A Journal of the Gesellschaft Deutscher Chemiker

Angewandte Chemie

GDCh

International Edition

www.angewandte.org

Accepted Article

Title: Palladium-Catalyzed Synthesis of Benzophenanthrosilines by C–H/C–H Coupling through 1,4-Palladium Migration/Alkene Stereoisomerization

Authors: Tomohiro Tsuda, Yuka Kawakami, Seung-Min Choi, and Ryo Shintani

To be cited as: *Angew. Chem. Int. Ed.* 10.1002/anie.202000217
Angew. Chem. 10.1002/ange.202000217

Link to VoR: http://dx.doi.org/10.1002/anie.202000217
http://dx.doi.org/10.1002/ange.202000217

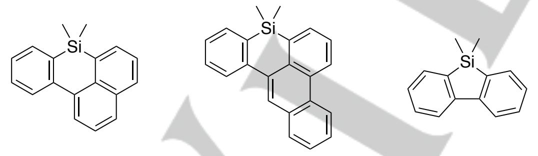
WILEY-VCH

Palladium-Catalyzed Synthesis of Benzophenanthrosilines by C–H/C–H Coupling through 1,4-Palladium Migration/Alkene Stereoisomerization

Tomohiro Tsuda,[a] Yuka Kawakami,[a] Seung-Min Choi,[a] and Ryo Shintani*[a]

Abstract: A new and efficient synthesis of 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines from 2-((2-(arylethynyl)aryl)silyl)aryl triflates has been developed under palladium catalysis. The reaction mechanism has been experimentally investigated and a catalytic cycle involving a C–H/C–H coupling through a new mode of 1,4-palladium migration with concomitant alkene stereoisomerization has been proposed.

Silicon-bridged π-conjugated compounds possessing a 6-membered silacycle such as 7*H*-benzo[*e*]naphtho[1,8-*bc*]silines and 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines constitute a potentially useful class of compounds based on the optoelectronic properties derived from their rigid and extended π-conjugation in plane (Figure 1).[1] However, in contrast to widely explored 5*H*-dibenzo[*b*,*d*]siloles and related compounds having a 5-membered silacycle,[2] these 6-membered silacycles have been significantly less investigated, which is presumably due to the lack of their general and efficient synthetic methods. In fact, only a few approaches have been reported for the synthesis of 7*H*-benzo[*e*]naphtho[1,8-*bc*]silines, such as dehydrogenative C–C coupling of methyl(1-naphthyl)(phenyl)silane by pyrolysis[3] and oxidative Si–C coupling of 1-naphthyltriphenylsilane by a radical process.[4,5] With regard to the synthesis of 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines, only one method has been reported to date by Wagner and coworkers, where they employed a conventional multi-step π-extension process through a 5,10-dihydrodibenzo[*b*,*e*]siline as an intermediate.[6] In light of this methodological deficiency, herein we describe a new and efficient synthesis of 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines from easily accessible 2-((2-(arylethynyl)aryl)silyl)aryl triflates under palladium catalysis, which involves a C–H/C–H coupling[7,8] via a new mode of 1,4-palladium migration.[8,9]



7*H*-benzo[*e*]naphtho-[1,8-*bc*]siline

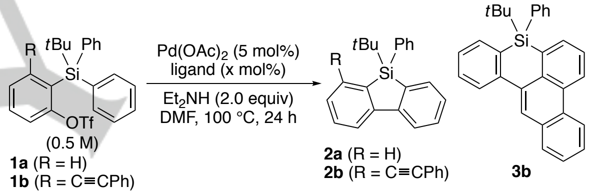
8*H*-benzo[*e*]phenanthro-[1,10-*bc*]siline

5*H*-dibenzo[*b*,*d*]silole

Figure 1. Structures of representative silicon-bridged π-conjugated compounds.

In 2008, Shimizu and coworkers reported a palladium-catalyzed synthesis of 5*H*-dibenzo[*b*,*d*]siloles from 2-(arylsilyl)aryl triflates via intramolecular C–H arylation.[10] This process is highly reliable and we could also obtain dibenzosilole **2a** in 90% yield from substrate **1a** under similar reaction conditions (Table 1, entry 1). However, we found that the use of substrate **1b** having a phenylethynyl group at the 3-position resulted in no formation of dibenzosilole **2b**, and the major product was found to be benzophenanthrosiline **3b** in 58% yield (entry 2).[11] Reactions using other ligands such as PPh_3 and dppf also gave **3b** as the major product with no **2b** (entries 3 and 4), and the same trend was observed even in the absence of any phosphine ligands (entry 5).

Table 1. Palladium-catalyzed reaction of **1**.



Entry	1	Ligand (x)	Yield of **2** [%][a]	Yield of **3** [%][a]
1	**1a**	PCy$_3$[b] (10)	90	—
2	**1b**	PCy$_3$[b] (10)	0	58
3	**1b**	PPh$_3$ (10)	0	39
4	**1b**	Dppf (5.5)	0	17
5	**1b**	None	0	59

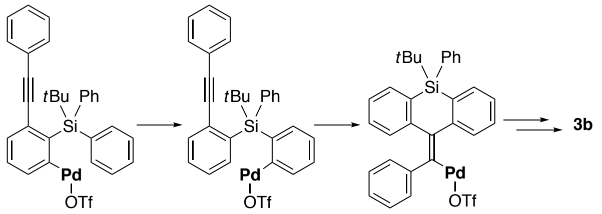
[a] Determined by ^{1}H NMR against internal standard ($MeNO_2$). [b] PCy_3•HBF_4/Et_2NH was used.

Based on these initial findings, we decided to focus on the synthesis of benzophenanthrosilines **3**. The formation of **3b** from **1b** presumably goes through a pathway illustrated in Scheme 1. Initial oxidative adduct **I** would undergo 1,5-palladium migration[11,12] to give arylpalladium species **II**, and subsequent insertion of alkyne to the aryl–palladium bond gives alkenylpalladium intermediate **III**. If this process is operating, the same product should be obtained from compound **4b** [Eq. (1)] that can directly generate intermediate **II** without going through 1,5-palladium migration. Indeed, as shown in Eq. 1, we found that the reaction of compound **4b**, which is more readily accessible than **1b**, efficiently gave benzophenanthrosiline **3b** in a much higher yield of 94% under the same conditions as in Table 1, entry 5.

---

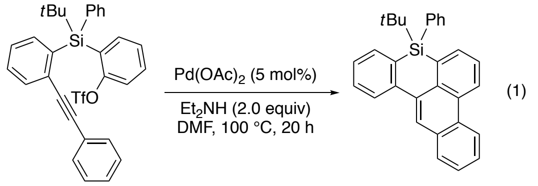
[a] T. Tsuda, Y. Kawakami, S.-M. Choi, Prof. Dr. R. Shintani
Division of Chemistry, Department of Materials Engineering Science
Graduate School of Engineering Science
Osaka University, Toyonaka, Osaka 560-8531 (Japan)
E-mail: shintani@chem.es.osaka-u.ac.jp

Supporting information for this article is given via a link at the end of the document.((Please delete this text if not appropriate))

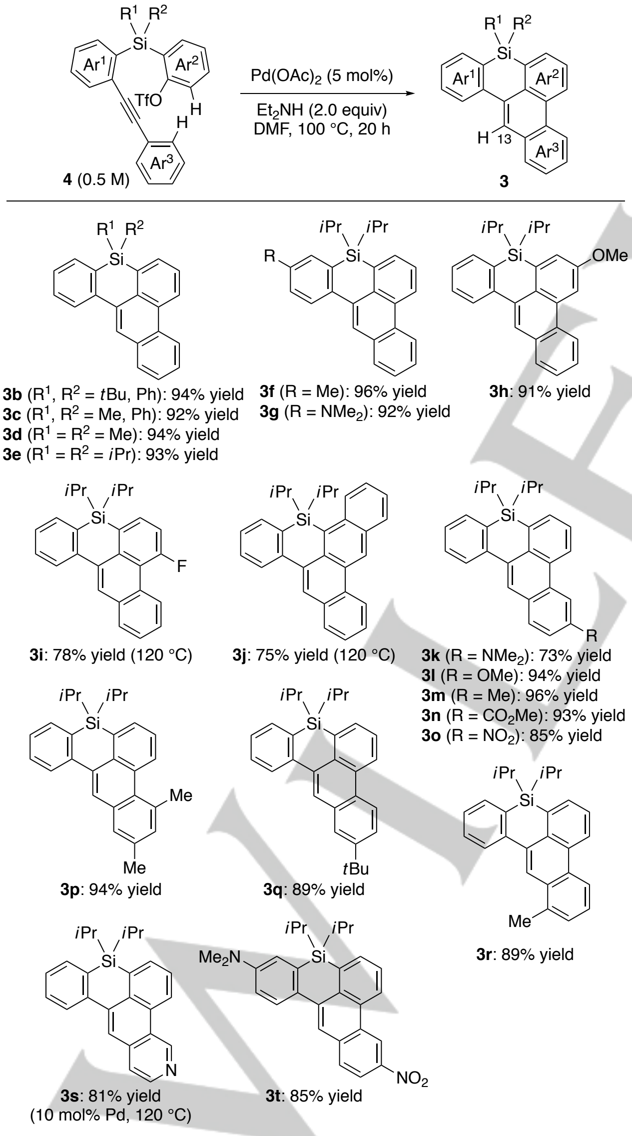


I II III

Scheme 1. Possible reaction pathway for the production of **3b**.



4b (0.5 M) **3b**: 94% yield



4 (0.5 M) **3**

3b (R^1, R^2 = *t*Bu, Ph): 94% yield
3c (R^1, R^2 = Me, Ph): 92% yield
3d (R^1 = R^2 = Me): 94% yield
3e (R^1 = R^2 = *i*Pr): 93% yield

3f (R = Me): 96% yield
3g (R = NMe_2): 92% yield

3h: 91% yield

3i: 78% yield (120 °C)

3j: 75% yield (120 °C)

3k (R = NMe_2): 73% yield
3l (R = OMe): 94% yield
3m (R = Me): 96% yield
3n (R = CO_2Me): 93% yield
3o (R = NO_2): 85% yield

3p: 94% yield

3q: 89% yield

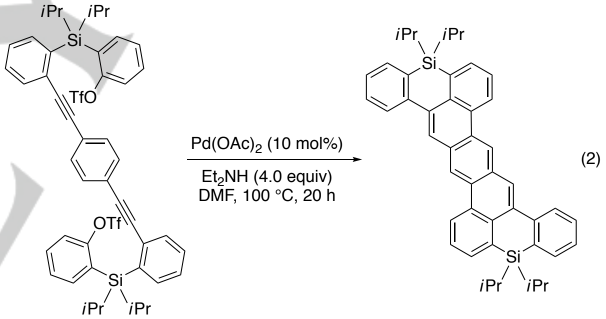
3r: 89% yield

3s: 81% yield
(10 mol% Pd, 120 °C)

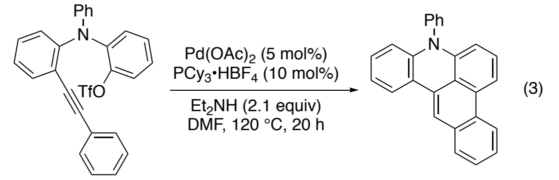
3t: 85% yield

Scheme 2. Scope of palladium-catalyzed synthesis of benzophenanthrosilines.

The scope of this reaction was found to be reasonably broad as summarized in Scheme 2. For example, in addition to compound **3b** having a (*tert*-butyl)phenylsilylene bridging unit, benzophenanthrosilines **3c–3e** with other silylene units can be obtained in similarly high yields (92–94% yield). With regard to the substituents on the aromatic rings, various groups can be installed at any of them (Ar^1, Ar^2, and Ar^3) with retaining high chemical yields, including functional groups such as dimethylamino (**3g**, **3k**, **3t**), methoxycarbonyl (**3n**), and nitro (**3o**) groups. The structures of products **3f–3j** clearly establish that the C–H/C–H couplings take place exclusively between Ar^2 and Ar^3 rather than between Ar^1 and Ar^3.[13] It is worth mentioning that substrate **4p** having 3,5-dimethylphenyl group as Ar^3 can also undergo the C–H/C–H coupling to give **3p** despite its steric hindrance. On the other hand, the reaction of **4q** with 3-*tert*-butylphenyl group as Ar^3 selectively provides **3q** by forming a carbon–carbon bond at the less hindered position. The present catalysis also accommodates a heteroaromatic ring as shown for **3s** and donor-acceptor-type benzophenanthrosiline **3t** can be synthesized as well.[14] Furthermore, the reaction of ditriflate **5** gives a new type of π-extended silicon-bridged compound **6** possessing a benzo[*k*]tetraphene moiety through the two-fold present reaction sequence [Eq. (2)]. In our preliminary experiment, we have also found that the present catalysis can be extended to the synthesis of a nitrogen-bridged analogue, 8*H*-naphtho[1,2,3-*kl*]acridine **8**, under slightly modified conditions [Eq. (3)].

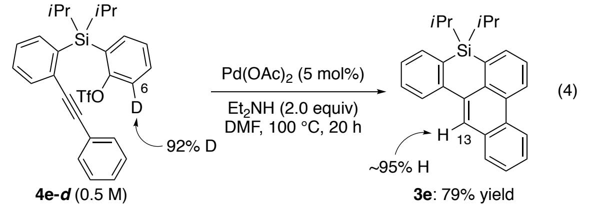


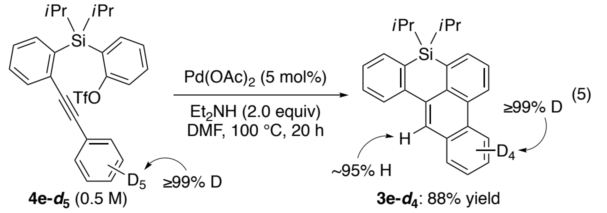
5 (0.25 M) **6**: 72% yield

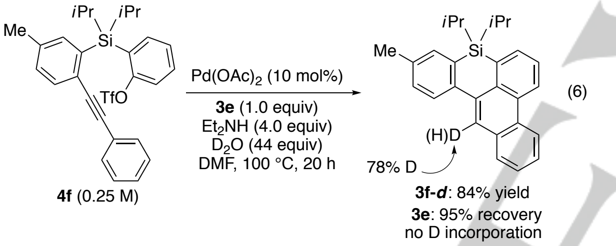


7 (0.5 M) **8**: 47% yield

In the present catalysis, two C–H bonds on Ar^2 and Ar^3 of substrate **4** (see Equation in Scheme 2) are cleaved to form a carbon–carbon bond between them, and a new C–H bond is generated at the 13-position of resulting benzophenanthrosiline **3**. To understand the fate and origin of these hydrogen atoms for elucidation of the reaction mechanism, we conducted several deuterium labeling experiments. The reaction of ***4e-d*** having a deuterium at the 6-position of Ar^2 was found to give product **3e** with almost no deuterium incorporation at the 13-position [Eq. (4)], and the reaction of ***4e-d*₅** having pentadeuteriophenyl group as Ar^3 gave the same result [Eq. (5)]. These results indicate that H at the 13-position of compound **3** is not directly derived from either C–H bond that engages in the carbon–carbon bond formation. In contrast, when the reaction of **4f** is conducted in the presence of excess D_2O, resulting product **3f** showed 78% deuterium incorporation at the 13-position [Eq. (6)], indicating that the H at this position is derived from an external hydrogen donor (H derived from Et_2NH and/or residual water in solvent DMF under the standard anhydrous conditions).[15] This reaction was carried out in the presence of non-deuterated benzophenanthrosiline **3e** and no deuterium incorporation to **3e** was observed under these conditions, confirming that the deuterium is incorporated during the formation of compound **3** from substrate **4** and no C–H/C–D exchange occurs once compound **3** is produced.

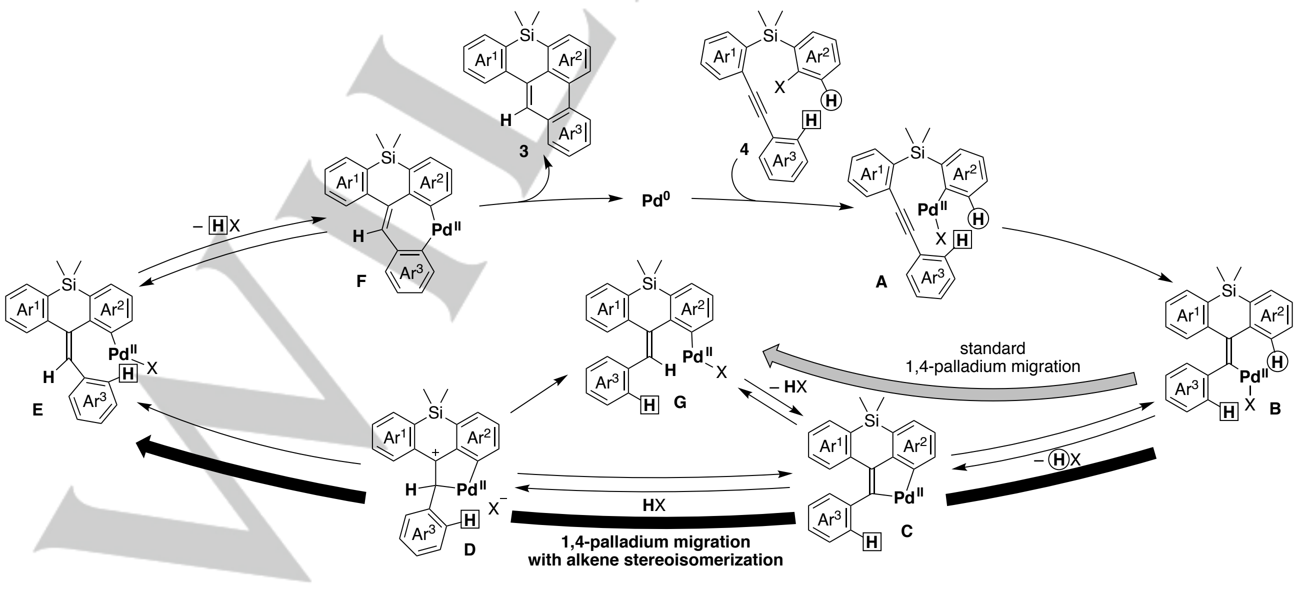




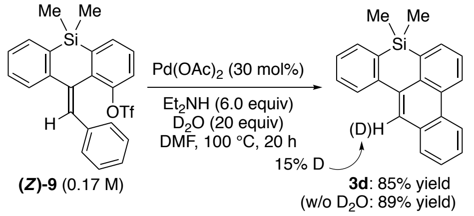


On the basis of these experiments and the fact that the C–H/C–H coupling takes place between Ar^2 and Ar^3, a proposed catalytic cycle for the present reaction is illustrated in Scheme 3. Thus, oxidative addition of aryl triflate **4** to palladium(0) gives arylpalladium species **A**. Intramolecular insertion of alkyne to the aryl–palladium bond takes place to give alkenylpalladium **B**. C–H bond activation on Ar^2 then leads to alkenyl(aryl)palladium intermediate **C**, which undergoes protonation by an external proton donor to give cationic alkyl(aryl)palladium **D**. Cleavage of alkyl–palladium bond with concomitant formation of (*Z*)-alkene gives arylpalladium **E**, which possesses the right stereochemistry toward subsequent C–H bond activation to give diarylpalladium **F**. Finally, carbon–carbon bond-forming reductive elimination gives product **3** along with regeneration of palladium(0). The alkyl–palladium bond cleavage of intermediate **D** could also lead to arylpalladium **G** with (*E*)-alkene moiety, which can reenter the catalytic cycle by alkenyl C–H bond activation to give intermediate **C**. Interconversion between complexes **B** and **G** represents a standard 1,4-palladium migration, which has been well explored in the literature.[8,9] On the other hand, the presently proposed conversion from **B** to **E** can be regarded as a new mode of 1,4-palladium migration that involves concomitant alkene stereoisomerization.

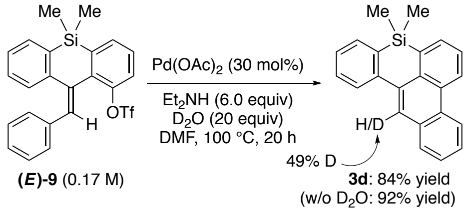
To probe the feasibility of the involvement of intermediate **E**, we prepared aryl triflate **9** with (*Z*)-alkene geometry and conducted the present palladium-catalyzed reaction to find that desired product **3d** was obtained in a high yield [Eq. (7)]. When this reaction was conducted in the presence of excess D_2O, 15% deuterium incorporation was observed at the 13-position, indicating the reversible conversion from **E** to **D** (and to **C**). In addition, to confirm that complex **G** can enter the present catalytic cycle toward benzophenanthrosiline **3**, compound (*E*)-**9**[13] was also prepared and subjected to this reaction to find that the same product **3d** was indeed obtained as expected [Eq. (8)]. It is worth noting that the degree of deuterium incorporation is significantly higher for the reaction of (*E*)-**9** than that of (Z)-**9**, which is consistent with the proposed reaction pathway where complex **G** generated from (*E*)-**9** undergoes the alkenyl C–H bond cleavage to generate intermediate **C** followed by subsequent reprotonation.



Scheme 3. Proposed catalytic cycle for the reaction of **4** to **3** (X = OTf; amine base is omitted for clarity).

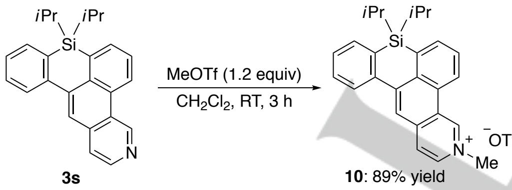


(7)



(8)

We have also briefly examined the optical properties of benzophenanthrosilines **3** obtained by the present catalysis. As summarized in Table S1,[16] we chose some of these compounds for comparison (**3e**: parent, **3g**: 10-NMe$_2$, **3o**: 3-NO$_2$, **3t**: 10-NMe$_2$-3-NO$_2$). In both UV-vis absorption (Figure S1) and fluorescence spectra (Figure S2),[16] introduction of an electron-donating group at 10-position (**3g**) or an electron-withdrawing group at 3-position (**3o**) led to a red-shift in their UV-vis absorption and emission band maxima compared to the parent compound (**3e**), and a significantly higher quantum yield was obtained for **3g** (Φ_F = 0.66 vs. Φ_F = 0.10 for **3e** and **3o**). Even more significant red-shifts of UV-vis absorption and emission band maxima were observed for donor-acceptor compound **3t**. Furthermore, while pyridine-containing compound **3s** had very similar absorption and emission spectra compared with the parent compound (**3e**), *N*-methylated derivative **10**, which can be readily synthesized from **3s** [Eq. (9)], showed red-shifts for both UV-vis absorption and emission band maxima with a high quantum yield (Φ_F = 0.83).[17] These results demonstrate that the optical properties can be effectively tuned by changing the substituents or derivatization of these benzophenanthrosilines.



(9)

In summary, we have developed a new and efficient synthesis of 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines, silicon-bridged π-conjugated compounds having a 6-membered silacycle, from 2-((2-(arylethynyl)aryl)silyl)aryl triflates under simple palladium catalysis. The reaction involves a C–H/C–H coupling via a 1,4-palladium migration with concomitant alkene stereoisomerization, which has been supported by a series of experimental mechanistic investigations. Future studies will be directed toward further development of synthetic methods for various functional organic compounds.

Acknowledgements

Support has been provided in part by JSPS KAKENHI Grant Number JP18H04653 (Hybrid Catalysis) and the Sumitomo Foundation. We thank Prof. Takeshi Naota and Dr. Soichiro Kawamorita at Osaka University for the measurement of fluorescence spectra.

Keywords: palladium • C–H coupling • 1,4-migration • silicon • π-conjugated compounds

[1] Appropriately substituted 7*H*-benzo[*e*]naphtho[1,8-*bc*]silines and 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines could be used as light-emitting materials: a) M. Jun, S. Kim, Y. Kim, S. Hwang, S. Yang, US 2016/019-449 A1, **2016**; b) M. Jun, S. Ko, H. Kim, Y. Kim, S. Hwang, US 2016/0365521 A1, **2016**.

[2] For reviews: a) H. Fu, Y. Cheng, *Curr. Org. Chem.* **2012**, *16*, 1423–1446; b) J. Y. Corey, *Adv. Organomet. Chem.* **2011**, *59*, 181–328; c) W. W. H. Wong, J. F. Hooper, A. B. Holmes, *Aust. J. Chem.* **2009**, *62*, 393–401; d) J. Chen, Y. Cao, *Macromol. Rapid Commun.* **2007**, *28*, 1714–1742.

[3] J. D. Citron, *J. Organomet. Chem.* **1975**, *86*, 359–367.

[4] a) D. Leifert, A. Studer, *Org. Lett.* **2015**, *17*, 386–389; b) C. Yang, J. Wang, J. Li, W. Ma, K. An, W. He, C. Jiang, *Adv. Synth. Catal.* **2018**, *360*, 3049–3054.

[5] For other synthetic approach: V. M. Hertz, H.-W. Lerner, M. Wagner, *Org. Lett.* **2015**, *17*, 5240–5243.

[6] V. M. Hertz, M. Bolte, H.-W. Lerner, M. Wagner, *Angew. Chem. Int. Ed.* **2015**, *54*, 8800–8804. Patents in Ref. [1] do not describe the synthetic methods of 8*H*-benzo[*e*]phenanthro[1,10-*bc*]siline (and 7*H*-benzo[*e*]naphtho[1,8-*bc*]siline) skeletons.

[7] For reviews: a) Y. Yang, J. Lan, J. You, *Chem. Rev.* **2017**, *117*, 8787–8863; b) B. V. Varun, J. Dhineshkumar, K. R. Bettadapur, Y. Siddaraju, K. Alagiri, K. R. Prabhu, *Tetrahedron Lett.* **2017**, *58*, 803–824; c) G. P. Chiusoli, M. Catellani, M. Costa, E. Motti, N. D. Ca, G. Maestri, *Coord. Chem. Rev.* **2010**, *254*, 456–469.

[8] For examples involving 1,4-palladium migration: a) M. A. Campo, Q. Huang, T. Yao, Q. Tian, R. C. Larock, *J. Am. Chem. Soc.* **2003**, *125*, 11506–11507; b) Q. Huang, A. Fazio, G. Dai, M. A. Campo, R. C. Larock, *J. Am. Chem. Soc.* **2004**, *126*, 7460–7461; c) J. Zhao, R. C. Larock, *Org. Lett.* **2005**, *7*, 701–704; d) J. Zhao, D. Yue, M. A. Campo, R. C. Larock, *J. Am. Chem. Soc.* **2007**, *129*, 5288–5295; e) Z. Lu, Y. Cui, Y. Jia, *Synthesis* **2011**, 2595–2599; f) T. Piou, A. Bunescu, Q. Wang, L. Neuville, J. Zhu, *Angew. Chem. Int. Ed.* **2013**, *52*, 12385–12389; g) M. Wang, X. Zhang, Y.-X. Zhuang, Y.-H. Xu, T.-P. Loh, *J. Am. Chem. Soc.* **2015**, *137*, 1341–1347; h) C.-W. Lee, E.-C. Liu, Y.-T. Wu, *J. Org. Chem.* **2015**, *80*, 10446–10456; i) S. K. Bhunia, A. Polley, R. Natarajan, R. Jana, *Chem. Eur. J.* **2015**, *21*, 16786–16791; j) R. Rocaboy, O. Baudoin, *Org. Lett.* **2019**, *21*, 1434–1437; k) R. Rocaboy, I. Anastasiou, O. Baudoin, *Angew. Chem. Int. Ed.* **2019**, *58*, 14625–14628.

[9] For reviews: a) F. Shi, R. C. Larock, *Top. Curr. Chem.* **2010**, *292*, 123–164; b) S. Ma, Z. Gu, *Angew. Chem. Int. Ed.* **2005**, *44*, 7512–7517; For selected examples: c) M. A. Campo, R. C. Larock, *J. Am. Chem. Soc.* **2002**, *124*, 14326–14327; d) A. Singh, P. R. Sharp, *J. Am. Chem. Soc.* **2006**, *128*, 5998–5999; e) T. Kesharwani, R. C. Larock, *Tetrahedron* **2008**, *64*, 6090–6102; f) T.-J. Hu, G. Zhang, Y.-H. Chen, C.-G. Feng, G.-Q. Lin, *J. Am. Chem. Soc.* **2016**, *138*, 2897–2900.

[10] a) M. Shimizu, K. Mochida, T. Hiyama, *Angew. Chem. Int. Ed.* **2008**, *47*, 9760–9764; For an asymmetric variant: b) R. Shintani, H. Otomo, K. Ota, T. Hayashi, *J. Am. Chem. Soc.* **2012**, *134*, 7305–7308.

[11] For the reaction of related aryl triflates having an amino group at the 3-position: a) Y. Sato, C. Takagi, R. Shintani, K. Nozaki, *Angew. Chem. Int. Ed.* **2017**, *56*, 9211–9216; b) N. Misawa, T. Tsuda, R. Shintani, K. Yamashita, K. Nozaki, *Chem. Asian J.* **2018**, *13*, 2566–2572.

[12] a) C. Bour, J. Suffert, *Org. Lett.* **2005**, *7*, 653–656; b) A. J. Mota, A. Dedieu, C. Bour, J. Suffert, *J. Am. Chem. Soc.* **2005**, *127*, 7171–7182;

c) A. J. Mota, A. Dedieu, *Organometallics* **2006**, *25*, 3130–3142; d) A. J. Mota, A. Dedieu, *J. Org. Chem.* **2007**, *72*, 9669–9678.

[13] The structures of compounds **3f** and (*E*)-**9** were determined by X-ray crystallographic analysis. CCDC 1973920 and 1973921 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

[14] Notes: (1) Substrates having Br instead of OTf show much lower reactivity (e.g., 10% yield of **3d** from the corresponding bromide). (2) A substrate having 2-benzothienyl group as Ar^3 is not applicable in the present catalysis, resulting in almost no reaction.

[15] See the Supporting Information for kinetic isotope effect using H_2O/D_2O.

[16] See the Supporting Information.

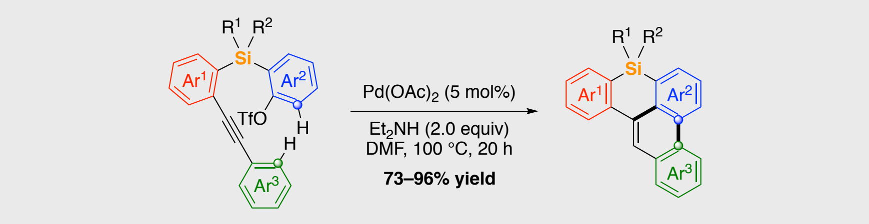
[17] a) H. Wang, R. Helgeson, B. Ma, F. Wudl, *J. Org. Chem.* **2000**, *65*, 5862–5867; b) I. Richter, M. R. Warren, J. Minari, S. A. Elfeky, W. Chen, M. F. Mahon, P. R. Raithby, T. D. James, K. Sakurai, S. J. Teat, S. D. Bull, J. S. Fossey, *Chem. Asian J.* **2009**, *4*, 194–198; c) M. T. Gabr, F. C. Pigge, *RSC Adv.* **2015**, *5*, 90226–90234; d) R. Shintani, N. Misawa, R. Takano, K. Nozaki, *Chem. Eur. J.* **2017**, *23*, 2660–2665.

10.1002/anie.202000217

Entry for the Table of Contents (Please choose one layout)

Layout 2:

COMMUNICATION



A new and efficient synthesis of 8*H*-benzo[*e*]phenanthro[1,10-*bc*]silines has been developed under palladium catalysis. The reaction mechanism has been experimentally investigated and a catalytic cycle involving a C–H/C–H coupling through a new mode of 1,4-palladium migration with concomitant alkene stereoisomerization has been proposed.

*Tomohiro Tsuda, Yuka Kawakami, Seung-Min Choi, Ryo Shintani**

Page No. – Page No.

Palladium-Catalyzed Synthesis of Benzophenanthrosilines by C–H/C–H Coupling through 1,4-Palladium Migration/Alkene Stereoisomerization