Highly active and recyclable silica gel-supported palladium catalyst for mild cross-coupling reactions of unactivated heteroaryl chlorides†

Dong-Hwan Lee, Ji-Young Jung and Myung-Jong Jin*

Received 23rd June 2010, Accepted 3rd September 2010
DOI: 10.1039/c0gc00251h

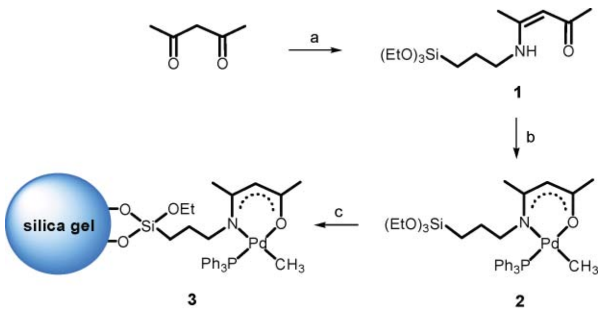
Silica gel-supported β-ketoiminatophosphane-Pd complex (Pd@SiO_2) was shown to be a highly active and long-lived catalyst for aqueous Suzuki, Stille and Sonogashira coupling reactions of heteroaryl chlorides. A wide range of heteroaryl chlorides could be efficiently coupled with different nucleophilic partners in the presence of only 0.5 mol% catalyst and under mild conditions. This is one of the most powerful heterogeneous catalysts for the couplings of diverse heteroaryl chlorides. Furthermore, the catalyst could be reused with almost consistent activity.

Introduction

Palladium-catalyzed coupling reactions are effective synthetic methods for the construction of carbon–carbon bonds.[1] Much progress has been achieved with homogeneous Pd catalysts in this area.[2] One practical limit in performing homogeneously catalyzed reactions is the difficulty of separating the catalysts from the products and reusing the expensive catalysts continuously. These limits are of significant environmental and economic concern in large-scale organic syntheses. The use of heterogeneous catalysts would be an attractive solution to this problem because of their easy separation and facile recycling. Therefore, successful development of homogeneous catalysts has been often followed by attempts to immobilize the catalysts on a variety of polymeric organic or inorganic supports.[3] Although considerable efforts have been devoted to the development of efficient heterogeneous catalysts, a long-standing limitation of the coupling reaction arises from the inability to effectively couple readily accessible and cheap deactivated aryl chlorides. Successful examples of this are quite rare.[4] Moreover, the couplings of heteroaryl chlorides encounter more difficulty because the competitive binding of such substrates to the metal center results in the formation of catalytically inactive complexes.[5] There is at present no general method for the heterogeneous reactions of heteroaryl chlorides. Recently, magnetic particle-supported β-ketoiminatophosphane-Pd complex was found to be an efficient catalyst for the coupling reactions of aryl chlorides.[6] Our interest in this area led us to explore a reusable palladium catalyst immobilized on commercial silica gel which may have advantages over the homogeneous counterpart. Silica gel is a well-established support for heterogeneous catalysts due to its excellent thermal/chemical stability, cost-effectiveness, and the fact that organic groups can be robustly anchored to the surface.[7] Herein, we describe the use of highly active silica gel-supported Pd catalyst **3** for the Suzuki, Stille and Sonogashira reactions of unreactive heteroaryl chlorides.

Results and discussion

Silica gel-supported palladium catalyst (Pd@SiO_2) **3** was prepared from acetylacetone as shown in Scheme 1. Condensation of acetylacetone and 3-aminopropyltriethoxysilane under microwave heating gave β-ketoiminopropyltriethoxysilane **1** in high yields. Impressively, this reaction was complete within 3 mins in the absence of solvent. Deprotonation of **1** with EtOTl or EtONa, followed by treatment with $Pd_2(\mu\text{-}Cl)_2Me_2(PPh_3)_2$, led to the formation of silylated Pd complex **2**. Pd@SiO_2 **3** was obtained by heating **2** with silica gel in toluene at 100 °C. Loading amounts of Pd on the surface can be controlled in this step. Pd@SiO_2 **3** of 0.19 mmol Pd/g was prepared for this study and the value was confirmed by inductively coupled plasma atomic emission spectrometry (ICP-AES).



a) $NH_2(CH_2)_3Si(OEt)_3$, MW b) EtOTl, $Pd_2(u\text{-}Cl)_2Me_2(PPh_3)_2$, THF, RT
c) silica gel, toluene, 100 °C, 8 h

Scheme 1 Synthesis of silica gel-supported β-ketoiminatophosphanyl palladium complex **3**.

Today, the Suzuki reaction is probably one of the most popular Pd-catalyzed coupling reactions.[8] This reaction involving heterocycles is of interest to the pharmaceutical industry because of the special biological activities displayed by the heterobiaryl compounds.[9] We first tested catalyst **3** in the Suzuki reaction of heteroaryl chlorides with arylboronic acids in water (Table 1). We used water as reaction media for environmental benefit, even though the activity was accelerated in organic solvents. Tetrabutylammonium bromide (TBAB) as a phase transfer agent was added to enhance the reactivity in water. Various

---

Department of Chemical Science and Engineering, Inha University, Incheon, 402-751, South Korea. E-mail: mjjin@inha.ac.kr; Fax: +82 32-872-0959; Tel: +82 32-860-7469

† Electronic supplementary information (ESI) available: Compound characterizations and NMR data. See DOI: 10.1039/c0gc00251h

Table 1 Suzuki coupling of heteroaryl chlorides with arylboronic acids[a]

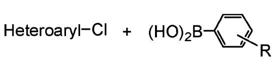
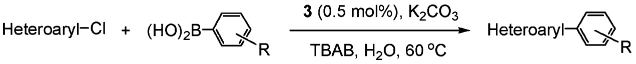
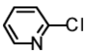
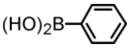
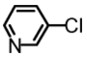
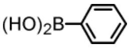
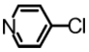
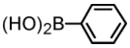
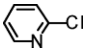
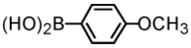
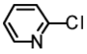
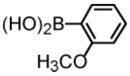
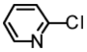
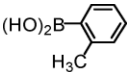
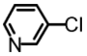
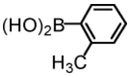
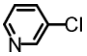
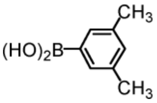
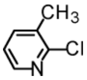
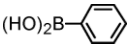
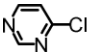
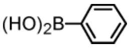
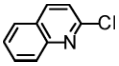
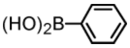
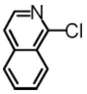
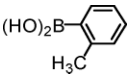
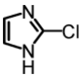
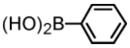
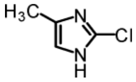
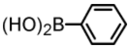
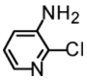
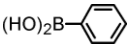
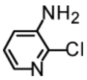
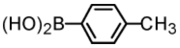
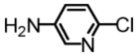
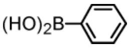
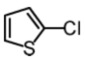
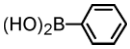
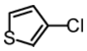
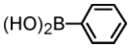
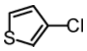
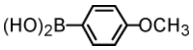
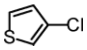
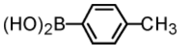
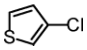
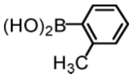
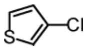
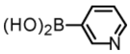
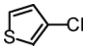
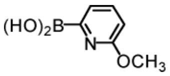
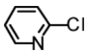
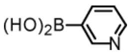
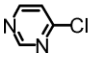
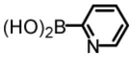


Table 1 *(Contd.)*

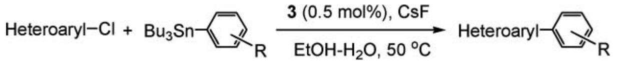


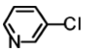
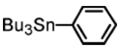
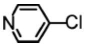
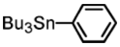
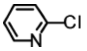
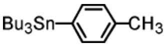
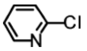
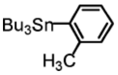
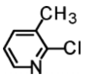
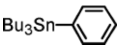
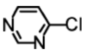
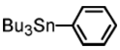
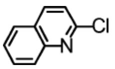
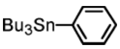
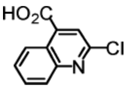
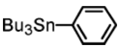
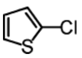
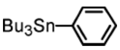
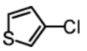
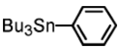
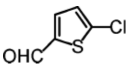
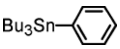
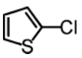
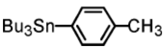
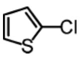
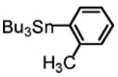
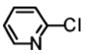
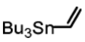
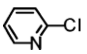
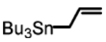
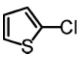
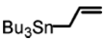
Entry	Heteroaryl chloride	Arylboronic aicd	Time/h	Yield (%)[b]
1			4	94 (96)
2			5	88 (90)
3			5	91 (95)
4			5	93 (95)
5			5	90 (94)
6			6	92 (96)
7			6	86 (89)
8			6	87 (92)
9			8	86 (90)
10			5	94 (96)
11			6	91 (93)
12			8	92 (94)
13			6	90 (92)
14			8	84 (87)
15[c]			10	86 (88)
16[c]			10	80 (84)
17[c]			8	92 (95)
18			5	93 (94)
19			6	90 (92)
20			6	92 (95)
21			6	88 (91)
22			8	87 (89)
23			8	86 (90)
24			10	84 (88)
25			8	91 (93)
26			8	85 (87)

[a] Reaction conditions: heteroaryl chloride (1.0 mmol), arylboronic acid (1.2 mmol), **3** (0.5 mol%), TBAB (0.5 mmol), H_2O (2 mL) and 60 °C. [b] Isolated yields (GC yields in parenthesis). [c] Reaction temperature: 80 °C.

chloro-pyridines were coupled with arylboronic acids in the presence of 0.5 mol% of **3** at 60 °C to afford the corresponding products in excellent yields (entries 1–9). The catalyst also displayed high rate in the coupling of heteroaryl chlorides such as 2-chloropyrimidine, 2-chloroquinoline, 1-chloroisoquinoline, and chloroimidazoles (entries 10–14). Importantly, unprotected aminochloropyridines were also deemed to be suitable coupling substrates (entries 15–17). It is known that the coupling of basic heteroaryl chlorides bearing an unprotected amino group is affected by a competitive binding affinity of the amino group to the Pd center of the catalyst.[10] The reaction is quite impressive when the scope of this catalytic system was further extended to the coupling of chlorothiophenes. 2- and 3-chlorothiophenes underwent coupling with arylboronic acids to provide the desired products in high yields (entries 18–22). These results came as a surprise since chlorothiophenes in the coupling reaction are challenging substrates due to the strong affinity of the sulfur to the Pd.[5c] Furthermore, this catalytic system allowed for the coupling with 2- and 3-pyridineboronic acid, known as a less efficient reagent, although somewhat longer time was required (entries 23–26). Regardless of the substituent, our catalyst showed unprecedented activity for the mild Suzuki coupling reaction of heteroaryl chlorides in water.

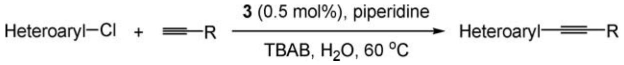
Table 2 Stille coupling of heteroaryl chlorides with organostannanes[a]

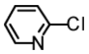
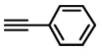
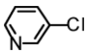
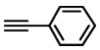
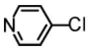
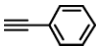
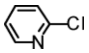
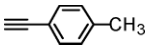
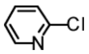
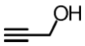
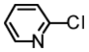
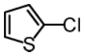
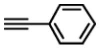
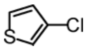
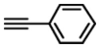


Entry	Heteroaryl chloride	Organostannane	Time/h	Yield (%)[b]
1			4	90 (94)
2			3	94 (96)
3			5	84 (86)
4			6	86 (88)
5			8	83 (87)
6			6	91 (93)
7			6	89 (92)
8			5	92 (96)
9			5	91 (92)
10			5	85 (87)
11			4	93 (95)
12			8	81 (84)
13			10	83 (85)
14			5	82 (86)
15			5	87 (91)
16			6	81 (84)

[a] Reaction conditions: heteroaryl chloride (1.0 mmol), organostannane (1.2 mmol), **3** (0.5 mol%), CsF (2.0 mmol), EtOH–H_2O (2 mL, 1 : 1) and 50 °C. [b] Isolated yields (GC yields in parenthesis).

Table 3 Sonogashira coupling of heteroaryl chlorides with alkynes[a]



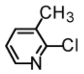
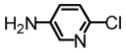
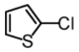
Entry	Heteroaryl chloride	Alkyne	Time/h	Yield (%)[b]
1			5	96 (98)
2			6	87 (88)
3			5	90 (92)
4			8	91 (93)
5			6	85 (88)
6		$\equiv C_6H_{13}$	10	82 (85)
7			6	90 (93)
8			8	86 (89)

[a] Reaction conditions: heteroaryl chloride (1.0 mmol), alkyne (1.2 mmol), **3** (0.5 mol%), piperidine (2.0 mmol), TBAB (0.5 mmol), H_2O and 60 °C (2 mL). [b] Isolated yields (GC yields in parenthesis).

We next investigated the Stille coupling of heteroaryl chlorides with arylstannanes in aqueous ethanol (Table 2). The Stille coupling of aryl and heteroaryl chlorides remains a challenge especially under mild conditions.[11] Chloropyridines were coupled well with only 0.5 mol% of **3** at 50 °C (entries 1–5). High reactivity was also observed for the coupling of 4-chloropyrimidine, 2-chloroquinoline, and 2-chloroquinoline-4-carboxylic acid (entries 6–8). Moreover, the catalyst was found to be active for the coupling of 2- and 3-chlorothiophene. (entries 9–13). The important aldehyde functional group was tolerated under the present conditions (entry 11). One of the most useful applications of the Stille reaction is the coupling with vinyl- and allystannanes. Satisfactory results were obtained in the reaction of 2-chloropyridine or 3-chlorothiophene with tributylvinystanne and allytributylstanne under mild heating (entries 14–16). The heterogeneous Stille coupling of heteroaryl chlorides has not been reported to date. Interestingly, these results are comparable to those of the homogeneous counterpart.[12] It is apparent that this catalyst has the specific advantages of homogeneous and heterogeneous catalysts.

The application range of catalyst **3** was extended to the Sonogashira reaction of heteroaryl chlorides with terminal alkynes in water (Table 3). The Sonogashira reaction is one of the most powerful methods for the construction of C(sp^2)–C(sp) bonds. In most cases, the reactions with aryl chlorides require high catalyst loadings, elevated reaction temperatures, and CuI as the co-catalyst.[13] Efficient copper-free Sonogashira coupling of heteroaryl chlorides was achieved in the presence of only 0.5 mol% catalyst. Excellent catalytic activity was observed in the coupling of 2- and 3-chloropyridine with phenylacetylene or 4-ethynyltoluene at 60 °C (entries 1–4). The catalyst was capable of performing this coupling with other alkynes such as propargyl alcohol and 1-octyne (entries 5 and 6). Besides, 2- and

Table 4 Recycling of catalyst **3** in Suzuki coupling of heteroaryl chlorides with phenylboronic acid[a]

Entry	Heteroaryl chloride	Cycle	Yield (%)[b]	Pd leaching (ppm)
1		1	90	0.151
		2	92	0.008
		3	91	0.006
		4	92	0.01
		5	91	0.007
		6	90	0.003
2		1	95	0.127
		2	92	0.034
		3	91	0.011
		4	93	0.006
		5	91	0.014
		6	89	0.012
3		1	94	0.108
		2	95	0.023
		3	94	0.009
		4	91	0.013
		5	93	0.008
		6	92	0.011

[a] Recycling tests were carried out under the same reaction conditions in Table 1. The reaction times were the same as those in Table 1. [b] GC yields.

3-chlorothiophene underwent the coupling very well under the same conditions (entries 7 and 8). All of the reactions afforded the corresponding products in excellent yields. To the best of our knowledge, this represents the first successful example of a heterogeneous Sonogashira reaction of heteroaryl chlorides in water.

The recycling of the catalyst is an important issue in the heterogeneous reaction. We turn our attention to reusability of our Pd catalyst. As shown in Table 4, catalyst **3** was recycled in the Suzuki couplings of 2-chloro-3-methylpyridine, 3-amino-6-chloropyridine and 2-chlorothiophene with phenylboronic acid, respectively. We have observed that the catalyst could be reused at least six times without significant loss of activity. After the reaction, Pd metal in the solution was analyzed by ICP-AES method. Less than 0.06% Pd of the initially added catalyst was leached out from the catalyst surface. The isolated solution did not exhibit any further reactivity. In addition, the recovered Pd catalyst was very similar to the original in the XANES and EXAFS patterns. It indicates that the Pd(II) catalyst on the support surface might be still maintained after the reaction.

Conclusions

We have demonstrated that silica gel-supported Pd complex **3** exhibits high catalytic activity for the Suzuki, Stille, and Sonogashira coupling reactions. A wide range of structurally and electronically diverse unreactive heteroaryl chlorides were coupled very well in aqueous solution. In particular, the performance of the catalyst was fully retained during the reuse process. These represent very successful heterogeneous coupling reactions of unreactive heteroaryl chlorides under mild conditions.

Experimental

All reagents were used as received from commercial source. All manipulations were conducted under an atmosphere of dry nitrogen. Microwave irradiation was performed with a Discover microwave synthesis system (CEM Co.). ^{1}H, ^{13}C, and ^{31}P NMR spectra were recorded on a Bruker AM 400 (400 MHz). Chemical shifts were quoted in parts per million (ppm) referenced to the appropriate solvent peak or 0.0 ppm for tetramethylsilane. ^{31}P NMR spectra were referenced to external PPh_3 (0 ppm relative to free PPh_3). Elemental analyses (EA) were carried out using EA-110 (Thermo Finnigan). GC/GC-MS analyses were performed on an Agilent 6890 N GC coupled to an Agilent 5975 Network Mass Selective Detector. Analysis of Pd content was measured by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) using OPTIMA 4300 DV (Perkin–Elmer).

Synthesis of β-ketoiminopropyltriethoxysilane 1

Acetylacetone (1.1 g, 11.0 mmol) and 3-aminopropyltriethoxysilane (2.21 g, 10.0 mmol) were placed in a 10 mL glass tube. The vessel was sealed with a septum and placed into the microwave cavity. The reaction temperature was raised from rt to 130 °C under microwave irradiation of 150 W. The power was maintained for 3 min. After allowing the mixture to cool to rt, the reaction mixture was vacuumed under reduced pressure to give β-ketoiminopropyltriethoxysilane **1** as a light yellow liquid (2.94 g, 97%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.82 (br s, 1H), 4.99 (s, 1H), 3.82 (q, $J = 6.8$ Hz, 6H), 3.24 (q, $J = 12$ Hz, 2H), 2.00 (s, 3H), 1.92 (s, 3H), 1.75 (t, $J = 7.2$ Hz, 2H), 1.22 (t, $J = 6.8$ Hz, 9H), 0.68 (t, $J = 7.2$ Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.29, 162.80, 94.91, 58.34, 45.41, 28.68, 23.82, 18.75, 18.25, 7.60 ppm; Anal. Calcd. for $C_{14}H_{29}NO_4Si$ (303.19): C, 55.41; H, 9.63; N, 4.62. Found: C, 55.62; H, 9.54; N, 4.58.

Synthesis of β-ketoiminatopropyltriethoxysilanephosphane-Pd complex 2

A solution of $Tl(OC_2H_5)$ (300 mg, 1.2 mmol) in THF (10 mL) was added dropwise at room temperature to a solution of β-ketoiminopropyltriethoxysilane (0.30 g, 1.0 mmol) in THF (10 mL). After stirring for 2 h at room temperature, a solution of $Pd_2(\mu\text{-}Cl)_2Me_2(PPh_3)_2$[14] (0.51 g, 0.6 mmol) in THF (5 mL) was dropwise added to the mixture. After 2 h, the mixture was filtered through celite on a frit. The solvent was removed under reduced pressure and the residue was washed with hexane (30 mL) and extracted with methylene chloride (10 mL). Removal of the solvent gave Pd complex **2** as a light brown oil (0.56 g, 82%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79–7.52 (m, 5H), 7.49–7.27 (m, 10H), 4.70 (s, 1H), 3.83 (q, $J = 6.8$ Hz, 6H), 3.45 (m, 2H), 2.00 (s, 3H), 1.75 (m, 2H), 1.52 (s, 3H), 1.22 (m, 9H), 0.63(t, $J = 7.2$ Hz, 2H), 0.097 (d, $J = 2.8$ Hz, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.86, 163.95, 134.74, 134,63, 132.00, 131.91, 131.78, 131.37, 130.90, 129.83, 128.43, 128.30, 128.05, 127.76, 127.66, 97.94, 67.93, 58.43, 58.33, 58.16, 26.14, 25.64, 18.59, 18.39, 18.34, 7.69, –2.21 ppm; ^{31}P NMR (162 MHz, $CDCl_3$) δ 43.88 ppm; Anal. Calcd. For $C_{33}H_{46}NO_4PPdSi$ (686.20): C, 57.76; H, 6.76; N, 2.04. Found: C, 57.74; H, 6.53; N, 2.10.

Synthesis of silica gel–supported β-ketoiminatophosphane-Pd complex 3

Silica gel (1.0 g, Merck® 9385, particle size 230–400 mesh, surface area 550 m^2 g^{-1}) was added to a solution of 2 (136 mg, 0.21 mmol) in toluene (10 mL) and the mixture was refluxed for 12 h. After cooling, the reaction mixture was filtered and washed with CH_2Cl_2 (10 mL × 3), and dried at 60 °C under vacuum to yield silica-supported Pd complex Pd@SiO_2 **3** (1.10 g) as a brown powder (Fig. 1). The Pd content of 0.19 mmol g^{-1} was measured by inductively coupled plasma (ICP) analysis.

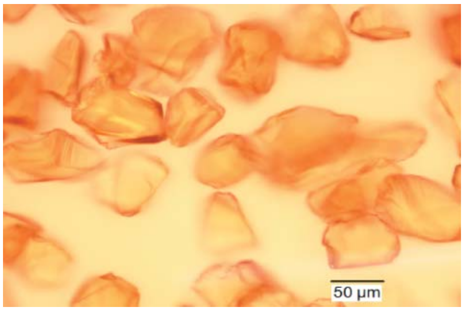


Fig. 1 Optical microscope image of Pd@SiO_2 **3**.

General procedure for the Suzuki coupling reaction

Heteroaryl chloride (1.0 mmol), arylboronic acid (1.2 mmol), K_2CO_3 (276 mg, 2.0 mmol), TBAB (161 mg, 0.5 mmol) and catalyst **3** (26 mg, 0.19 mmol g^{-1}, 0.5 mol%) were mixed in H_2O (2.0 mL). The mixture was stirred at 60 °C in an air atmosphere. The reaction was monitored periodically by GC. After completion of the reaction, the mixture was cooled to room temperature, filtered, and extracted with diethyl ether three times. The filtered catalyst was washed with diethyl ether and the combined organic layers were concentrated under reduced pressure. The crude product was analysed by GC/GC-MS and then purified by short-column chromatography on silica gel. The product was confirmed by ^{1}H NMR. The separated catalyst was successively reused for the next reaction without any pre-treatment.

General procedure for the Stille coupling reaction

Heteroaryl chloride (1.0 mmol), organostannane (1.2 mmol), CsF (302 mg, 2.0 mmol) and catalyst **3** (26 mg, 0.5 mol%) were mixed in EtOH–H_2O (2.0 mL, 1 : 1). The reaction mixture was stirred at 50 °C and monitored periodically by GC. After completion of the reaction, the mixture was cooled to room temperature and filtered. After removal of EtOH, diethyl ether (5 mL) and water (2 mL) was added. The layers were separated and the aqueous layer was extracted with diethyl ether two times. The combined organic layers were concentrated under reduced pressure. The crude product was analysed by GC/GC-MS and then purified by short column chromatography on silica gel to afford the desired product. The product was confirmed by ^{1}H NMR.

General procedure for the Sonogashira coupling reaction

Heteroaryl chloride (1.0 mmol), alkyne (1.2 mmol), piperidine (170 mg, 2.0 mmol), TBAB (161 mg, 0.5 mmol) and catalyst **3** (26 mg, 0.5 mol%) were mixed in H_2O (2.0 mL). The mixture was stirred at 60 °C in an air atmosphere. The reaction was monitored periodically by GC. After completion of the reaction, the mixture was cooled to room temperature, filtered, and extracted with diethyl ether three times. The combined organic layers were concentrated under reduced pressure. The crude was analysed by GC/GC-MS and then purified by short-column chromatography on silica gel. The product was confirmed by ^{1}H NMR.

Acknowledgements

This work was supported by National Research Foundation of Korea Grant funded by Korean Government (2009-0072013) and the Carbon Dioxide Reduction & Sequestration R&D Center of the 21st Century Frontier R&D Programs.

References

1 (*a*) L. A. Agrofoglio, I. Gillaizeau and Y. Saito, *Chem. Rev.*, 2003, **103**, 1875; (*b*) A. de Meijere and F. Diederich, ed. *Metal-Catalyzed Cross-Coupling Reactions, Vol. 2*, Wiley-VCH, Weinheim, 2004.
2 For reviews, see: (*a*) K. C. Nicolaou, P. G. Bulger and D. Sarlah, *Angew. Chem., Int. Ed.*, 2005, **44**, 4442; (*b*) E. A. B. Kantchev, C. J. O'Brien and M. G. Organ, *Angew. Chem., Int. Ed.*, 2007, **46**, 2768; (*c*) R. Chinchilla and C. Najera, *Chem. Rev.*, 2007, **107**, 874; (*d*) R. Martin and S. L. Buchwald, *Acc. Chem. Res.*, 2008, **41**, 1461; (*e*) G. C. Fu, *Acc. Chem. Res.*, 2008, **41**, 1555.
3 (*a*) C. E. Garrett and K. Prasad, *Adv. Synth. Catal.*, 2004, **346**, 889; (*b*) N. T. S. Phan, M. V. D. Sluys and C. W. Jones, *Adv. Synth. Catal.*, 2006, **348**, 609; (*c*) D. Astruc, *Inorg. Chem.*, 2007, **46**, 1884; (*d*) L. Yin and J. Liebscher, *Chem. Rev.*, 2007, **107**, 133; (*e*) M. Lamblin, L. Nassar-Hardy, J.-C. Hierso, E. Fouquet and F.-X. Felpin, *Adv. Synth. Catal.*, 2010, **352**, 33.
4 (*a*) M. Lysén and K. Köhler, *Synlett*, 2005, 1671; (*b*) R. Sayah, K. Glegola, E. Framery and V. Dufaud, *Adv. Synth. Catal.*, 2007, **349**, 373; (*c*) S. Schweizer, J.-M. Becht and C. L. Drian, *Org. Lett.*, 2007, **9**, 3777; (*d*) A. Komáromi and Z. Novák, *Chem. Commun.*, 2008, 4968.
5 (*a*) I. Kondoff, H. Doucet and M. Santelli, *J. Mol. Catal. A: Chem.*, 2007, **269**, 110; (*b*) K. Billingsley and S. L. Buchwald, *J. Am. Chem. Soc.*, 2007, **129**, 3358; (*c*) I. J. S. Fairlamb, *Chem. Soc. Rev.*, 2007, **36**, 1036; (*d*) S. Shi and Y. Zhang, *Green Chem.*, 2008, **10**, 868.
6 M.-J. Jin and D.-H. Lee, *Angew. Chem., Int. Ed.*, 2010, **49**, 1119.
7 (*a*) M. K. Richmond, S. L. Scott and H. Alper, *J. Am. Chem. Soc.*, 2001, **123**, 10521; (*b*) C. Baleizao, A. Corma, H. Garcia and A. Leyva, *Chem. Commun.*, 2003, 606; (*c*) P.-H. Li and L. Wang, *Adv. Synth. Catal.*, 2006, **348**, 681.
8 For heterogeneous Suzuki reaction, see (*a*) S. Schweizer, J.-M. Becht and C. L. Drian, *Adv. Synth. Catal.*, 2007, **349**, 1150; (*b*) J. D. Webb, S. MacQuarrie, K. McEleney and C. M. Crudden, *J. Catal.*, 2007, **252**, 97; (*c*) K. Köhler, R. G. Heidenreich, S. S. Soomro and S. S. Pröckl, *Adv. Synth. Catal.*, 2008, **350**, 2930; (*d*) G. M. Scheuermann, L. Rumi, P. Steurer, W. Bannwarth and R. Mülhaupt, *J. Am. Chem. Soc.*, 2009, **131**, 8262; (*e*) J. Shin, J. Bertoia, K. R. Czerwinski and C. Bae, *Green Chem.*, 2009, **11**, 1576; (*f*) Y.-Y. Peng, J. Liu, X. Lei and Zenlan Yin, *Green Chem.*, 2010, **12**, 1072; (*g*) N. T. S. Phan and P. Styring, *Green Chem.*, 2008, **10**, 1055.
9 (*a*) A. F. Pozharskii, A. T. Soldartenko and A. Katritzky, *Heterocycles in Life and Society*, Wiley, New York, 1997; (*b*) C. Torborg and M. Beller, *Adv. Synth. Catal.*, 2009, **351**, 3027.
10 (*a*) N. Kudo, M. Perseghini and G. C. Fu, *Angew. Chem., Int. Ed.*, 2006, **45**, 1282; (*b*) K. L. Billingsley, K. W. Anderson and S. L. Buchwald, *Angew. Chem., Int. Ed.*, 2006, **45**, 3484.
11 For heterogeneous Stille reaction, see (*a*) J. C. Garcia-Martinez, R. Lezutekong and R. M. Crooks, *J. Am. Chem. Soc.*, 2005, **127**, 5097;

(*b*) H. Zhao, Y. Wang, J. Sha, S. Sheng and M. Cai, *Tetrahedron*, 2008, **64**, 7517; (*c*) M. Bernechea, E. de Jesús, C. López-Mardomingo and P. Terreros, *Inorg. Chem.*, 2009, **48**, 4491.

12 D.-H. Lee, A. Taher, W.-S. Ahn and M.-J. Jin, *Chem. Commun.*, 2010, **46**, 478.

13 For heterogeneous Sonogashira reaction, see (*a*) L. Djakovitch and P. Rollet, *Adv. Synth. Catal.*, 2004, **346**, 1782; (*b*) M. Trilla, R. Pleixalts, M. W. C. Man, C. Bied and J. J. E. Moreau, *Adv. Synth. Catal.*, 2008, **350**, 577; (*c*) S. M. Islam, P. Mondal, A. S. Roy, S. Mondal and D. Hossain, *Tetrahedron Lett.*, 2010, **51**, 2067; (*d*) D. A. Fulmer, W. C. Shearouse, S. T. Medonza and J. Mack, *Green Chem.*, 2009, **11**, 1821.

14 F. T. Ladipo and G. K. Anderson, *Organometallics*, 1994, **13**, 303.