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PREPARATION OF IMIDES VIA THE PALLADIUM-CATALYZED COUPLING REACTION OF ORGANOSTANNANES WITH METHYL *N*-[METHOXY(METHYLTHIO)METHYLENE]CARBAMATE

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Abstract – The preparation of imides via the palladium-catalyzed coupling reaction of organostannanes is described. The palladium-catalyzed coupling reaction of aryl-, heteroaryl-, and alkenyl(tributyl)stannanes with methyl *N*-[methoxy(methylthio)methylene]carbamate in the presence of Cu(I) thiophene-2-carboxylate (CuTC) affords imino ethers, which are converted to the corresponding imides in high yield through acid hydrolysis.

α,β-Unsaturated imides have been used in the catalytic asymmetric conjugate additions,[1] and their transformation into various functional groups has been studied,[1] suggesting their potential utility in organic synthesis. Typically, imides are prepared through the acylation of amides with carboxylic acid derivatives by bond connection at A[2] or B[3] in Scheme 1. These reactions require the corresponding carboxylic acids or their derivatives as starting materials, which limits their versatility. Alternatively, the reaction of nucleophiles with acylated isocyanates affords imides through bond connection at C (Scheme 1).[4] However, this method is limited to reactions of electron-rich nucleophiles such as organometalic reagents; electron-deficient alkenes are generally inert toward the electrophiles.

The palladium-catalyzed C–C cross-coupling reactions of organoboranes[5a,b] or organostannanes[5c] with thioesters, known as the Liebeskind–Srogl coupling reaction, are highly attractive and beneficial for the synthesis of complex natural products because the coupling reactions afford ketones under neutral conditions. This C–C bond-forming reaction has been extended to cross-coupling reactions between a variety of organosulfur and organometallic reagents.[5d] Among them, cross-coupling reactions using

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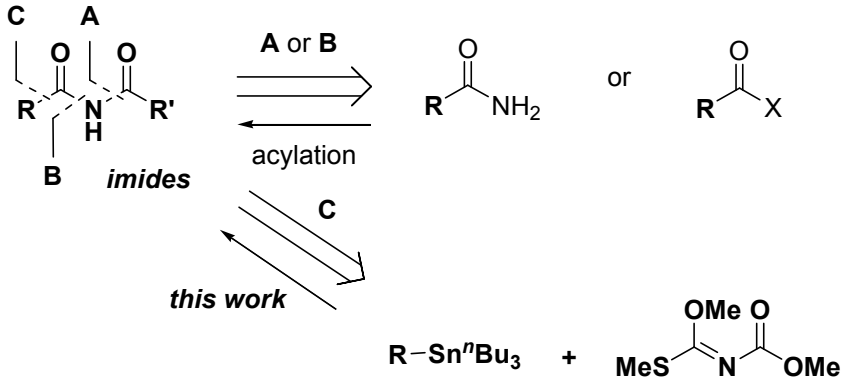
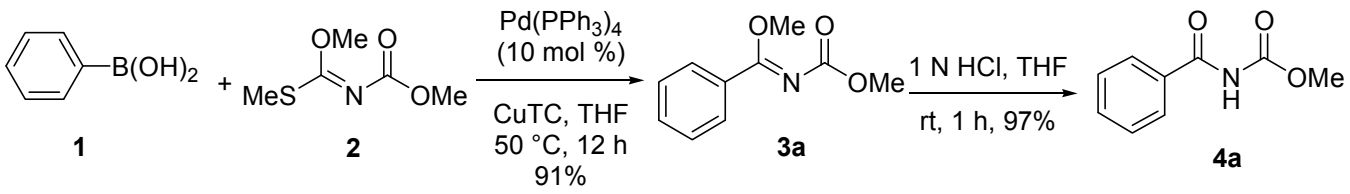
organostannanes are useful for the synthesis of complex natural products because most organostannanes and organosulfur compounds are stable to air and moisture, and can be purified by silica gel chromatography. Moreover, a variety of organostannanes can be prepared through various reactions.[6]



Scheme 1

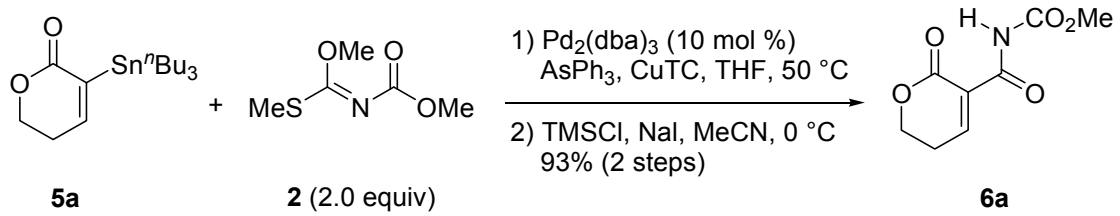
A one-carbon elongation reaction is a useful and important transformation in organic synthesis. As palladium-catalyzed one-carbon elongation reactions utilizing organostannanes, reactions of organic halides with carbon monoxide and tin hydride,[7] and reactions of organostannanes with carboxylic acid chlorides,[8] chloroformates, and carbamoyl chlorides[9] have been reported. However, to the best of our knowledge, the palladium-catalyzed one-carbon elongation reaction of organostannane to afford the imide product has never reported.

Recently, we found that the palladium-catalyzed coupling reaction of phenylboronic acid (**1**) with methyl *N*-[methoxy(methylthio)methylene]carbamate (**2**) affords the corresponding imino ether **3a**,[10] and subsequent acid hydrolysis gives the imide **4a**[11] in 88% overall yield (Scheme 2).[12] This palladium-catalyzed reaction also work with alkenyl- and alkylborons indicating its wide applicability.[12]



Scheme 2

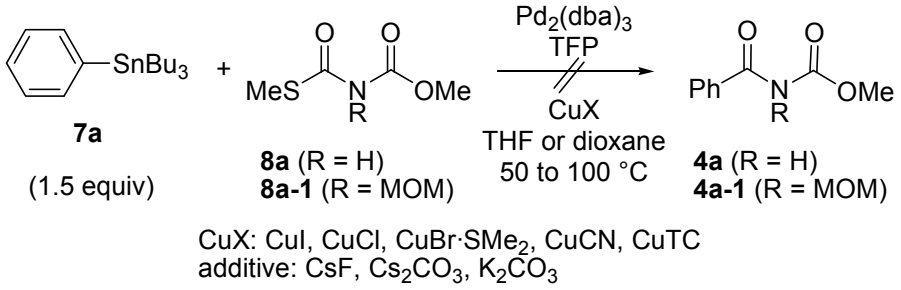
We also reported the preparation of imide **6a** by the palladium-catalyzed coupling reaction of alkenyl(tributyl)stannane **5a** with **2** and subsequent conversion of the resultant imino ether (Scheme 3).[13]



5a **2** (2.0 equiv) **6a**

Scheme 3

Some reactive imides were prepared in high yields through this method.[13] Therefore, to verify the scope and limitations of the method, we studied the preparation of imides via the palladium-catalyzed coupling reactions of aryl(tributyl)stannanes and alkenyl(tributyl)stannanes with **2**; the results are reported herein.



7a (1.5 equiv)

8a (R = H)
8a-1 (R = MOM)

4a (R = H)
4a-1 (R = MOM)

CuX: CuI, CuCl, CuBr·SMe$_2$, CuCN, CuTC
additive: CsF, Cs_2CO_3, K_2CO_3

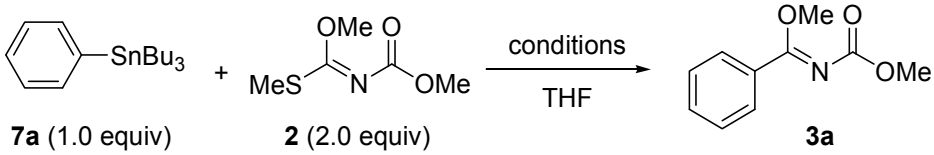
Scheme 4

We first examined the palladium-catalyzed coupling reaction of tributyl(phenyl)stannane **7a** with the imide **8a** under the conditions reported by Liebeskind and Srogl (Scheme 4).[5c,d] However, no products were obtained, and only the consumption of **8a** was observed. This result suggested that **8a** decomposed under the reaction conditions, as observed previously in the reaction between **1** and **2a**.[12] The reaction of **7a** with **8a-1**, which has a methoxymethyl (MOM) group on the nitrogen atom, gave the same result.

Consequently, we examined the palladium-catalyzed coupling reaction of **7a** with **2**, which was successfully used in the reaction with **1** (Table 1). Usually, palladium-catalyzed coupling reactions of alkylthio esters with organostannanes require copper(I) salt as an additive,[5c,d] and likewise, the reaction of **7a** with **2** did not proceed in the absence of copper(I) salt (entry 1). The reaction of **7a** using a catalytic amount of $Pd(PPh_3)_4$ in the presence of CuI afforded **3a** (30%, entry 2), and the reaction using CuBr·SMe_2 improved the yield to 50% (entry 3).

The use of Cu(I) thiophene-2-carboxylate (CuTC) in THF gave a better yield (81%, entry 4). The use of $Pd_2(dba)_3$ and TFP as a ligand did not improve the yield (49%, entry 5), but the reaction using $Pd_2(dba)_3$ and Ph_3As proceeded faster, and the yield was improved to 91% (entry 6). The reaction with a reduced amount of CuTC (1.5 equiv) was slow and the yield was reduced to 62% (entry 7).

Table 1. Optimization of the palladium-catalyzed coupling reaction of aryl(tributyl)stannane **7a** with **2**.

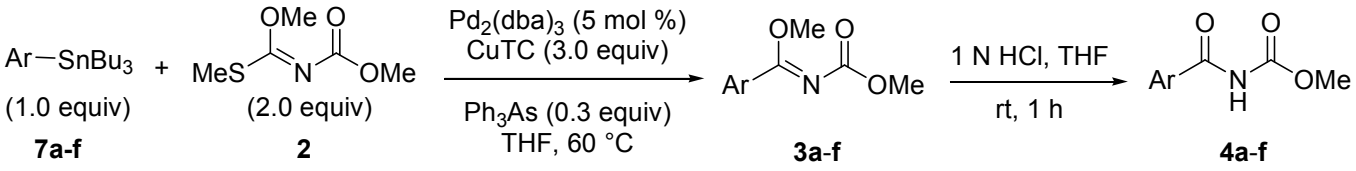


7a (1.0 equiv) **2** (2.0 equiv) **3a**

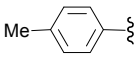
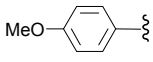
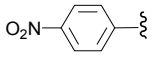
Entry	Pd (10 mol %)	ligand (mol %)	additive (equiv)	Temp (°C)	Time (h)	yield (%)[a]
1	$Pd(PPh_3)_4$	–	–	60	48	0
2	$Pd(PPh_3)_4$	–	CuI (3.0)	60	48	30
3	$Pd(PPh_3)_4$	–	$CuBr{\cdot}SMe_2$ (3.0)	60	10	50
4	$Pd(PPh_3)_4$	–	CuTC (3.0)	60	4	81
5	$Pd_2(dba)_3$	TFP[c] (30)	CuTC (3.0)	60	5.5	49
6	$Pd_2(dba)_3$	Ph_3As (30)	CuTC (3.0)	60	3	91
7	$Pd_2(dba)_3$	Ph_3As (30)	CuTC (1.5)	60	15	62

[a]Isolated yields. [b]Reaction was carried out at the indicated temperatures for the indicated times, respectively. [c]TFP = tris(2-furyl)phosphine.

Table 2. Preparation of imides **4a-f** via imino ethers **3a-f** which were prepared by the palladium-catalyzed coupling reactions of aryl(tributyl)stannanes **7a-f** (1.0 equiv) with **2** (2.0 equiv)



(1.0 equiv) **7a-f** (2.0 equiv) **2** **3a-f** **4a-f**

entry	Ar–	**7**	time (h)	yield (%)[a] of **3**	yield (%)[a] of **4**
1		**7a**	3	91 (**3a**)	97 (**4a**)
2		**7b**	4	99 (**3b**)	95 (**4b**)
3		**7c**	2	–[b]	90 (**4c**)[c]
4		**7d**	4	–[b]	90 (**4d**)[c]
5		**7e**	1	100 (**3e**)	95 (**4e**)
6		**7f**	1	–[b]	91 (**4f**)[c]

[a]Isolated yields. [b]Products were subjected to acid hydrolysis without purification owing to impurities. [c]Yields for 2 steps.

The preparation of imides **4b-f** through the palladium-catalyzed coupling reactions of other aryl(tributyl)stannanes **7b-f** with **2** and the subsequent hydrolysis of imino ethers **3b-f** were examined (Table 2). The coupling reaction of tributyl(*p*-tolyl)stannane **7b** with **2** afforded **3b** in 99% yield, and its hydrolysis using 1 *N* HCl in THF at room temperature gave **4b**[14] in 95% yield (entry 2). The reactions of tributyl(*p*-methoxyphenyl)stannane **7c** and tributyl(*p*-nitrophenyl)stannane **7d** with **2** also gave the corresponding imino ethers, which were subjected to acid hydrolysis to give **4c** and **4d**, respectively, in high yields (90%, 2 steps, entries 3 and 4).

The reaction of heteroarylstannanes was also examined. The reaction of tributyl(2-thienyl)stannane **7e** with **2** was completed within 1 h to afford **3e** quantitatively, and subsequent acid hydrolysis gave **4e** in 95% yield (entry 5). The palladium-catalyzed coupling reaction of **7e** with **2** was superior to the reaction of 2-thienylboronic acid with **2** (cf. 12 h, 60% (**3e**)).[12]

The reaction of 2-furanboronic acid **7f** with **2** and subsequent acid hydrolysis also proceeded smoothly to afford imide **4f** in 91% overall yield (entry 6). As summarized in Table 2, the palladium-catalyzed coupling reactions of aryl(tributyl)stannanes **7a-f** with **2** were completed within four hours.

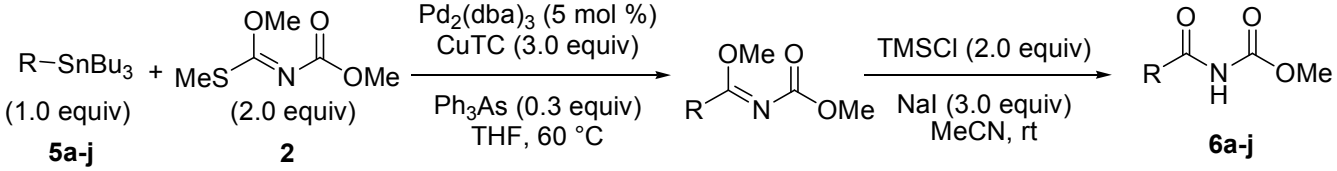
The palladium-catalyzed coupling reactions of alkenyl(tributyl)stannanes **5a-j** were examined next (Table 3). We reported the palladium-catalyzed coupling reactions of **5a** and **5b** with **2**, but 20 mol % of palladium reagent was used for the reaction.[13] Therefore, the reactions of **5a** and **5b** with **2** were carried out under the optimized reaction conditions, using 10 mol % of palladium reagent. Transformation of the imino ethers to **6a-j** was achieved using TMSCl and NaI in acetonitrile at room temperature, which are the optimized reaction conditions that we found.

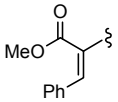
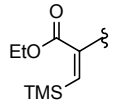
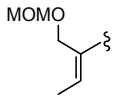
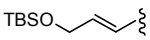
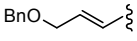
As a result, the yield of **6a** was reduced from 93% to 87% (2 steps) (entry 1), and that of **6b** was improved from 59% to 69% (2 steps) (entry 2), but no starting material remained in either reaction. Hence, further optimizations could improve the yields, and these results indicate 10 mol % of palladium reagent is sufficient for the catalytic reaction.

Next, the palladium-catalyzed coupling reaction of **5c** was performed. Compound **5c** was prepared through the palladium-catalyzed coupling reaction of the known **5c-1**[15] (Scheme 5) and hexabutyldistannane.[6e,g] Compound **5c** contains dienyl ether and lactone in the molecule, and is therefore sensitive to the reaction conditions, but subsequent treatment with TMSCl and NaI afforded **6c** in 66% yield (2 steps) (entry 3).

Compounds **5d** was prepared starting from known **5d-1**[16] (Scheme 5), which was converted to **5d-2** by carbometallation and subsequent acid-catalyzed lactonization. Compound **5d-2** was subjected to the halogen-metal exchange reaction using isopropylmagnesium bromide,[17] and subsequent reaction with tributyltin chloride afforded **5d**.

Table 3. The palladium-catalyzed coupling reactions of alkenyl(tributyl)stannanes **5a-j** (1.0 equiv) with **2** (2.0 equiv) and subsequent conversion of imino ethers to afford imides **6a-j**

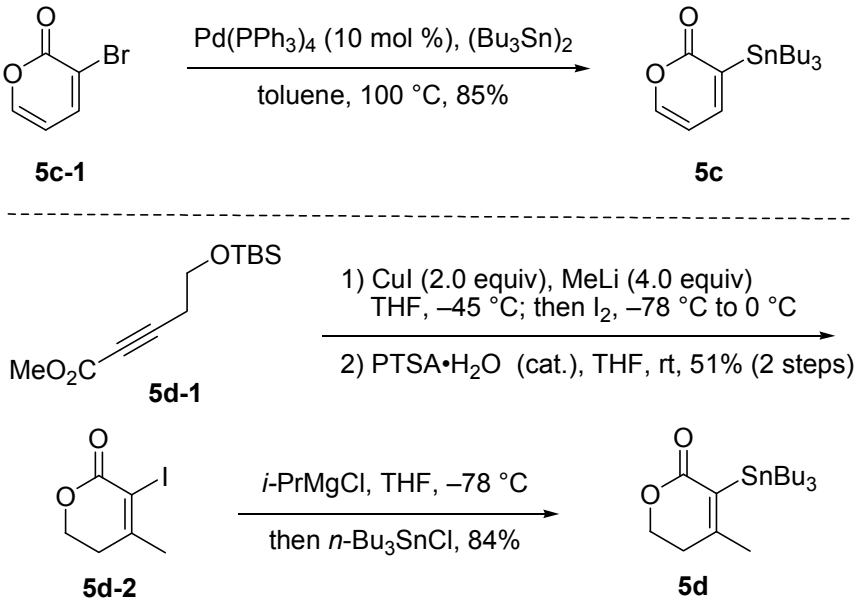


entry	R–	**5**	time (h)	yield (%)[a] of **6**
1		**5a**	1	87 (**6a**) [93][b]
2		**5b**	10	69 (**6b**) [59][b]
3		**5c**	12	66 (**6c**)
4		**5d**	1.5	75 (**6d**)
5		**5e**	1.3	84 (**6e**)
6		**5f**	1	86 (**6f**)
7		**5g**	1	66 (**6g**)
8		**5h**	7	69[c] (**6h**)
9		**5i**	1.5	53[c,d] (**6i**)
10		**5j**	1.3	69[c] (**6j**)

[a]Isolated overall yields. [b]Yields in brackets are those of the reactions using 20 mol % of palladium catalyst. [c]Acid hydrolysis was carried out using PPTS (0.3 equiv), THF, and H_2O at room temperature. [d]The corresponding imino ether was obtained in 93% yield.

Compound **5e** was prepared from the corresponding alkenyl iodide[18] according to the procedure for the preparation of **5c**. Compounds **5d** (entry 4) and **5e** (entry 5) are tetrasubstituted alkenylstannanes, and hence, these compounds were surmised to be affected by steric interactions during the coupling reactions.

However, the reactions proceeded smoothly and were completed within 90 min, and subsequent treatment with TMSCl and NaI afforded **6d** and **6e**, respectively, in high yields.



Scheme 5

Compounds **5f**[19] (entry 6) and **5g**[20] (entry 7) are known acyclic trisubstituted alkenylstannanes, and isomerization of the double bond was suspected to occur during the palladium-catalyzed coupling reaction and subsequent transformation. However, no isomerization was observed during the two-step sequence, and the corresponding imides **6f** and **6g**, respectively, were afforded in good to high yields.

Compound **5h** (entry 8) was prepared through the reaction of the corresponding alcohol[21] with chloromethyl methyl ether, which has no conjugated carbonyl group. The coupling reaction of **5h** proceeded smoothly, and subsequent acid hydrolysis of the imino ether with pyridinium *p*-toluenesulfonate (PPTS) and H_2O in THF afforded **6h** in 69% yield (2 steps). Mild acid hydrolysis conditions were required in this case owing to the acid-sensitive MOM ether in the molecule.

The coupling reaction of compound **5i**[22] (entry 9) also proceeded without problem to afford the corresponding imide in 93% yield. However, as is well known, the allylic TBS ether was labile even under these mild acidic conditions (PPTS, THF, and H_2O). Therefore, yield of **6i** was 53% (2 steps), but the reaction of compound **5j**[23] (entry 10) bearing an acid-resistant benzyl group provided **6j**[1p] in a higher yield. No isomerization of the alkene was observed in the reactions of **5h**, **5i**, and **5j**.

In summary, we have developed a new imide-preparation method via the palladium-catalyzed coupling reaction of organostannanes with methyl *N*-[methoxy(methylthio)methylene]carbamate. This method involves a one-carbon elongation that does not require the use of toxic carbon monoxide. The

palladium-catalyzed coupling reaction is broadly applicable to aryl-, heteroaryl-, and alkenylstannanes, affording a variety of imino ethers, which are easily converted to the corresponding imides in high to excellent yields under mild acidic conditions. Organostannanes can be prepared by a variety of reactions, as described above, and furthermore, most organostannanes are usually stable in air and moisture, and can be purified by silica gel chromatography. Therefore, the developed method could be useful for the preparation of a variety of imides.

EXPERIMENTAL

^{1}H and ^{13}C NMR spectra were recorded on a JEOL AL-400 spectrometer. ^{1}H and ^{13}C chemical shifts are reported in ppm downfield from tetramethylsilane (TMS, δ scale) with the solvent resonances as internal standards. The following abbreviations were used to explain the multiplicities: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; band, several overlapping signals; br, broad. IR spectra were recorded on a JASCO FT/IR-8300. Optical rotations were measured using a 2 mL cell with a 1 dm path length on a JASCO DIP-1000. Mass spectra and elemental analyses were provided at the Materials Characterization Central Laboratory, Waseda University. All reactions were carried out under an argon atmosphere with dry, freshly distilled solvents under anhydrous conditions, unless otherwise noted. Melting point (mp) is uncorrected and recorded on a Yamato capillary melting point apparatus. All reactions were monitored by thin-layer chromatography carried out on 0.25 mm E. Merck silica gel plates (60F-254) using UV light as visualizing agent and phosphomolybdic acid and heat as developing agents. Kanto Chemical Silica Gel 60N (spherical, neutral, 63-210 μm or 40-50 μm partial size) was used for flash chromatography. Preparative thin-layer chromatography (PTLC) separations were carried out on self-made 0.3 mm E. Merck silica gel plates (60F-254). In general, reactions were carried out in dry solvents under an argon atmosphere. Unless otherwise noted, materials obtained from commercial suppliers were used without further purification. Acetonitrile was distilled from calcium hydride before use. Tetrahydrofuran (THF) were distilled from sodium/benzophenone ketyl. Toluene was distilled from sodium.

Preparation of methyl *N*-[methoxy(methylthio)methylene]carbamate (2).[13] To a flame-dried 300 mL round-bottomed flask equipped with stir bar were added KSCN (2.77 g, 28.5 mmol, 1.1 equiv), THF (120 mL), and then methyl chloroformate (2.45 g, 25.9 mmol) at 0 °C. The reaction mixture was stirred at room temperature for 4 h, and then MeOH (1.78 mL, 44.0 mmol, 1.7 equiv) was added to the reaction mixture at room temperature. After 4 h, to the reaction mixture were added dimethyl sulfate (2.694 mL, 28.5 mmol, 1.1 equiv) and K_2CO_3 (7.15 g, 51.8 mmol, 2.0 equiv) at room temperature. The reaction mixture was stirred at room temperature for 12 h. After the starting material disappeared, the mixture was filtered through a plug of Celite, and the filtrate was concentrated under reduced pressure. The residue was purified by recrystallization to afford **2** (1.99 g, 47%): R_f = 0.50 (hexane/EtOAc = 2/1); mp 62 °C; ^{1}H

NMR (400 MHz,$CDCl_3$) δ 3.96 (s, 3H), 3.76 (s, 3H), 2.37 (s, 3H); ^{13}C NMR (100 MHz,$CDCl_3$) δ 174.8 (C), 161.2 (C), 57.6 (CH_3), 53.2 (CH_3), 13.8 (CH_3); IR (neat) ν_{max} 3038, 2958, 1672, 1533, 1437, 1279, 1182, 1054 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_5H_9NO_3NaS$: 186.02008, found: 186.02088.

General procedure for the preparation of imides.

Methyl methoxy(phenyl)methylenecarbamate (3a). To a stirred solution of **1a** (39.8 mg, 0.206 mmol) in THF (2 mL) was added $Pd_2(dba)_3$ (9.4 mg, 0.010 mmol, 0.05 equiv), Ph_3As (18.9 mg, 0.062 mmol, 0.3 equiv), CuTC (0.118 g, 0.619 mmol, 3.0 equiv) and methyl *N*-[methoxy(methylthio)methylene]carbamate (67.2 mg, 0.412 mmol, 2.0 equiv) at room temperature, and the resultant solution was stirred at 60 °C. After the starting material disappeared, the mixture was filtered through a Celite pad, and the filtrate was concentrated under reduced pressure. The residue was purified by flash chromatography (hexane/EtOAc = 20/1) to afford **3a**[10] (33.7 mg, 91%): ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64-7.59 (m, 2H), 7.53-7.38 (m, 3H), 3.93 (s, 3H), 3.73 (s, 3H).

Methyl benzoylcarbamate (4a). To a stirred solution of **3a** (33.7 mg, 0.514 mmol) in THF (2 mL) was added 1 *N*-HCl (3 drops) at room temperature. After the reaction was completed, H_2O (2 mL) was added to the reaction mixture, and the aqueous layer was extracted with CH_2Cl_2 (5 mL×2). The combined organic layers were washed with brine (2 mL×1), dried (Na_2SO_4), filtered, and concentrated under reduced pressure. The residue was purified by flash chromatography (hexane/EtOAc = 10/1) to afford **4a**[11] (30.5 mg, 97%): ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.03 (s, 1H), 7.81 (d, J = 7.3 Hz, 2H), 7.60 (t, J = 7.3 Hz, 1H), 7.81 (t, J = 7.3 Hz, 2H) 3.87 (s, 3H).

Methyl methoxy(*p*-tolyl)methylenecarbamate (3b): R_f = 0.50 (hexane/EtOAc = 2/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, J = 8.3 Hz, 2H), 7.15 (d, J = 8.3 Hz, 2H), 3.86 (s, 3H), 3.68 (s, 3H), 2.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.2 (C), 161.5 (C), 142.3 (C), 129.2 (CH), 128.0 (CH), 127.8 (C), 54.9 (CH_3), 53.3 (CH_3), 21.4 (CH_3); IR (neat) ν_{max} 3024, 2952, 1713, 1662, 1264, 1179, 1108 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{11}H_{13}NO_3Na$: 230.0800, found: 230.0793.

Methyl 4-methylbenzoylcarbamate (4b):[14] ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.03 (s, 1H), 7.71 (d, J = 7.6 Hz, 2H), 7.60 (d, J = 7.6 Hz, 2H), 3.86 (s, 3H), 2.42 (s, 3H).

Methyl 4-methoxybenzoylcarbamate (4c): ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.25 (bs, 1H), 7.83 (d, J = 8.8 Hz, 2H), 6.95 (d, J = 8.8 Hz, 2H), 3.87 (s, 3H), 3.84 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.1, 163.4, 151.9, 129.8, 125.0, 114.0, 55.5, 53.1; IR(neat) ν_{max} 3279, 2955, 2842, 1753, 1603, 1490, 1169, 776 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{10}H_{11}NO_4Na$: 232.05858, found: 232.05837.

Methyl 4-nitrobenzoylcarbamate (4d): ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (d, J = 8.3 Hz, 2H), 8.05 (bs, 1H), 7.96 (d, J = 8.3 Hz, 2H), 3.89 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.6, 166.9, 128.9, 125.3, 124.0, 116.4, 53.5; IR(neat) ν_{max} 3383, 3117, 3074, 2959, 2922, 2853, 1770, 1515, 1351cm^{-1}; HRMS

(ESI) $[M+Na]^+$ calcd for $C_9H_8N_2O_5Na$: 247.03309, found: 247.03398.

Methyl thiophene-2-carbonylcarbamate (4e): R_f = 0.20 (hexane/EtOAc = 2/1); ^1H NMR (400 MHz, $CDCl_3$) δ 7.96 (s, 1H), 7.65-7.62 (m, 2H), 7.14 (dd, *J* = 3.9 Hz, 3.9 Hz, 1H), 3.87 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.7 (C), 151.7 (C), 137.3 (C), 133.1 (CH), 130.4 (CH), 128.1 (CH), 53.3 (CH_3); IR(neat) ν_{max} 3273, 2955, 2926, 1749, 1502, 1183 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_7H_7NO_3NaS$: 208.0044, found: 208.0040.

Methyl furan-2-carbonylcarbamate (4f): ^1H NMR (400 MHz, $CDCl_3$) δ 8.35 (bs, 1H), 7.54 (d, *J* = 1.7 Hz, 1H), 7.35 (d, *J* = 3.7 Hz, 1H), 6.59 (dd, *J* = 1.7, 3.7 Hz, 1H), 3.87 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 154.4, 151.1, 146.2, 145.2, 117.7, 113.1, 53.2; IR(neat) ν_{max} 3275, 3135, 2957, 1758, 508, 1205, 1017, 771 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_7H_7NO_4Na$: 192.02728, found: 192.02745.

Methyl 2-oxo-5,6-dihydro-2*H*-pyran-3-carbonylcarbamate (6a). To a stirred solution of **5a** (50.6 mg, 0.131 mmol) in THF (2 mL) was added $Pd_2(dba)_3$ (6.0 mg, 0.007 mmol, 0.05 equiv), Ph_3As (12.0 mg, 0.039 mmol, 0.3 equiv), CuTC (74.8 mg, 0.392 mmol, 3.0 equiv) and methyl *N*-[methoxy(methylthio)methylene] carbamate (42.6 mg, 0.261 mmol, 2.0 equiv) at room temperature, and the resultant solution was stirred at 60 °C. After stirring at 60 °C for 1 h, the reaction mixture was cooled to room temperature, the mixture was filtered through a Celite pad, and the filtrate was concentrated under reduced pressure. The residue was filtered through a short plug of silica gel to afford the imino ether, which was used for the next step without further purification.

To a stirred solution of the imino ether obtained as above in MeCN (3 mL) was added TMSCl (0.03 mL, 0.261 mmol, 2.0 equiv), NaI (58.8 mg, 0.392 mmol, 3.0 equiv) at room temperature. After the reaction was completed, H_2O (2 mL) was added to the reaction mixture, and the aqueous layer was extracted with EtOAc (5 mL × 2). The combined organic layers were washed with brine (2 mL), dried (Na_2SO_4), filtered, and concentrated under reduced pressure. The residue was purified by flash chromatography (CH_2Cl_2/MeOH = 10/1) to afford **6a** (22.6 mg, 87% (2 steps)): R_f = 0.10 (hexane/EtOAc = 1/1); ^1H NMR (400 MHz, $CDCl_3$) δ 10.71 (bs, 1H), 8.29 (t, *J* = 4.4 Hz, 1H), 4.50 (t, *J* = 6.1 Hz, 2H), 3.82 (s, 3H), 2.78 (dt, *J* = 6.1, 4.4 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.0, 159.1, 157.2, 151.1, 122.1, 66.3, 52.9, 25.1; IR(neat) ν_{max} 3266, 1778, 1713, 1499, 1188, 1012, 800 cm^{-1}; mp 115 °C; HRMS (ESI) $[M+Na]^+$ calcd for $C_8H_9NO_5Na$: 222.0378, found: 222.0383.

Methyl 6-oxocyclohex-1-enecarbonylcarbamate (6b): R_f = 0.20 (hexane/EtOAc = 1/1); ^1H NMR (400 MHz, $CDCl_3$) δ 10.9 (br, 1H), 8.43 (t, *J* = 4.4 Hz, 1H), 3.81 (s, 3H), 2.67 (dt, *J* = 6.8, 4.4 Hz, 2H), 2.59 (t, *J* = 6.8 Hz, 2H), 2.09 (tt, *J* = 6.8, 6.8 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.6, 164.4, 160.6, 151.4, 130.0, 52.7, 38.6, 27.0, 21.8; IR(neat) ν_{max} 3235, 2955, 1786, 1715, 1660, 1506, 1229, 1186 cm^{-1}; mp = 87–88 °C; HRMS(FAB) $[M+H]^+$ calcd for $C_9H_{12}NO_4$: 198.0766, found: 198.0776.

3-(Tributylstannyl)-2*H*-pyran-2-one (5c): R_f = 0.80 (hexane/EtOAc = 10/1); ^1H NMR (400 MHz,

$CDCl_3$) δ 7.43 (dd, *J* = 2.2, 5.1 Hz, 1H), 7.38 (dd, *J* = 2.2, 5.9 Hz, 1H), 6.14 (dd, *J* = 5.1, 5.9 Hz, 1H), 1.55-1.46 (m, 6H), 1.39-1.24 (m, 6H), 1.10-1.02 (m, 6H), 0.90-0.84 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 151.6, 151.1, 133.0, 106.6, 28.9, 27.3, 13.6, 9.72; IR(neat) ν_{max} 2954, 2919, 2870, 2851, 1701, 1525, 1081, 957, 776 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{17}H_{30}O_2NaSn$: 401.11917, found: 401.11950.

Methyl 2-oxo-2*H*-pyran-3-carbonylcarbamate (6c): R_f = 0.50 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.8 (br, 1H), 8.63 (dd, *J* = 2.2, 6.8 Hz, 1H), 7.80 (dd, *J* = 2.2, 4.9 Hz, 1H), 6.63 (dd, *J* = 4.9, 6.8 Hz, 1H), 3.85 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.9, 159.4, 156.2, 151.0, 150.2, 117.9, 107.6, 53.0; IR(neat) ν_{max} 3239, 3099, 2960, 1779, 1710, 1506, 1280, 1196, 784 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_8H_7NO_5Na$: 220.02219, found: 220.02181.

4-Methyl-3-(tributylstannyl)-5,6-dihydropyran-2-one (5d): R_f = 0.20 (hexane/EtOAc = 10/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.30 (t, *J* = 6.1 Hz, 2H), 2.37 (t, *J* = 6.1 Hz, 2H), 2.03 (s, 3H), 1.59-1.45 (m, 6H), 1.38-1.29 (m, 6H), 1.10-1.01 (m, 6H), 0.94-0.86 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.6, 165.0, 130.4, 65.3, 31.0, 28.7, 27.0, 13.4, 13.3, 11,1; IR(neat) ν_{max} 2954, 2922, 2870, 2852, 1706, 1686, 1278, 1153, 766, 668 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{18}H_{34}O_2NaSn$: 417.15047, found: 417.14964.

Methyl 4-methyl-2-oxo-5,6-dihydro-2*H*-pyran-3-carbonylcarbamate (6d): R_f = 0.60 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$); δ 9.58 (br, 1H), 4.41 (t, *J* = 6.1 Hz, 2H), 3.78 (s, 3H), 2.62 (t, *J* = 6.1 Hz, 2H), 2.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.4, 162.8, 151.6, 130.0, 122.7, 64.9, 52.9, 32.1, 22.5; IR(neat) ν_{max} 3265, 2999, 2957, 1756, 1695, 1496, 1404, 1208, 801 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_9H_{11}NO_5Na$: 236.05349, found: 236.05453.

3-Methyl-2-(tributylstannyl)cyclohex-2-enone (5e): R_f = 0.50 (hexane/EtOAc = 10/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.36 (t, *J* = 6.1 Hz, 2H), 2.34 (t, *J* = 6.1 Hz, 2H), 2.01 (s, 3H), 1.95 (tt, *J* = 6.1, 6.1 Hz, 2H), 1.52-1.44 (m, 6H), 1.36-1.27 (m, 6H), 1.00-0.96 (m, 6H), 0.94-0.88 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 202.7, 170.0, 140.5, 36.8, 33.5, 29.0, 27.2, 26.3, 22.5, 13.5, 11.5; IR(neat) ν_{max} 2953, 2922, 2869, 2852, 1646, 1590, 1269, 1188, 669 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{19}H_{36}ONaSn$: 45.17121, found: 415.17192.

Methyl 2-methyl-6-oxocyclohex-1-enecarbonylcarbamate (6e): R_f = 0.50 (EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.11 (br, 1H), 3.75 (s, 3H), 2.50 (t, *J* = 6.6 Hz, 2H), 2.48 (t, *J* = 6.6 Hz, 2H), 2.13 (s, 3H), 2.03 (tt, *J* = 6.6, 6.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 196.7, 166.6, 164.9, 151.8, 132.4, 52.8, 37.2, 33.0, 22.8, 21.2; IR(neat) ν_{max} 3265, 2954, 1758, 1693, 1665, 1490, 1201, 775 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{10}H_{13}NO_4Na$: 2234.07423, found: 234.07524.

(*Z*)-Methyl 2-(methoxycarbonylcarbamoyl)-3-phenylacrylate (6f): R_f = 0.50 (hexane/EtOAc = 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.14 (br, 1H), 7.77 (s, 1H), 7.49 (d, *J* = 7.6 Hz, 2H), 7.37-7.36 (m, 3H),

3.85 (s, 3H), 3.74 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.4, 151.6, 142.0, 132.5, 130.6, 129.7, 128.9, 127.1, 126.8, 53.3, 52.6; IR(neat) ν_{max} 3275, 2954, 1788, 1760, 1685, 1490, 1203, 841, 808 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{13}H_{13}NO_5Na$: 286.06914, found: 286.06786.

(*Z*)-Methyl 2-(methoxycarbonylcarbamoyl)-3-(trimethylsilyl)acrylate (6g): R_f = 0.80 (hexane/EtOAc = 1/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.93 (br, 1H), 7.62 (s, 1H), 3.82 (s, 3H), 3.78 (s, 3H), 0.21 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.5, 161.8, 151.5, 124.2, 120.0, 53.0, 52.8, -1.04; IR(neat) ν_{max} 2172, 2955, 1760, 1698, 1489, 1260, 1199, 773, 692 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{10}H_{17}NO_5SiNa$: 282.07737, found: 282.07832.

(*E*)-tributyl(1-(methoxymethoxy)but-2-en-2-yl)stannane (5h): R_f = 0.60 (hexane/EtOAc = 20/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.70-5.64 (m, 1H), 4.63 (s, 2H), 4.27 (s, 2H), 3.37 (s, 3H), 1.69 (d, *J* = 6.6 Hz, 3H), 1.51-1.44 (m, 6H), 1.35-1.26 (m, 6H), 0.90-0.84 (m, 15H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.7, 134.0, 96.0, 69.1, 55.2, 29.2, 27.4, 15.4, 13.7, 10.0; IR(neat) ν_{max} 2954, 2923, 2871, 2852, 1463, 1153, 1055. 668 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{18}H_{38}O_2NaSn$: 421.18177, found: 421.18043.

(*E*)-Methyl 2-((methoxymethoxy)methyl)but-2-enoylcarbamate (6h): R_f = 0.70 (hexane/EtOAc = 20/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.90 (br, 1H), 7.10 (q, *J* = 7.6 Hz, 1H), 4.68 (s, 2H), 4.35 (s, 2H), 3.80 (s, 3H), 3.43 (s, 3H), 1.91 (d, *J* = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 151.7, 142.7, 130.0, 95.2, 60.2, 55.8, 52.8, 14.0; IR(neat) ν_{max} 3295, 2952, 1763, 1499, 1190, 1147, 1006, 919, 776 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_9H_{15}NO_5Na$: 240.08479, found: 240.08462.

(*E*)-*tert*-butyldimethyl(3-(tributylstannyl)allyloxy)silane (5i): R_f = 0.70 (hexane/EtOAc = 20/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.20 (d, *J* = 18.8 Hz, 1H), 6.05 (dt, *J* = 4.1, 18.8 Hz, 1H), 4.21 (d, *J* = 4.1 Hz, 2H), 1.53-1.46 (m, 6H), 1.35-1.26 (m, 6H), 0.96-0.86 (m, 24H), 0.08 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.3, 126.8, 66.7, 29.1, 27.3, 25.9, 18.5, 13.7, 9.4, –5.1; IR(neat) ν_{max} 2954, 2926, 2845, 1462, 1252, 1091, 834, 773 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{21}H_{46}OSiNaSn$: 477.22638, found: 2477.22747.

(*E*)-Methyl 4-(*tert*-butyldimethylsilyloxy)but-2-enoylcarbamate (6i): R_f = 0.20 (hexane/EtOAc = 2/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65 (br, 1H), 7.18 (dt, *J* = 3.2, 15.1 Hz, 1H), 7.02 (dt, *J* = 2.0, 15.1 Hz, 1H), 4.55 (dd, *J* = 2.0, 3.2 Hz, 2H), 3.80 (s, 3H), 0.94 (s, 9H), 0.1 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.6, 152.0, 149.4, 119.5, 622.5, 53.1, 25.8, 18.3, -5.5; IR(neat) ν_{max} 3270, 2954, 2928, 2856, 1770, 1518, 1227, 1064, 835, 777 cm^{-1}; HRMS (ESI) $[M+Na]^+$ calcd for $C_{12}H_{23}NO_4NaSi$: 296.12940, found: 296.13072.

(*E*)-Methyl 4-(benzyloxy)but-2-enoylcarbamate (6j):[1p] ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (br, 1H), 7.36-7.26 (m, 5H), 7.14 (dt, *J* = 3.7, 15.4 Hz, 1H), 7.05 (d, *J* = 15.4 Hz, 1H). 4.58 (s, 2H), 4.22 (dd, *J* = 2.2, 3.7 Hz, 2H), 3.79 (s, 3H).

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