura, T.; Yamamoto, Y.; Miyaura, N. *J. Am. Chem. Soc.* **2000**, *122*, 4990. (e) Clay, J. M.; Vedejs, E. *J. Am. Chem. Soc.* **2005**, *127*, 5766. (f) Iwadate, N.; Suginome, M. *Org. Lett.* **2009**, *11*, 1899. (g) Cid, J.; Carbó, J. J.; Fernández, E. *Chem.—Eur. J.* **2012**, *18*, 1512. (h) Gunanathan, C.; Hölscher, M.; Pan, F.; Leitner, W. *J. Am. Chem. Soc.* **2012**, *134*, 14349. (i) Haberberger, M.; Enthaler, S. *Chem.—Asian J.* **2013**, *8*, 50. (j) Sundararaju, B.; Fürstner, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 14050.

(4) For hydroboration of alkynes using B_2pin_2, see: (a) Jang, H.; Zhugralin, A. R.; Lee, Y.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2011**, *133*, 7859. (b) Grirrane, A.; Corma, A.; Garcia, H. *Chem.—Eur. J.* **2011**, *17*, 2467. (c) Takahashi, K.; Ishiyama, T.; Miyaura, N. *J. Organomet. Chem.*

2001, *625*, 47. (d) Zhao, J.; Niu, Z.; Fu, H.; Li, Y. *Chem. Commun.* **2014**, *50*, 2058.
(5) (a) Satoh, M.; Miyaura, N.; Suzuki, A. *Synthesis* **1987**, 373. (b) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *Organometallics* **1993**, *12*, 589. (c) Pergament, I.; Srebnik, M. *Org. Lett.* **2001**, *3*, 217. (d) Soderquist, J. A.; Colberg, J. C.; Valle, L. D. *J. Am. Chem. Soc.* **1989**, *111*, 4873. (e) Hoffmann, R. W.; Krüger, J.; Brückner, D. *New J. Chem.* **2001**, *25*, 102. (f) Molander, G. A.; Ellis, N. M. *J. Org. Chem.* **2008**, *73*, 6841. For a recent work involving hydroboration of ynol ethers, see: (g) Cui, W.; Mao, M.; He, Z.; Zhu, G. *J. Org. Chem.* **2013**, *78*, 9815.
(6) (a) Lee, J.-E.; Kwon, J.; Yun, J. *Chem. Commun.* **2008**, 733. (b) Kim, H. R.; Jung, I. G.; Yoo, K.; Jang, K.; Lee, E. S.; Yun, J.; Son, S. U. *Chem. Commun.* **2010**, *46*, 758. (c) Kim, H. R.; Yun, J. *Chem. Commun.* **2011**, *47*, 2943.
(7) Semba, K.; Fujihara, T.; Terao, J.; Tsuji, Y. *Chem.—Eur. J.* **2012**, *18*, 4179.
(8) Yuan, W.; Ma, S. *Org. Biomol. Chem.* **2012**, *10*, 7266.
(9) Sasaki, Y.; Horita, Y.; Zhong, C.; Sawamura, M.; Ito, H. *Angew. Chem., Int. Ed.* **2011**, *50*, 2778.
(10) (a) Moure, A. L.; Arrayás, R. G.; Cárdenas, D. J.; Alonso, I.; Carretero, J. C. *J. Am. Chem. Soc.* **2012**, *134*, 7219. (b) Moure, A. L.; Mauleón, P.; Arrayás, R. G.; Carretero, J. C. *Org. Lett.* **2013**, *15*, 2054.
(11) Park, J. K.; Ondrusek, B. A.; McQuade, D. T. *Org. Lett.* **2012**, *14*, 4790.
(12) *Comprehensive Organic Functional Group Transformations II*; Katritzky, A. R., Taylor, R. J. K., Eds.; Elsevier: Oxford, U.K., 2005.
(13) (a) Flynn, A. B.; Ogilvie, W. W. *Chem. Rev.* **2007**, *107*, 4698. (b) Negishi, E.; Huang, Z.; Wang, G.; Mohan, S.; Wang, C.; Hattori, H. *Acc. Chem. Res.* **2008**, *41*, 1474 and references therein.
(14) (a) Chen, X.; Kong, W.; Cai, H.; Kong, L.; Zhu, G. *Chem. Commun.* **2011**, *47*, 2164. (b) Cai, H.; Yuan, Z.; Zhu, W.; Zhu, G. *Chem. Commun.* **2011**, *47*, 8682. (c) Chen, X.; Chen, D.; Lu, Z.; Kong, L.; Zhu, G. *J. Org. Chem.* **2011**, *76*, 6338. (d) Lu, Z.; Kong, W.; Yuan, Z.; Zhao, X.; Zhu, G. *J. Org. Chem.* **2011**, *76*, 8524. (e) Zhu, G.; Chen, D.; Wang, Y.; Zheng, R. *Chem. Commun.* **2012**, *48*, 5796. (f) Bai, Y.; Yin, J.; Kong, W.; Mao, M.; Zhu, G. *Chem. Commun.* **2013**, *49*, 7650. (g) Yang, Y.; Wang, L.; Zhang, J.; Jin, Y.; Zhu, G. *Chem. Commun.* **2014**, *50*, 2347.
(15) For other representative borylations of alkynes, see: (a) Ishiyama, T.; Matsuda, N.; Miyaura, N.; Suzuki, A. *J. Am. Chem. Soc.* **1993**, *115*, 11018. (b) Lesley, G.; Nguyen, P.; Taylor, N. J.; Marder, T. B.; Scott, A. J.; Clegg, W.; Norman, N. C. *Organometallics* **1996**, *15*, 5137. (c) Lee, Y.; Jang, H.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 18234. (d) Gao, F.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2010**, *132*, 10961. (e) Suginome, M.; Yamamoto, A.; Murakami, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 2380. (f) Suginome, M.; Shirakura, M.; Yamamoto, A. *J. Am. Chem. Soc.* **2006**, *128*, 14438. (g) Ohmura, T.; Oshima, K.; Taniguchi, H.; Suginome, M. *J. Am. Chem. Soc.* **2010**, *132*, 12194. (h) Iwadate, N.; Suginome, M. *J. Am. Chem. Soc.* **2010**, *132*, 2548. (i) Ito, H.; Sasaki, Y.; Sawamura, M. *J. Am. Chem. Soc.* **2008**, *130*, 15774. (j) Yoshida, H.; Kawashima, S.; Takemoto, Y.; Okada, K.; Ohshita, J.; Takaki, K. *Angew. Chem., Int. Ed.* **2012**, *51*, 235. (k) Takemoto, Y.; Yoshida, H.; Takaki, K. *Chem.—Eur. J.* **2012**, *18*, 14841. (l) Alfaro, R.; Parra, A.; Alemán, J.; Ruano, J. L. G.; Tortosa, M. *J. Am. Chem. Soc.* **2012**, *134*, 15165. (m) Zhang, L.; Cheng, J.; Carry, B.; Hou, Z. *J. Am. Chem. Soc.* **2012**, *134*, 14314. (n) Jung, H.-Y.; Yun, J. *Org. Lett.* **2012**, *14*, 2606. (o) Liu, P.; Fukui, Y.; Tian, P.; He, Z.-T.; Sun, C.-Y.; Wu, N.-Y.; Lin, G.-Q. *J. Am. Chem. Soc.* **2013**, *135*, 11700. (p) Chen, Q.; Zhao, J.; Ishikawa, Y.; Asao, N.; Yamamoto, Y.; Jin, T. *Org. Lett.* **2013**, *15*, 5766.
(16) For the synthesis of polysubstituted alkenes via the iterative cross-coupling strategy, see: (a) Lee, S. J.; Gray, K. C.; Paek, J. S.; Burke, M. D. *J. Am. Chem. Soc.* **2008**, *130*, 466. (b) Fujii, S.; Chang, S. Y.; Burke, M. D. *Angew. Chem., Int. Ed.* **2011**, *50*, 7862. (c) Shimizu, M.; Nakamaki, C.; Shimono, K.; Schelper, M.; Kurahashi, T.; Hiyama, T. *J. Am. Chem. Soc.* **2005**, *127*, 12506. (d) Minato, A.; Suzuki, K.; Tamao, K. *J. Am. Chem. Soc.* **1987**, *109*, 1257. (e) Roush, W. R.; Koyama, K.; Curtin, M. L.; Moriarty, K. J. *J. Am. Chem. Soc.* **1996**, *118*, 7502. (f) Zeng, X.; Hu, Q.; Qian, M.; Negishi, E. *J. Am. Chem. Soc.* **2003**, *125*, 13636. (g) Zeng, X.; Qian, M.; Hu, Q.; Negishi, E. *Angew. Chem., Int. Ed.* **2004**, *43*, 2259. (h) Tan, Z.; Negishi, E. *Angew. Chem., Int. Ed.* **2006**, *45*, 762. (i) Bonazzi, S.; Güttinger, S.; Zemp, I.; Kutay, U.; Gademann, K. *Angew. Chem., Int. Ed.* **2007**, *46*, 8707. (j) Marjanovic, J.; Kozmin, S. A. *Angew. Chem., Int. Ed.* **2007**, *46*, 8854. (k) Roulland, E. *Angew. Chem., Int. Ed.* **2008**, *47*, 3762. (l) Arthuis, M.; Lecup, A.; Roulland, E. *Chem. Commun.* **2010**, *46*, 7810. For a recent review, see:: (m) Chelucci, G. *Chem. Rev.* **2012**, *112*, 1344 and references therein. For the leading reports on template synthesis of multisubstituted olefins, see: (n) Itami, K.; Nokami, T.; Ishimura, Y.; Mitsudo, K.; Kamei, T.; Yoshida, J. *J. Am. Chem. Soc.* **2001**, *123*, 11577. (o) Itami, K.; Kamei, T.; Yoshida, J. *J. Am. Chem. Soc.* **2003**, *125*, 14670. (p) Itami, K.; Mineno, M.; Muraoka, N.; Yoshida, J. *J. Am. Chem. Soc.* **2004**, *126*, 11778. (q) Jiao, J.; Hyodo, K.; Hu, H.; Nakajima, K.; Nishihara, Y. *J. Org. Chem.* **2014**, *79*, 285.
(17) Lipshutz, B. H.; Bošković, Ž. V.; Aue, D. H. *Angew. Chem., Int. Ed.* **2008**, *47*, 10183.
(18) Seeman, J. I. *Chem. Rev.* **1983**, *83*, 83.
(19) The natural charge difference between C(α) and C(β) in **Iα** and **Iβ** is very close (Δq = −0.26 and −0.27), while the difference in **TS1β** (Δq = −0.25) is obviously higher than that in **TS1α** (Δq = −0.14), indicating the larger electrostatic interactions in **TS1β** may account for the reversed stability of **TS1β** compared with **TS1α**.
(20) (a) Nakamura, E.; Miyachi, Y.; Koga, N.; Morokuma, K. *J. Am. Chem. Soc.* **1992**, *114*, 6686. For a recent review, see: (b) Yoshikai, N.; Nakamura, E. *Chem. Rev.* **2012**, *112*, 2339.
(21) Subjection of 1-phenyl-1-pentyne to the reaction conditions described in Table 2 or 4 resulted in both low conversions (<10%) and poor regioselectivity, indicating that the S atom serves as not only the directing group for regioselectivity but also the activating group for this Cu-catalyzed borylation reaction. For more details, see the Supporting Information.
(22) For a review on the Ni-catalyzed coupling of the C−S bond with Grignard reagents, see: Dubbaka, S. R.; Vogel, P. *Angew. Chem., Int. Ed.* **2005**, *44*, 7674.
(23) Doi, H.; Ban, I.; Nonoyama, A.; Sumi, K.; Kuang, C.; Hosoya, T.; Tsukada, H.; Suzuki, M. *Chem.—Eur. J.* **2009**, *15*, 4165.
(24) Zhao, X.; Wu, G.; Yan, C.; Lu, K.; Li, H.; Zhang, Y.; Wang, J. *Org. Lett.* **2010**, *12*, 5580.
(25) Yang, Z.; Chen, X.; Kong, W.; Xia, S.; Zheng, R.; Luo, F.; Zhu, G. *Org. Biomol. Chem.* **2013**, *11*, 2175.