Organosilicon and organotin compounds are useful reagents in organic synthesis and can be applied to a variety of synthetic transformations, including transition metal-catalyzed cross-coupling reactions. Organogermanium compounds, however, have attracted much less attention. Germanium is located between silicon and tin in the periodic table, and the properties of a C-Ge bond are intermediate between a C-Si bond and a C-Sn bond. Arylgermanes are expected to be more reactive toward electrophiles than arylsilanes due to the stronger $\beta$-effect from the C-Ge bond compared with the C-Si bond. Organotin compounds are more reactive, but highly toxic. Therefore, arylgermanes are potentially attractive synthetic intermediates, but only a limited number of synthetic reactions using arylgermanes are reported. This is in part due to the high cost of germanium, but the lack of the general methods to prepare arylgermanes is also an important issue. Nucleophilic substitution of halogermanes by aryllithium or Grignard reagents is the most reliable method for accessing arylgermanes. These highly reactive organometallic reagents are, however, incompatible with sensitive functional groups.

Transition metal-catalyzed silylation of aryl (pseudo)halides using disilanes or hydrosilanes has been extensively investigated over the last several decades for synthesizing arylsilanes without using aryllithium or Grignard reagents. On the other hand, studies of transition metal-catalyzed germylation of aryl halides are scarce, although such reactions enable the direct synthesis of functionalized arylgermanes. Oshima achieved Pd-catalyzed germylation of aryl iodides using tri(2-furyl)germane, but electron-deficient aryl iodides were not investigated, and an aryl bromide was unreactive. Yamanoi and Nishihara reported general conditions for Pd-catalyzed coupling reactions of various aryl iodides and hydrogermanes. In contrast to aryl iodides, less reactive aryl bromides are still
difficult substrates for germylation (Figure 1b). Earborn reported Pd-catalyzed germylation of aryl bromides with hexaethylgermane, but the reactions required harsh conditions (140–180 °C) and resulted in a low yield. Tanaka reported Pd-catalyzed germylation of bromobenzene and 2,5-dichlorotetramethyldigermane was required, and the results were rather complicated due to halogen exchange. To date, general and practical conditions for transition metal-catalyzed germylation of aryl bromides and aryl triflates have not been reported.

In this article, we report Pd-catalyzed germylation of aryl bromides 1a and aryl triflates 2a using commercially available hexamethyldigermane 3 (Figure 1c).

We initiated our investigation by optimizing the reaction conditions for germylation of aryl bromide 1a using hexamethyldigermane 3 (Table 1, entries 1–10). We selected the reaction conditions of Pd-catalyzed silylation of aryl halides with hexamethyldisilane reported by Shirakawa and Hiyama as the initial conditions (entries 1,2). These conditions afforded the desired germylated arenne 4a in moderate yield along with several byproducts. GC/MS analysis revealed the formation of reduced product 6, biaryl 7, and unidentified products bearing an alkyl or propenyl group. We then investigated other palladium sources using toluene/H2O as the solvent to circumvent incorporation of the C3 units derived from PdCl(allyl). With Pd(dba)3, we instead exhibited inferior catalytic activity (entry 3), the use of Pd(OAc)2 resulted in 62% yield (entry 4). In these cases, incorporation of the C3 unit was avoided, but a significant amount of 7 was produced. Several bases and phase transfer catalysts (PTC) were then screened to improve the selectivity (entries 5-9), and Cs2CO3 and Et4NHCO3 were the most effective for providing 4a in 93% yield, with only a tiny amount of 6 (entry 9). The use of Ph3P for a ligand instead of 3.

Table 1 Optimization of Reaction Conditions for Germylation of 1a and 2a

| Entry | Substrate | Pd cat. | Solvent | Base | PTC | Additive | Temp. (°C) | % Yield of 4a | Ratio of 1a or 2a : 4a : 6 : 7 : 8 | Other |
|-------|-----------|---------|---------|------|-----|----------|------------|--------------|----------------|----------------|-------|
| 1     | 1a        | (PdCl(allyl)) | THF/H2O | NaOH | Bu3NBr | –     | 100       | 44            | 2 : 75 : 4 : 18 : 0 : 0 | 0     |
| 2     | 1a        | (PdCl(allyl)) | toluene/H2O | NaOH | Bu3NBr | –     | 100       | 60            | 3 : 80 : 13 : 3 : 1 : 0 | 0     |
| 3     | 1a        | Pd(dba)3 | toluene/H2O | NaOH | Bu3NBr | –     | 100       | 39            | 0 : 65 : 12 : 21 : 2 : 0 | 0     |
| 4     | 1a        | Pd(OAc)2 | toluene/H2O | NaOH | Bu3NBr | –     | 100       | 62            | 0 : 73 : 3 : 23 : 1 : 0 | 0     |
| 5     | 1a        | Pd(OAc)2 | toluene/H2O | KOH-Bu | Bu3NBr | –     | 100       | 48            | 0 : 66 : 2 : 32 : 1 : 0 | 0     |
| 6     | 1a        | Pd(OAc)2 | toluene/H2O | KOAc | Bu3NBr | –     | 100       | 47            | 0 : 67 : 25 : 6 : 2 : 0 | 0     |
| 7     | 1a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Bu3NBr | –     | 100       | 77            | 0 : 89 : 6 : 4 : 1 : 0 | 0     |
| 8     | 1a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Bu3NBr | –     | 100       | 56            | 20 : 59 : 0 : 21 : 0 : 0 | 0     |
| 9     | 1a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Bu3NBr | –     | 100       | 93 (86%0 | 0 : 92 : 8 : 0 : 0 : 0 | 0     |
| 10    | 1a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | – | 100     | 63            | 0 : 71 : 3 : 0 : 26 : 0 | 0     |
| 11    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | – | 100     | 0            | 99 : 0 : 0 : 0 : 0 : 1 | 0     |
| 12    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | – | 100     | 11            | 25 : 16 : 0 : 16 : 0 : 0 : 0 | 0     |
| 13    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | LiCl | 100     | 33            | 61 : 11 : 0 : 5 : 23 : 0 : 0 | 0     |
| 14    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | LiBr | 100     | 94           | 5 : 1 : 0 : 0 : 0 : 0 : 0 | 0     |
| 15    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | Bu3NBr | 100     | 2   | 94 : 2 : 0 : 0 : 0 : 0 : 0 | 0     |
| 16    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | Bu3NBr | 100     | 8   | 88 : 7 : 0 : 0 : 0 : 0 : 0 | 0     |
| 17    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | Bu3Ni | 100     | 15   | 57 : 22 : 0 : 4 : 1 : 16 | 0     |
| 18    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | Et3NCO | 100     | 35   | 7 : 54 : 1 : 0 : 9 | 0     |
| 19    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | Et3NBr | 100     | 40   | 30 : 42 : 0 : 2 : 14 : 12 | 0     |
| 20    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | Et3NBr | 120     | 77   | 2 : 59 : 0 : 0 : 27 : 12 | 0     |
| 21    | 2a        | Pd(OAc)2 | toluene/H2O | Cs2CO3 | Et4NHCO3 | – | 120 | 85 (83%) | 1 : 66 : 2 : 0 : 24 : 7 | 0     |
Me₆Ge₂\(^3\) (1.2 equiv) + Ar-X\(^1\)\(^\text{X = Br}\)\(^2\) (X = OTf) → Me₆Ge₅\(^4\)

Pd(OAc)\(_2\) (10 mol %), Cs\(_2\)CO₃ (1.2 equiv), Et₄NHCO₃ (10 mol %) in toluene/H\(_2\)O, 100 °C, 24 h

Substrate: \(^1\) [X = Br]

Cl-GeMe₃ \(^4\)a, conditions A 86%

MeO-GeMe₃ \(^4\)b, conditions A\(^a\) 73%

OH-GeMe₃ \(^4\)c, conditions A 82%

PinB-GeMe₃ \(^4\)d, conditions A 80%

BzHN-GeMe₃ \(^4\)e, conditions B 45%

MeO-GeMe₃ \(^4\)f, conditions B 83%

Br-GeMe₃ \(^4\)g, conditions A 85%

BzHN-GeMe₃ \(^4\)h, conditions B 45%

MeO-GeMe₃ \(^4\)i, conditions A/B <5%

MeO-GeMe₃ \(^4\)j, conditions B \(^6\) 68%

MeO-GeMe₃ \(^4\)k, conditions B\(^6\) 65%

MeO-GeMe₃ \(^4\)l, conditions B 68%

Substrate: \(^2\) [X = OTf]

Cl-GeMe₃ \(^4\)m, conditions B 83%

MeO-GeMe₃ \(^4\)n, conditions B 50%

AcN-GeMe₃ \(^4\)o, conditions B \(^7\) 35%

MeO-GeMe₃ \(^4\)p, conditions B 15%

MeO-GeMe₃ \(^4\)q, conditions B 61%

MeO-GeMe₃ \(^4\)r, conditions B 79%

MeO-GeMe₃ \(^4\)s, conditions B\(^5\) 47%

MeO-GeMe₃ \(^4\)t, conditions B\(^5\) 47%

MeO-GeMe₃ \(^4\)u, conditions B\(^5\) \(^6\) 67%

MeO-GeMe₃ \(^4\)v, conditions B\(^5\) \(^6\) 67%

Figure 2 Scope and limitations of the germylation of aryl bromides \(^1\) and aryl triflates \(^2\). Conditions A: \(^1\) (1.0 equiv), \(^3\) (1.2 equiv), Pd(OAc)\(_2\) (10 mol %), \(^5\) (20 mol %), Et₄NHCO₃ (10 mol %), and Cs\(_2\)CO₃ (1.2 equiv) in toluene/H\(_2\)O at 100 °C for 24 h. Conditions B: \(^1\) or \(^2\) (1.0 equiv), \(^3\) (1.2 equiv), Pd(OAc)\(_2\) (10 mol %), ligand \(^5\) (20 mol %), Cs\(_2\)CO₃ (1.2 equiv), and Et₄NBr (1.0 equiv) in toluene at 120 °C for 24 h. Isolated yields are shown. See experimental section for detailed conditions and scale of each substrate. \(^7\) 120 °C. \(^8\) Only a trace amount of the desired product was observed in GC/MS analysis. \(^9\) Pd(OAc)\(_2\) (20 mol %) and \(^5\) (40 mol %) were used. \(^6\) KOAc instead of Cs\(_2\)CO₃ was used. \(^\ast\) 130 °C. \(^\dagger\) 2.0 equiv was used. \(^\ddagger\) 62 h.
germylated product 4j and phenol was detected as a major product under both reaction conditions. Germylated drug-like structures (4k,13 4l15) were accessible from the corresponding aryl bromides under Conditions B. In addition to aryl bromides, various types of aryl triflates afforded the desired germylated arenes. Electron-rich arenes such as 2n and 2s exhibited low reactivity (4n, 4s), while highly electron-deficient substrates resulted in low yields due to fast hydrolysis of the sulfonate group (4o, 4p). In some cases, the use of K2CO3 instead of Cs2CO3 was beneficial for avoiding the hydrolysis (4o, 4u). Moderately electron-deficient aryl triflates were good substrates, and the products were obtained in good yield (4a, 4q, 4r, 4h) under the standard conditions. The triflate of estrone 2t exhibited low reactivity, but moderate yield was obtained using 20 mol % of Pd(OAc)2 (4t).

We also investigated germylation of aryl iodide 10 under the optimized conditions for aryl bromides (Scheme 1). The conditions for aryl bromides were effective to provide 4a in 95% yield at 80 °C, but the lower reaction temperature resulted in lower conversion.

![Scheme 1 Germylation of aryl iodide 10](image)

When β-bromostyrene was used as a substrate, both Conditions A and Conditions B in Figure 2 afforded a dimerized product as a major product (see Supporting Information). Thus, the developed conditions were not suitable for germylation of alkenyl bromides.

The exact catalytic cycle was not elucidated, but a plausible cycle comprises oxidative addition of 1 or 2 to Pd(0), transmetalation with digermane 3, and reductive elimination to release arylgermane 4. The use of PPh3 as a ligand also aﬀorded the product in moderate yield (Table 1, entry 10), and therefore a hydroxy group of 5 would only have minor eﬀects for the desired catalytic cycle, in contrast to the dramatic ligand eﬀects observed in silylation.9 The role of Et3NB in germylation of aryl triflates was unclear. A tetraethylammonium ion might be important rather than a bromide ion (Table 1, entries 13–19).

In summary, we developed general conditions for the germylation of aryl bromides 1 and aryl triflates 2 using hexamethyldigermane 3 under palladium catalysis. Various functionalized substrates, including drug-like molecules, afforded the germylated products in moderate to good yield, demonstrating the versatility of the presented protocols. These methods enable easy access to functionalized arylgermanes, and may encourage further investigation of the properties and reactivity of arylgermane derivatives.

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**Procedures**

**General:** Reported melting points were uncorrected. Infrared (IR) spectra were recorded on a JASCO FT/IR-5300 spectrophotometer and absorbance bands are reported in wave numbers (cm⁻¹). NMR spectra were recorded on JEOL JNM-ECS400 spectrometers operating at 391.78 MHz for 1H NMR and 98.52 MHz for 13C NMR, JEOL JNM-ECX400 spectrometers operating at 395.88 MHz for 1H NMR and 99.55 MHz for 13C NMR, and JNM-ECS500 spectrometers operating at 500.16 MHz for 1H NMR and 125.77 MHz for 13C NMR. Chemical shifts were reported in the scale relative to TMS (0.00 ppm for 1H NMR), CHCl3 (7.26 ppm for 1H NMR), CH2Cl2 (7.70 ppm for 13C NMR), CDCl3 (7.55 ppm for 1H NMR) and CD2Cl2 (128.06 ppm for 13C NMR) as an internal reference, respectively. ESI mass spectra were measured on JEOL JMS-T100LC spectrometer. silica gel column chromatography was performed with Kanto Silica gel 60 N (40-50 mesh). Gel permeation chromatography was performed with YMC LC-forte/R using CHCl3 as an eluent. Commercially available THF, toluene (Wako Ltd., deoxidized grade) were used without further manipulation unless otherwise stated. All aryl triflates 2 were prepared from corresponding commercially available phenol. Aryl bromides 1a, 1b, 1c, 1d, 1h, 1i were commercially available and distilled under reduced pressure or recrystallized before use. 1-(4-Bromophenethyl)piperidine 1f10-15-bromo-1-tyl-1H-indole 1g10-16 2-bromobenzene[b]thiophene 1l17 and ethyl 8-bromo-5-methyl-6-oxo-5,6-dihydro-4H-benzo[b]fimidazol[1,5-d][1,3]diazepine-3-carboxylate 1k14 were synthesized according to the literature. Structures of bromides 1 and aryl triflates 2 are listed in Figure S1 in Supporting Information. Hexamethyldigermane 3 was purchased from Sigma-Aldrich and used as received. All other reagents were commercially available and used as received.

**General Procedure for Germylation of Aryl Bromides and Triflates**

**Conditions A:** To a screw vial with a septum cap were added aryl bromide 1 (0.50 mmol), Pd(OAc)2 (11.2 mg, 0.05 mmol, 10 mol %), ligand 5 (27.8 mg, 0.10 mmol, 20 mol %), Cs2CO3 (195.5 mg, 0.60 mmol, 1.2 equiv.), Et3NHCOC3 (9.5 mg, 0.05 mmol, 10 mol %), hexamethyldigermane 3 (120 µL, 0.60 mmol, 1.2 equiv.) and toluene (2.5 mL) under Ar atmosphere in a glove box. The vial was capped and heated at 120 °C for 24 h with stirring. After cooled to room temperature, the organic layer was separated, and the aqueous layer was extracted with EtOAc (3 mL × 3). The combined organic layers were washed with brine (3 mL), dried over Na2SO4. Filtration and evaporation gave a crude product, which was purified by silica gel column chromatography to give a corresponding product 4.

**Conditions B:** To a dried screw capped vial were added aryl bromide 1 or aryl triflate 2 (0.50 mmol), Pd(OAc)2 (11.2 mg, 0.05 mmol, 10 mol %), ligand 5 (27.8 mg, 0.10 mmol, 20 mol %), Cs2CO3 (195.5 mg, 0.60 mmol, 1.2 equiv.), Et3NHBAr (105.1 mg, 0.5 mmol, 1.0 equiv.), hexamethyldigermane 3 (120 µL, 0.60 mmol, 1.2 equiv.) and toluene (2.5 mL) under Ar atmosphere in a glove box. The vial was capped and heated at 120 °C for 24 h with stirring. After cooled to room temperature, H2O (2 mL) was added. After dilution with EtOAc, the organic layer was separated, and the aqueous layer was extracted with EtOAc (3 mL × 3). The combined organic layers were washed with brine (3 mL), and dried over Na2SO4. Filtration and evaporation gave a crude product, which was purified by silica gel column chromatography to give a corresponding product 4.

**4-Chlorophenyltribromide (4a)**

**Conditions A** using 1-bromo-4-chlorobenzene 1a (0.50 mmol) and purification of the crude product by silica gel column chromatography (hexane) followed by gel permeation chromatography afforded 4a as a colorless oil (98.6 mg, 86% yield).

**Conditions B** using 4-chlorophenyl trifluoromethanesulfonate 2a (0.50 mmol) and purification of the crude product by silica gel column chromatography (hexane) afforded 4a as a colorless oil (95.1 mg, 83% yield).

**TLC:** Rf 0.75 (hexane)

**IR (neat):** 2972, 2907, 1481, 1381, 1238, 1077, 1015, 825, 602, 571 cm⁻¹

The procedures and conditions for the germylation of aryl substrates were developed to enable the synthesis of a variety of arylgermanes, which are useful in various applications. The development of general procedures for the germylation of aryl bromides and triflates allowed for the efficient preparation of functionalized arylgermanes, demonstrating the versatility of this palladium-catalyzed reaction.
TLC: R_f column chromatography (hexane/EtOAc = 20:1)

Conditions A using 1-bromo-4-methoxybenzene 1b at 120 °C and purification of the crude product by silica gel column chromatography afforded the crude product by silica gel column chromatography (hexane/EtOAc = 20:1) afforded 4b as a colorless oil (82.0 mg, 73% yield).

HRMS (ESI): m/z (M+) calcd for C9H13Cl70Ge: 225.9956; found: 225.9945
HRMS (El): m/z 334.0601 calcd for C16H19ON70GeNa: 334.0601; found: 334.0603

1-[(4-Trimethylgermyl)phenethyl]piperidine (4f)

Conditions A using 4-bromobenzaldehyde 1c and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 20:1) followed by gel permeation chromatography afforded 4c as a colorless oil (91.2 mg, 82% yield).

HRMS (El): m/z (M+) calcd for C15H25B70GeO2Na: 340.1124; found: 340.1134;
HRMS (ESI): m/z (M+N+) calcd for C15H25B70GeNa: 334.0601; found: 334.0603

1-[(4-Trimethylgermyl)phenethyl]piperidine (4f)

Conditions A using 4-bromobenzaldehyde 1c and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 20:1) afforded 4b as a colorless oil (82.0 mg, 73% yield).

TLC: R_f 0.59 (hexane/EtOAc = 8:1)

IR (neat): 3311, 2972, 1578, 1525, 797, 744, 726, 656, 602 cm–1

1H NMR (400 MHz, CDCl3): δ = 7.78 (d, J = 8.2 Hz, 2 H), 7.49 (d, J = 8.2 Hz, 2 H), 2.17, 2.10 (d, J = 11.9 Hz, 1 H), 2.13 (s, 3 H), 1.95-1.90 (m, 2 H), 1.67-1.59 (m, 2 H), 1.50-1.44 (m, 2 H), 0.36 (s, 9 H)

13C NMR (100 MHz, CDCl3): δ = 140.8, 134.5, 134.3, 128.1, 59.3 cm–1

IR (KBr): 3140, 3111, 2968, 2907, 1447, 1371, 1257, 1127, 1171, 1095, 996, 585, 576 cm–1

1H NMR (500 MHz, CDCl3): δ = 7.92 (d, J = 8.3 Hz, 1 H), 7.77 (d, J = 8.3 Hz, 2 H), 7.63 (s, 1 H), 7.54 (d, J = 1.7 Hz, 1 H), 7.39 (dd, J = 8.3, 4.2 Hz, 1 H), 7.22 (d, J = 8.3 Hz, 2 H), 6.64 (d, J = 3.7 Hz, 1 H), 2.34 (m, 3 H), 0.38 (s, 9 H)

13C NMR (125 MHz, CDCl3): δ = 149.9, 136.6, 135.4, 135.0, 130.6, 129.9, 128.9, 128.6, 128.1, 126.0, 116.0, 108.7, 21.5, 1.62

HRMS (ESI): m/z (M+N+) calcd for C18H21O2N70GeNa: 408.0428; found: 408.0442

Toxyl-5-(trimethylgermyl)-1H-indole (4g)

Conditions A using 4-bromobenzaldehyde 1c and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 20:1) afforded 4g as a colorless solid (165 mg, 85% yield).

TLC: R_f 0.50 (hexane/EtOAc = 5:1)

M.p.: 110.2-110.8 °C

IR (KBr): 3140, 3111, 2968, 2916, 1447, 1371, 1257, 1127, 1171, 1095, 996, 585, 576 cm–1

1H NMR (500 MHz, CDCl3): δ = 7.97 (d, J = 8.3 Hz, 1 H), 7.77 (d, J = 8.3 Hz, 2 H), 7.63 (s, 1 H), 7.54 (d, J = 3.7 Hz, 1 H), 7.39 (dd, J = 8.3, 4.2 Hz, 1 H), 7.22 (d, J = 8.3 Hz, 2 H), 6.64 (d, J = 3.7 Hz, 1 H), 2.34 (m, 3 H), 0.38 (s, 9 H)

13C NMR (125 MHz, CDCl3): δ = 149.9, 136.6, 135.4, 135.0, 130.6, 129.9, 128.9, 128.6, 128.1, 126.0, 116.0, 108.7, 21.5, 1.62

HRMS (ESI): m/z (M+N+) calcd for C16H19ON70GeNaS: 408.0459; found: 408.0461

6-[(Trimethylgermyl)quinoline (4h)

Conditions A using 6-bromoquinoline 1h and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 5:1) afforded 4h as a colorless oil (107 mg, 87% yield).

TLC: R_f 0.30 (hexane/EtOAc = 4:1)

IR (neat): 3311, 2968, 1564, 1491, 1341, 1237, 1071, 856, 831, 799, 771, 623, 601, 587, 567 cm–1

1H NMR (500 MHz, CDCl3): δ = 8.91 (dd, J = 4.0, 1.7 Hz, 1 H), 8.15 (d, J = 8.0 Hz, 1 H), 8.08 (d, J = 8.0 Hz, 1 H), 7.92 (s, 1 H), 7.82 (dd, J = 8.0, 1.1 Hz, 1 H), 7.40 (dd, J = 8.0, 4.0 Hz, 1 H), 0.48 (s, 9 H)

13C NMR (125 MHz, CDCl3): δ = 150.4, 148.3, 141.4, 135.8, 133.5, 132.8, 128.5, 127.9, 121.1, 1.77

HRMS (ESI): m/z (M+H+) calcd for C16H12O2N70GeNaS: 444.0523; found: 444.0523

Benzo[b]thiophen-2-yltrimethylgermane (4i)

Conditions B using 2-Bromobenz[b]thiophene 1i and purification of the crude product by silica gel column chromatography (hexane) followed by gel permeation chromatography afforded 4i as a colorless oil (87.1 mg, 69% yield).

TLC: R_f 0.67 (hexane/EtOAc = 20:1)

IR (neat): 3056, 2973, 2907, 1453, 1240, 945, 826, 761, 744, 726, 605, 574, 561 cm–1

1H NMR (400 MHz, CDCl3): δ = 7.87 (d, J = 7.7 Hz, 1 H), 7.79 (d, J = 7.7 Hz, 1 H), 7.38 (s, 1 H), 7.35-7.26 (m, 2 H), 0.51 (s, 9 H)
Ethyl 2-(4-bromophenoxy)-2-methylpropanoate (1k) 4-Bromophenol (519 mg, 3.0 mmol) and Cs₂CO₃ (2.44 g, 7.5 mmol, 2.5 equiv) were dissolved in anhydrous DMF (10 mL). The solution was stirred for 10 min, and then ethyl 2-bromosubstitute (1.17 g, 6.0 mmol, 2.0 equiv) was added. The resulting reaction mixture was stirred at 100 °C for 23 h. After cooled to room temperature, the residue was taken up in EtOAc (50 mL). The solution was successively washed with H₂O (20 mL x 2) and brine (20 mL) and dried over Na₂SO₄. Filtration and evaporation gave a crude product, which was purified by silica gel column chromatography to give 1k as a colorless oil (63.2 mg, 50 % yield).

IR (KBr): 3438, 2979, 2899, 2830, 1625, 1592, 1455, 1432, 1234, 998, 730, 711, 603 cm⁻¹

M.p.: 164.5-165.2 °C

Ethyl 2-methyl-2-(4-(trimethylgermyl)phenoxy)propanoate (4k) Conditions B using ethyl 2-(4-bromophenoxy)-2-methylpropanoate 1k (114.9 mg, 0.40 mmol), Pd(OAc)₂ (20 mol %), and ligand 5 (40 mol %) and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 1:1) followed by gel permeation chromatography afforded 4k as a colorless oil (84.4 mg, 65% yield).

IR (KBr): 3438, 3037, 2979, 2905, 1594, 1513, 1386, 1351, 1240, 835, 730, 711, 603 cm⁻¹

M.p.: 66.7-67.8 °C

Ethyl 5-methyl-6-oxo-8-(trimethylgermyl)-5,6-dihydro-4H-benzo[f][imidazo[1,5-a][1,4]diazepine-3-carboxylate (4l) Conditions B using ethyl 8-bromo-5-methyl-6-oxo-5,6-dihydo-4H-benzo[f][imidazo[1,5-a][1,4]diazepine-3-carboxylate (4i) (109.3 mg, 0.30 mmol) and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 1:2 to 1:3) and afforded 4l as a pale yellow solid (92 mg, 68% yield).

IR (KBr): 3421, 2961, 2905, 2865, 1383, 1267, 1235, 1078, 818, 760, 602, 576, 552 cm⁻¹

M.p.: 69.2-70.0 °C

Ethyl 2-(4-(trimethylgermyl)phenyl)piperazin-1-yl)ethan-1-one (4m) Conditions B using 4-(4-(acetyl)piperazin-1-yl)phenyl trifluoromethanesulfonate 2q and purification of the crude product by silica gel column chromatography (EtOAc/MeOH = 19:1) followed by gel permeation chromatography afforded 4m as a pink solid (47.2 mg, 29 % yield).

IR (KBr): 3342, 3037, 2979, 2905, 1594, 1513, 1386, 1351, 1240, 835, 730, 711, 603 cm⁻¹

M.p.: 60.5-61.7 °C

Ethyl 3-(trimethylgermyl)benzoate (4p)

IR (KBr): 3438, 3037, 2979, 2899, 2830, 1625, 1592, 1455, 1432, 1234, 998 cm⁻¹

M.p.: 60.5-61.7 °C

Ethyl 5-(tert-butyl)phenyltrimethylgermylene (4q) Conditions B using ethyl 5-((trifluoromethyl)sulfonyl)oxy)benzoate 2q and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 20:1) followed by reverse phase column chromatography (CH₃OH/MeCN = 15/85) afforded 4q as a colorless oil (20.4 mg, 50 % yield).

IR (KBr): 3421, 2961, 2905, 2865, 1383, 1267, 1235, 1078, 818, 760, 602, 576, 552 cm⁻¹

M.p.: 69.2-70.0 °C

Ethyl 4-(4-acetyl)piperazin-1-yl)phenyl trifluoromethanesulfonate 2q and purification of the crude product by silica gel column chromatography (EtOAc/MeOH = 19:1) followed by gel permeation chromatography afforded 4q as a pink solid (47.2 mg, 29 % yield).

IR (KBr): 3438, 3037, 2979, 2899, 2830, 1625, 1592, 1455, 1432, 1234, 998 cm⁻¹

M.p.: 60.5-61.7 °C

Ethyl 3-(trimethylgermyl)benzoyl (4r)

IR (KBr): 3438, 3037, 2979, 2899, 2830, 1625, 1592, 1455, 1432, 1234, 998 cm⁻¹

M.p.: 60.5-61.7 °C

Ethyl 5-(4-acetyl)phenyl trifluoromethanesulfonate 2q and purification of the crude product by silica gel column chromatography (hexane/EtOAc = 20:1) followed by reverse phase column chromatography (CH₃OH/MeCN = 15/85) afforded 4q as a colorless oil (20.4 mg, 50 % yield).

IR (KBr): 3421, 2961, 2905, 2865, 1383, 1267, 1235, 1078, 818, 760, 602, 576, 552 cm⁻¹

M.p.: 69.2-70.0 °C

Ethyl 3-(trimethylgermyl)benzoate (4q)
 Instead of C₆H₄O₂NGeNa: 416.1231; found: 416.1234

**TLC**: Rₛ = 0.75 (hexane/EtOAc = 7:3)