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Coupling Reactions of Alkynylsilanes Mediated by a Cu(I) Salt: Novel Syntheses of Conjugate Diynes and Disubstituted Ethynes

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Reaction of 1-trimethylsilylalkyne with copper(I) chloride in a polar solvent, DMF, at 60 °C under an aerobic conditions smoothly undergoes homo-coupling to give the corresponding symmetrical 1,3-butadiynes in 70−99% yields. In addition, (arylethynyl)trimethylsilanes are found to couple with aryl triflates and chlorides in the presence of Cu(I)/Pd(0) (10 mol %/5 or 10 mol %) cocatalyst system to give the corresponding diarylethynes in 49−99% yields. The cross-coupling reaction is applied to a one-pot synthesis of the corresponding unsymmetrical diarylethynes from (trimethylsilyl)ethyne via sequential Sonogashira−Hagihara and the present cross-coupling reactions using two different aryl triflates. The reactions of (arylethynyl)trimethylsilanes with aryl(chloro)ethynes in the presence of 10 mol % of CuCl also yield the corresponding unsymmetrical 1,3-butadiynes in 43−97% yields.

Introduction

Conjugated polyyne structures[1] have received much attention, since they are found in many natural products,[2] particularly antifungal agents.[3] Among a large number of synthetic methods for conjugated diynes developed,[4] Hay's coupling, a coupling reaction of terminal alkynes by an oxidative dimerization, is recognized to be particularly practical.[5−7] In these reactions the generation of alkynylcopper species by transmetalation of an alkynyl group to copper is considered a key step. Subsequent oxidative dimerization gives the corresponding 1,3-butadiynes.[8]

In addition to conjugate diynes, aryl- and alkenylethynes are also key structural moieties of a large number of natural[9] and unnatural products.[10] In particular, unsymmetrical diarylethynes are often used in the studies on liquid crystals[11] and nonlinear optical (NLO) materials.[12] A variety of synthetic examples including polymers[13] and dendrimers[14] have also been documented. The Sonogashira−Hagihara coupling,[15] a cross-coupling reaction of terminal alkynes with aryl halides in the presence of a base with a Cu(I)/Pd(0) cocatalyst, is one of the most practical and widely used synthetic routes to unsymmetrical diarylethynes.

On the other hand, trimethylsilylated alkynes are inert to the Sonogashira−Hagihara coupling. The coupling reaction of (trimethylsilyl)ethyne, for example, occurs at the terminal alkyne while the silyl group remains intact. In addition, the trimethylsilyl group is often employed as a protective group for the preparation of a substrate for the Sonogashira−Hagihara coupling, which is generally carried out after deprotection of the silyl group.[16]

By contrast, the palladium-catalyzed coupling reactions of alkynylsilanes proceed to give the coupling product,[17] although the addition of a fluoride ion as an activator to

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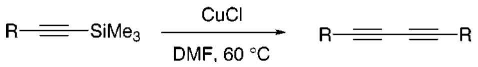
Table 1. Homo-Coupling Reaction of Alkynylsilanes (1 and 2)



entry	R	time, h	product	yield,[a] %
1	C_6H_5- (**1a**)	6	**3a**	>99
2	4-MeO-C_6H_4- (**1b**)	12	**3b**	74
3	4-MeCO-C_6H_4- (**1c**)	12	**3c**	75
4	2-thienyl (**1d**)	12	**3d**	70
5	*n*-C_6H_{13} (**2a**)	3	**4**	80

[a] Yields were determined by GC.

form a pentacoordinate organosilicate is essential for the reaction to occur. Thereby, the direct coupling of alkynyltrimethylsilane without an additive activator, if successful, under the modified condition of the Sonogashira–Hagihara coupling would be a rather straightforward synthesis and open a new area of organosilicon chemistry.

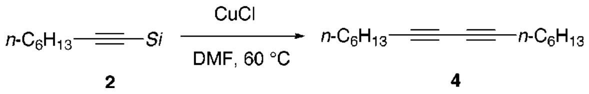
Herein we describe the following: (i) The homo-coupling of 1-trimethylsilylalkyne in a polar solvent in the presence of copper(I) chloride affords symmetrical conjugate diynes. (ii) Unsymmetrical diarylethynes are synthesized from the cross-coupling reaction of (arylethynyl)trimethylsilanes with aryl triflates or chlorides by the use of a Cu(I)/Pd(0) cocatalyst. (iii) Unsymmetrical conjugate diynes are obtained by the copper(I)-catalyzed cross-coupling reaction of alkynylsilanes with aryl-(chloro)ethynes.[18]

Results and Discussion

Homo-Coupling Reaction of Alkynylsilanes: Formation of Symmetrical Conjugate Diynes. In place of a palladium catalyst for the fluoride ion-mediated cross-coupling reaction, we examined the reaction of 1-phenyl-2-trimethylsilylethyne (**1a**) with iodobenzene using a stoichiometric amount of CuCl, in the presence of an equimolar amount of KF as an activator in DMF, but found that homo-coupled product 1,4-diphenyl-1,3-butadiyne (**3a**) was quantitatively formed. During the course of these studies, we found that KF did not participate in the reaction when the reaction was performed in the polar solvent DMF. In sharp contrast to the earlier method for the preparation of symmetrical conjugate diynes,[6] the reaction with alkynylsilanes is a synthetically useful protocol in view of the straightforward carbon–carbon bond formation.[19] The results for the synthesis of symmetrical conjugate diynes such as **3a**–**d** (aromatic) and **4** (aliphatic) are shown in Table 1.

We examined substituent effects on silicon using (1-octynyl)silanes **2a**–**2g** with various substituents, and the results are summarized in Table 2. Although trimethyl(1-octynyl)silane (**2a**) gave homo-coupled product **4**, no trace of **4** was obtained from triethyl- (**2b**) or triisopropylsilane (**2c**) (entry 1 vs entries 2 and 3). On the other hand, dimethylphenyl(1-octynyl)silane (**2d**) afforded **4** in 83% yield (entry 4). Oxygen-substituted alkynylsilanes such as trimethoxysilane (**2e**), pentamethyldisiloxane (**2f**), and dimethylsilanol (**2g**) also underwent the homo-coupling reactions to give **4** in good to excellent yields (entries 5–7).

Table 2. Substituent Effect on Alkynylsilanes 2[a]



entry	Si		time, h	yield of **4**,[b] %
1	$SiMe_3$	(**2a**)	3	80
2	$SiEt_3$	(**2b**)	24	0
3	Si^iPr_3	(**2c**)	24	0
4	$SiPhMe_2$	(**2d**)	7.5	83
5	$Si(OMe)_3$	(**2e**)	1	>99
6	$SiMe_2OSiMe_3$	(**2f**)	3	92
7	$SiMe_2(OH)$	(**2g**)	7.5	89

[a] A mixture of **2** (0.2 mmol) and CuCl (0.2 mmol) in DMF (0.5 mL) was stirred at 60 °C. [b] GC yield based on alkynylsilanes **2**.

In these reactions, the alkynyl group presumably migrates from silicon to copper without a nucleophilic activator such as a fluoride ion. Thus, the process for the generation of alkynylcopper species is postulated as follows: CuCl first coordinates to a triple bond in alkynylsilanes.[20] The alkynyl group is successively transferred from silicon to copper to generate alkynylcopper species, which then oxidatively dimerize to furnish symmetrical conjugate diynes. The reason no desired product was obtained in cases of substrates **2b** and **2c** is that the steric bulk of triethyl- and triisopropylsilyl groups inhibits the approach of CuCl to a triple bond leading to transmetalation.

Cross-Coupling Reaction of Alkynylsilane: Formation of Unsymmetrical Diarylethynes. In the above homo-coupling reactions of alkynyltrimethylsilane **1**, we suggested the formation of the alkynylcopper species as an intermediate via transmetalation of the alkynyl group from silicon to copper.[21] Thus, the postulated mechanism involving the transmetalation allowed us to effect the cross-coupling reaction using alkynyltrimethylsilanes. A planned catalytic cycle of the cross-coupling reaction using alkynyltrimethylsilanes and a coupling partner, aryl halides or triflate, is illustrated in Scheme 1.

First, an alkynyl group is transferred from the silicon of alkynyltrimethylsilane **1** to copper to form alkynylcopper **5**, while Pd(II) complex **9** is generated by oxidative addition of the C–X bond of the aryl halides or triflate **6**–**8** to the Pd(0) complex. The alkynyl group in **5**

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(19) The use of triethylamine or pyridine barely effected the reaction of **1a** with a stoichiometric amount of CuCl to yield **3a** in 9% and 1%, respectively. No trace of **3a** was obtained in acetonitrile, THF, or toluene.

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(21) The use of a polar solvent, DMF, is essential to promote the reaction. We consider that DMF would coordinate to an alkynylsilane to form the pentacoordinate but tetravalent species, which may behave as a pentavalent organosilicate that is formed by the addition of a fluoride ion to the organosilane and is known to be highly active to transmetalation.

Scheme 1. Catalytic Cycle for the Coupling of Alkynylsilanes 1 with Aryl Halides or Triflate 6−8 in a Cu(I)/Pd(0) System

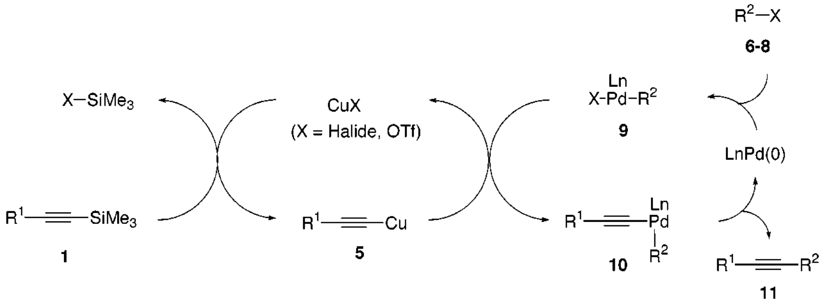
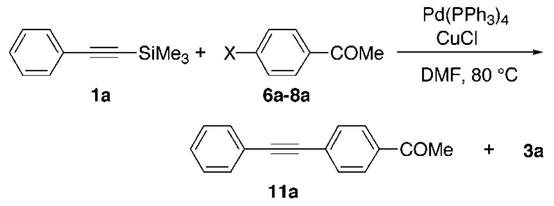


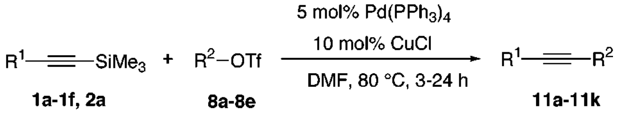
Table 3. Reaction of Alkynylsilane 1a with Aryl Halides or Triflate 6a−8a[a]



entry	X	$Pd(PPh_3)_4$, mol %	CuCl, mol %	time, h	yield of **11a**,[b] %	yield of **3a**,[b] %
1	Br (**6a**)	5	120	12	27	20
2	I (**7a**)	5	120	12	84	7
3	OTf (**8a**)	5	120	12	41	40
4		5	10	12	97	0
5		1	2	24	97	0
6		5[c]	5	12	93	0
7		0	10	12	0	0
8		5	0	12	0	0

[a] Reaction conditions: **1a** (1.2 mmol); **6a**−**8a** (1.0 mmol); DMF (5 mL) unless otherwise noted. [b] GC yield based on **1a**. [c] $Pd(PPh_3)_2Cl_2$ was used as a catalyst.

Table 4. Cu/Pd-Catalyzed Cross-Coupling Reaction of Alkynylsilanes 1 with Aryl Triflates 8[a]



entry	alkynylsilane **1**, R^1 =	triflate **8**, R^2 =	**11**	yield,[b] %
1	C_6H_5- (**1a**)	4-MeCO−C_6H_4- (**8a**)	**11a**	97 (89)
2	4-MeO−C_6H_4- (**1b**)	**8a**	**11b**	>99 (65)
3	**1b**	C_6H_5- (**8b**)	**11c**	64 (50)
4	**1b**	4-NC-C_6H_4- (**8c**)	**11d**	>99 (51)
5	**1b**	2,4-F_2-C_6H_3- (**8d**)	**11e**	82 (79)
6	**1b**	2-MeO-C_6H_4- (**8e**)	**11f**	49 (40)
7	4-MeCO-C_6H_4- (**1c**)	**8c**	**11g**	95
8	2-thienyl (**1d**)	**8a**	**11h**	60 (43)
9	**1d**	**8c**	**11i**	79 (52)
10	4-NC-C_6H_4- (**1e**)	**8a**	**11g**	98 (65)
11	4-^{t}BuMe$_2$SiO-C_6H_4- (**1f**)	**8c**	**11j**	82 (71)
12	*n*-C_6H_{13}- (**2a**)	**8a**	**11k**	87 (65)

[a] Conditions: **1** (1.2 mmol); **8** (1.0 mmol); CuCl (10 mol %); $Pd(PPh_3)_4$ (5 mol %); DMF (5 mL) unless otherwise noted. [b] GC yield based on alkynylsilanes **1** and isolated yields were shown in parentheses.

successively migrates from copper to palladium to generate **10** whose reductive elimination furnishes the desired cross-coupled product **11**, regenerating CuX (X = halide or triflate) as a catalyst. If the regenerated copper catalyst is effective for the transmetalation of the alkynyl group from silicon to copper, an initial addition of a catalytic amount of CuCl is enough for completion of the catalytic cycles.

On the basis of our plan, we first optimized the palladium-catalyzed cross-coupling reaction of **1a** with 4-acetylphenyl bromide (**6a**), iodide (**7a**), or triflate (**8a**) in the presence of a stoichiometric or catalytic amount of CuCl and a palladium(0) catalyst. The results are listed in Table 3.

Combination of a stoichiometric amount of CuCl and **6a** mediated the coupling with **1a** to furnish cross-coupled product **11a** in 27% yield and homo-coupled product **3a** derived from **1a** in 20% yield (entry 1). In place of **6a** the use of **7a** provided **11a** in 84% yield, although an equimolar amount of CuCl was required (entry 2). This is probably because regenerated CuI is less effective in the transmetalation.

Accordingly, we employed triflate **8a** as the coupling partner. However, with a stoichiometric amount of CuCl, undesired homo-coupled product **3a** was obtained in 40% yield (entry 3). A successful cross-coupling reaction utilized 5 mol % of palladium(0) complex and 10 mol % of copper(I) chloride and furnished **11a** in 97% yield (entry 4). The cross-coupling reaction was also achieved with 1 mol % of $Pd(PPh_3)_4$ and 2 mol % of CuCl albeit with longer reaction times (entry 5). A palladium(II) complex, $Pd(PPh_3)_2Cl_2$, was also an effective precatalyst, generating a Pd(0) species for the reaction (entry 6). The reaction did not occur in the absence of either the palladium catalyst or the copper catalyst (entries 7 and 8).

The generality of the reaction of alkynylsilanes **1a**−**1f** and **2a** with aryl triflates **8a**−**8e** was studied under the optimum conditions, i.e., 10 mol % of CuCl and 5 mol % of $Pd(PPh_3)_4$. The results are summarized in Table 4. Notable is that this reaction is considerably affected by substituents of aryl triflates **8**, probably owing to the efficiency of oxidative addition of Pd(0) to the C−O bond of **8**. In general, triflates with an electron-withdrawing substituent, for example, **8a** (entries 1, 8, 10, and 13) and **8c** (entries 4, 7, 9, and 12), were viable and gave the cross-coupled products **11** in high to excellent yields. On the other hand, electron-rich triflates such as 2-methoxyphenyl trifluoromethanesulfonate (**8e**) and 4-methoxyphenyl trifluoromethanesulfonate (**8f**) gave **11** in low yields.[22] Therefore, the appropriate combination of alkynylsilane **1** and triflate **8** is important for the formation of **11** in high yield. The reaction of **1b** with **8d** smoothly gave the corresponding cross-coupled product **11e** in 82%

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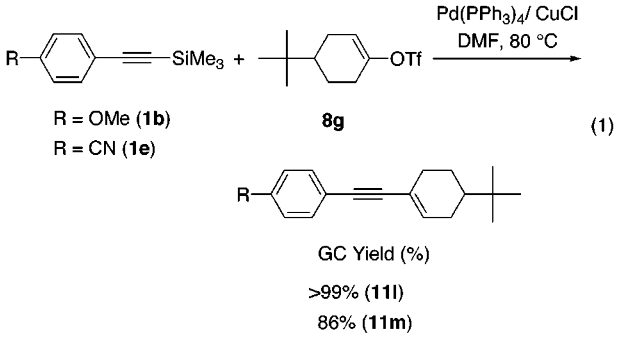
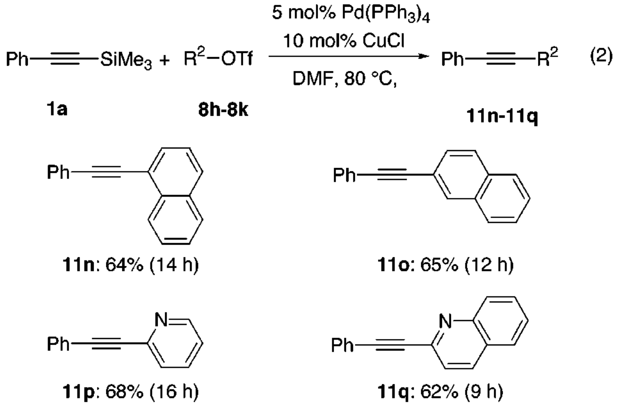
(22) For instance, the appropriate choice of **1** and **8** furnished cross-coupling products **11a**, **11b**, and **11d** in 97, >99, and >99% yields, respectively, whereas the unfavored combination (**1c** with **8b**, **1c** with **8f**, and **1e** with **8f**) decreased the yields (30, 19, and 27%, respectively).

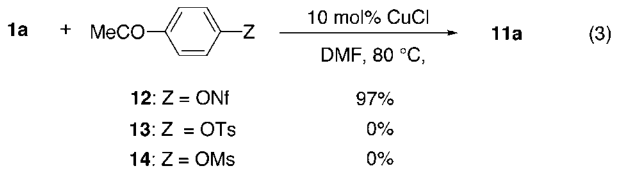
yield (entry 5),[23] whereas the reaction of **1b** with **8e** with an *o*-OMe group resulted in the formation of **11f** in lower yield (entry 6). (2-Thienylethynyl)trimethylsilane (**1d**) was treated with **8a** and **8c** to afford **11h** and **11i**, in 60 and 79% yields, respectively (entries 8 and 9). Since the present protocol allows the cross-coupling reaction without a fluoride ion, alkynylsilane **1f** bearing a silyl protective group cleanly coupled with aryl triflate **8c** to afford **11j** without removal of a TBDMS group (entry 11). The coupling reaction of trimethyl(1-octynyl)silane (**2a**) with aryl triflate **8a** smoothly proceeded to afford **11k** in 87% yield (entry 12).

This cross-coupling reaction was applicable to alkenyl triflate **8g** which gave **11l** and **11m** in >99 and 86% yields, respectively, upon coupling with alkynylsilanes **1b** and **1e** as shown in eq 1. We further studied the reaction of **1a** with polycyclic and heterocyclic triflates **8h**−**8k** to observe the formation of corresponding cross-coupled products **11n**−**11q** in moderate yields (eq 2).



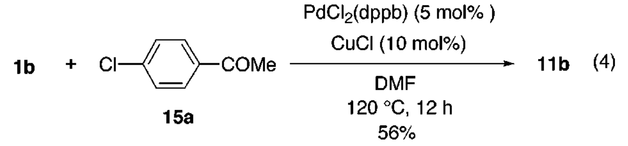


We examined the effect of a leaving group in the reaction of **1a** with 4-acetylphenyl *p*-nonafluorobutanesulfonate (**12**, nonaflate, Nf), *p*-toluenesulfonate (**13**, tosylate, Ts), or methanesulfonate (**14**, mesylate, Ms) to afford the cross-coupled product **11a** (eq 3). As with a similar cross-coupling reaction performed with aryl triflate **8a**, a comparable yield of **11a** was obtained with an aryl nonaflate. This suggests that the coproduced copper(I) nonaflate is also effective for catalyzing the cross-coupling reactions. However, mesylate and tosylate were shown to be ineffective.



Because CuCl is found to be highly effective in mediating transmetalation of an alkynyl group from silicon to copper, an aryl chloride could be employed as the substrate, based on the catalytic cycles of the cross-coupling reactions of alkynylsilanes with aryl halides shown in Scheme 1. Thus, we next examined a cross-coupling reaction using an aryl chloride as a coupling partner. Although aryl chlorides are inexpensive and easily available compared with aryl bromides and iodides, they have been rarely used for the Pd-catalyzed cross-coupling reaction because of inertness to an insertion of palladium(0) to the C−Cl bond of the aryl chloride. Recently, with electron-rich phosphines as a ligand, a number of Pd-catalyzed cross-coupling reactions with aryl chlorides including Mizoroki−Heck reaction have been reported.[24]

We examined a palladium catalyst for the cross-coupling of alkynylsilane **1b** and 4-acetylphenyl chloride (**15a**) in DMF at 120 °C for 12 h. The use of a palladium complex with two monodentate phosphines, PCy_3, $\mathrm{P}^i\mathrm{Pr}_3$, PPh_3, or PPhEt_2, gave a trace of cross-coupled product **11b**. We next employed a bidentate phosphine ligand such as dppf, dppe, dppp, or dppb[25] and found that, in particular, PdCl_2(dppb) proved to be most effective and furnished **11b** in 56% yield as shown in eq 4.



Accordingly, we optimized the amount of PdCl_2(dppb) and CuCl and found that 86% yield of **11b** was attained when 10 mol % of each catalyst was employed. Reactions of a variety of aryl chlorides **15** under the optimum conditions were conducted. The results are shown in Table 5. Aryl chlorides **15** are more affected by a substituent at the *para*-position of an aromatic ring than are aryl triflates. Alkynylsilane **1b** bearing an electron-donating methoxy group coupled smoothly with **15a** bearing an electron-withdrawing acetyl group to give **11b** in 86% yield. Both alkynylsilane **1e** having an electron-withdrawing group (entry 1 vs 3) and aryl chloride **15c** having an electron-donating group (entry 3 vs 6) tend to lower the yields of cross-coupled products **11**.

The protocol disclosed herein allows us to use bis(trimethylsilyl)ethyne (**16**) as an alternative to ethyne. Indeed, the reaction of **16** (1 mol amount) with 4-cyano-

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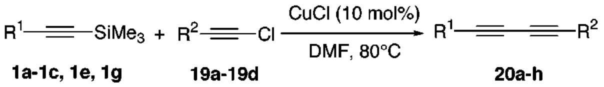
[23] On the contrary, a triflate bearing an acetyl group at the *ortho*-position gave a trace amount of the cross-coupled product.

[24] (a) Mitchell, M. B.; Wallbank, P. J. *Tetrahedron Lett.* **1991**, *32*, 2273. (b) Portnoy, M.; Ben-David, Y.; Milstein, D. *Organometallics* **1993**, *12*, 4734. (c) Grushin, V. V.; Alper, H. *Chem. Rev.* **1994**, *94*, 1047. (d) Niecke, E.; Becker, P.; Nieger, M.; Stalke, D.; Schoeeller, W. W. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1849. (e) Gouda, K.-i.; Hagiwara, E.; Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1996**, *61*, 7232. (f) Shen, W. *Tetrahedron Lett.* **1997**, *38*, 5575. (g) Reddy, N. P.; Tanaka, M. *Tetrahedon Lett.* **1997**, *38*, 4807. (h) Littke, A. F.; Fu, G. C. *J. Org. Chem.* **1999**, *64*, 10. (i) Littke, A. F.; Fu, G. C. *Angew. Chem., Int. Ed.* **1999**, *38*, 2411. (j) Zhang, C.; Huang, J.; Trudell, M. L.; Nolan, S. P. *J. Org. Chem.* **1999**, *64*, 3804.

[25] dppf = 1,1′-bis(diphenylphosphino)ferrocene, dppe = 1,2-bis(diphenylphosphino)ethane, dppp = 1,3-bis(diphenylphosphino)propane, and dppb = 1,4-bis(diphenylphosphino)butane.

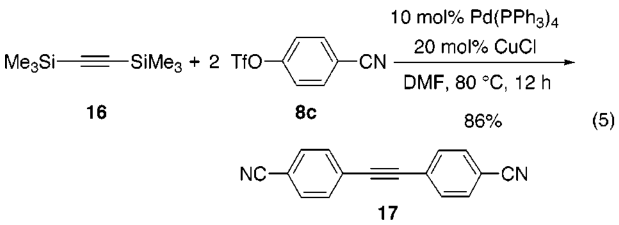
Table 5. Cross-Coupling Reaction of Alkynylsilanes 1 with Aryl Chlorides 15[a]



entry	alkynylsilane **1**, $R^1 =$	aryl chloride **15**, $R^2 =$	**11**	yield,[b] %
1	4-MeO-C_6H_4- (**1b**)	4-MeCO-C_6H_4- (**15a**)	**11b**	86
2	C_6H_5- (**1a**)	**15a**	**11a**	47
3	4-NC-C_6H_4- (**1e**)	**15a**	**11g**	42
4	**1b**	C_6H_5- (**15b**)	**11c**	43
5	4-MeCO-C_6H_4- (**1c**)	**15b**	**11a**	3
6	**1e**	4-MeO-C_6H_4- (**15c**)	**11d**	0

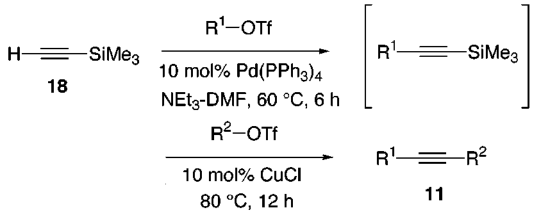
[a] Conditions: **1** (1.0 mmol); **15** (1.2 mmol); CuCl (10 mol %); $PdCl_2(dppb)$ (10 mol %); DMF (5 mL). [b] GC yield based on alkynylsilanes **1**.

phenyl triflate (**8c**, 2 mol amounts) under the conditions described in eq 5 furnished 1,2-bis(4-cyanophenyl)ethyne (**17**) in 86% yield. This method for the synthesis of symmetrical diarylethynes is useful because precise control of the amount of ethyne is considerably difficult in laboratory experiments although ethyne is usually used for the synthesis of symmetrical diarylethynes through the Sonogashira−Hagihara coupling.



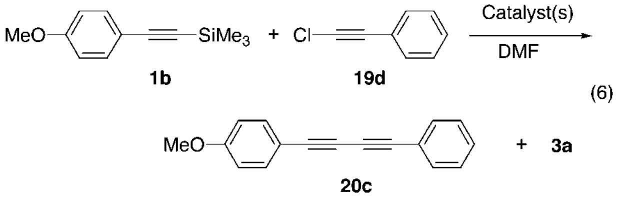
The utility of the cross-coupling reaction with alkynylsilanes is demonstrated by a one-pot synthesis of unsymmetrical diarylethynes **11**. Unsymmetrical diarylethynes have usually been prepared via the following reaction pathways: (i) a coupling reaction of aryl halides with (1-trimethylsilyl)ethyne (Sonogashira−Hagihara coupling), (ii) a desilylation to convert the resulting (arylethynyl)trimethylsilane into the terminal alkyne, and (iii) a second cross-coupling reaction with another aryl triflate. In contrast, a sequence of the Sonogashira−Hagihara reaction of 1-trimethylsilylethyne (**18**) with R^1-OTf using a $Pd(PPh_3)_4$ catalyst and triethylamine as a base,[26] without isolation of the formed compound, followed by the present coupling reaction using another triflate, R^2OTf, allows the preparation of unsymmetrical diarylalkynes in one pot as shown in Scheme 2. As a result, three-component coupling of (trimethylsilyl)-ethyne, R^1OTf, and R^2OTf is readily attained to give $R^1C{\equiv}CR^2$ **11d**, **11g**, and **11r** in fairly good yields. Compound **11r** serves as an important skeleton found in liquid crystals and NLO materials.[12,27]

Scheme 2. One-Pot Sequential Sonogashira−Hagihara and CuCl/Pd(0)-Catalyzed Coupling of (Trimethylsilyl)ethyne (18)



R^1−OTf	R^2−OTf	GC Yield (%)
R^1 = 4-MeCOC$_6$H$_4$- (**8a**)	R^2 = 4-NCC$_6$H$_4$- (**8c**)	94 (**11g**)
R^1 = 4-MeOC$_6$H$_4$- (**8f**)	R^2 = 4-NCC$_6$H$_4$- (**8c**)	80 (**11d**)
R^1 = 4-*n*-C$_5$H$_{11}$C$_6$H$_4$- (**8l**)	R^2 = 3-F-4-FC$_6$H$_3$- (**8m**)	72 (**11r**)

Cu(I)-Catalyzed Cross-Coupling Reaction of Alkynylsilanes with Aryl(chloro)ethynes: Formation of Unsymmetrical Conjugate Diynes. We next examined the synthesis of unsymmetrical conjugate diynes **20** using alkynylsilanes **1** and aryl(chloro)ethynes **19**. To synthesize unsymmetrical 1,4-disubstituted 1,3-butadiynes, the Cadiot−Chodkiewicz coupling is often employed, i.e., a copper(I)-catalyzed reaction of $R^1C{\equiv}CH$ with $R^2C{\equiv}CX$ (X = Br, I) in the presence of diethylamine as base.[28] However, the Cadiot−Chodkiewicz reaction is not applicable to aryl(chloro)ethynes as these substrates often fail to give unsymmetrical conjugate diynes under the standard conditions[29] (a copper(I)/palladium cocatalyst system)[30] probably owing to the lower reactivity of 1-chloroalkynes than 1-bromo- and 1-iodoalkynes. We first examined the catalyst and substrate ratio for the reaction of [(4-methoxyphenyl)ethynyl]trimethylsilane (**1b**) with 1-chloro-2-phenylethyne (**19d**) as shown in eq 6. In the presence of a catalytic amount of CuCl (10 mol %) and $Pd(PPh_3)_2Cl_2$ (10 mol %), which is the most effective catalyst system in the cross-coupling reaction of alkynylsilanes with aryl triflates, the reaction with a 1:1.1 molar ratio of **19d** to **1b** at 80 °C for 24 h resulted in the formation of cross-coupled product **20c** in 35% yield along with a homo-coupled product derived from **19d**, 1,4-diphenyl-1,3-butadiyne (**3a**, 21% yield). The reaction using only CuCl improved the yield of **20c** to 80%. The use of 1.5 molar amounts of **19d** to **1b** afforded **20c** in 90% yield, although the homo-coupled product **3a** was detected in 29% yield as a byproduct. The use of palladium catalyst $Pd(PPh_3)_2Cl_2$ alone was futile. The reaction proceeded in a manner similar to the Cadiot−Chodkiewicz coupling reaction, in which the oxidative addition of 1-haloalkyne to an alkynylcopper species or σ-bond metathesis mechanism is proposed.



Various alkynylsilanes **1** and 1-chloroalkynes **19** were coupled in the presence of 10 mol % of CuCl. The results are summarized in Table 6. The reaction of 1-phenyl-2-

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[26] The palladium-catalyzed cross-coupling reaction of aryl triflates with terminal alkynes to give the corresponding Sonogahshira coupling products without CuI has been reported. See: Chen, Q.-Y.; Yang, Z.-Y. *Tetrahedron Lett.* **1986**, *27*, 1171.

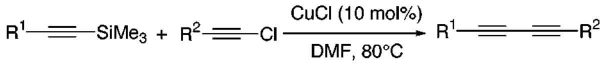
[27] (a) Stiegman, A. E.; Miskowski, V. M.; Perry, J. W.; Coulter, D. R. *J. Am. Chem. Soc.* **1987**, *109*, 5884. (b) Graham, E. M.; Miskowski, V. M.; Perry, J. W.; Coulter, D. R.; Stiegman, A. E.; Schaefer, W. P.; Marsh, R. E. *J. Am. Chem. Soc.* **1989**, *111*, 8771. (c) Stiegman, A. E.; Graham, E.; Perry, K. J.; Khundkar, L. R.; Cheng, L.-T.; Perry, J. W. *J. Am. Chem. Soc.* **1991**, *113*, 7658.

[28] (a) Cadiot, P.; Chodkiewicz, W. *C. R. Hebd. Seance Acad. Sci.* **1955**, *241*, 1055. (b) Chodkiewicz, W. *Ann. Chim. Paris* **1957**, *2*, 819.

[29] Philippe, J. L.; Chodkiewicz, W.; Cadiot, P. *Tetrahedron Lett.* **1970**, 1795.

[30] Alami, M.; Ferri, F. *Tetrahedron Lett.* **1996**, *37*, 2763 and references therein.

Table 6. Cu(I)-Catalyzed Cross-Coupling Reaction of Alkynylsilanes 1 with 1-Chloroalkynes 19[a]



1a-1c, 1e, 1g **19a-19d** **20a-h**

entry	alkynylsilane **1**, R^1 =	1-chloroalkyne **19**, R^2 =	product	yield,[b] %
1	C_6H_5- (**1a**)	4-MeCO-C_6H_4- (**19a**)	**20a**	62 (56)
2	**1a**	4-Cl-C_6H_4- (**19b**)	**20b**	85 (53)
3	**1a**	4-MeO-C_6H_4- (**19c**)	**20c**	43
4	4-MeO-C_6H_4- (**1b**)	**19a**	**20d**	97 (52)
5[c]	**1b**	**19b**	**20e**	95 (54)
6	**1b**	C_6H_5- (**19d**)	**20c**	90 (65)
7	4-MeCO-C_6H_4- (**1c**)	**19b**	**20f**	60 (42)
8	**1c**	**19c**	**20d**	60
9	**1c**	**19d**	**20a**	69
10	4-NC-C_6H_4- (**1e**)	**19a**	**20g**	93 (61)
11	4-^{t}BuMe$_2$SiO-C_6H_4- (**1f**)	**19b**	**20h**	62 (32)

[a] Typical procedure: **1** (1.0 mol) and **19** (1.5 mol) were used in DMF (5 mL) for 48 h otherwise noted. [b] GC yield based on **1** and isolated yields are given in parentheses. [c] Reaction time was 96 h.

trimethylsilylethyne (**1a**) with electron-deficient 1-chloroalkynes (**19a** or **19b**) gave coupled products **20a** and **20b** in 62 and 85% yields, respectively (entries 1 and 2). The reaction of **1a** and **19c** furnished **20c** in only 43% yield (entry 3), whereas the opposite substituent combination of substrates (**1b** and **19d**) gave **20c** in 90% yield (entry 6). Electron-rich alkynylsilane **1b** produced unsymmetrical 1,3-butadiynes **20** in higher yields (entries 4−6) than electron-deficient alkynylsilane **1c** (entries 7−9). Thus, successful formation of the desired cross-coupled products requires not only an appropriate choice of a substituent on the aromatic ring but also an appropriate combination of starting materials.

Conclusion

We have developed a convenient synthesis of conjugated diynes through the homo-coupling of alkynyltrimethylsilanes using copper(I) salt in DMF under aerobic conditions. The reaction proceeds on the basis of transmetalation of the alkynyl group from silicon to copper followed by oxidative dimerization leading to the diyne. The successful transmetalation allowed us to effect the cross-coupling of alkynylsilanes with aryl- or alkenyl triflates using a Cu(I)/Pd(0) cocatalyst system. An alternative route to Cadiot−Chodkiewicz coupling leading to the synthesis of unsymmetrical conjugate diynes starting with aryl(chloro)ethynes and (arylethynyl)silanes was explored. These coupling reactions are synthetically useful since a readily available trimethylsilyl group is employed as substrate in contrast to the coupling of aryl or alkenyl silicon compounds that generally require heteroatom substituent(s) on the silicon for a smooth reaction.[17c,31] Because these coupling reactions take place *under neutral conditions,* a wide variety of synthetic applications for the construction of novel molecules bearing a carbon−carbon triple bond would be possible.

Experimental Section

DMF, triethylamine, pyridine, and acetonitrile were distilled from CaH_2 and stored over MS-4A under an argon atmosphere. Tetrahydrofuran (THF) and toluene were distilled from sodium and benzophenone prior to use. $Pd(PPh_3)_2Cl_2$ was prepared according to the literature.[32] Copper(I) chloride, bromide, and iodide were purified by the literature method.[33]

The following alkynylsilanes were prepared by literature procedures:[34] 1-phenyl-2-trimethylsilylethyne (**1a**),[35] [(4-methoxyphenyl)ethynyl]trimethylsilane (**1b**),[15b] 1-{4-[(trimethylsilyl)ethynyl]phenyl}ethanone (**1c**),[15b] (2-thienylethynyl)trimethylsilane (**1d**),[36] 4-[(trimethylsilyl)ethynyl]benzonitrile (**1e**),[37] trimethyl(1-octynyl)silane (**2a**),[38] triethyl(1-octynyl)silane (**2b**),[39] and dimethylphenyl(1-octynyl)silane (**2d**).[40]

Spectroscopic data and physical properties of new alkynylsilanes **1** and **2** are listed below.

[(4-*tert*-Butyldimethylsiloxyphenyl)ethynyl]trimethylsilane (1f): isolated in 99% yield as a colorless liquid; IR (neat) 2959, 2932, 2897, 2860, 2159, 1262, 841 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.19 (s, 6 H), 0.25 (s, 9 H), 0.98 (s, 9 H), 6.76 (d, J = 9.0 Hz, 2 H), 7.36 (d, J = 9.0 Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ −4.44, 0.06, 18.21, 25.63, 92.56, 105.23, 115.96, 120.08, 133.44, 156.12; HRMS calcd for $C_{17}H_{28}OSi_2$ 304.1679, found M$^+$, 304.1681.

Triisopropyl(1-octynyl)silane (2c): isolated in 74% yield as a colorless oil; bp 140 °C/0.6 Torr; IR (neat) 2959, 2942, 2867, 2172, 1464, 1383, 883 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.91 (t, J = 7.0 Hz, 3 H), 0.99−1.56 (m, 29 H), 2.24 (t, J = 7.0 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 11.37, 14.01, 18.63, 19.85, 22.63, 28.42, 28.87, 31.35, 79.92, 109.28; HRMS calcd for $C_{17}H_{34}Si$ 266.2428, found M$^+$, 266.2427.

General Procedure for Homo-Coupling Reaction of Alkynylsilanes: Formation of 1,4-Diphenyl-1,3-butadiyne (3a).[41] To a DMF (0.5 mL) solution of CuCl (57 mg, 0.58 mmol) placed in a reaction tube equipped with a magnetic stirring bar was added **1a** (100 mg, 0.58 mmol). The reaction mixture was stirred for 3 h at 60 °C and quenched with 1 M hydrochloric acid. The aqueous layer was separated and extracted with 20 mL of diethyl ether. The combined ethereal layer was washed with brine and dried over Na_2SO_4. Bulb-to-bulb distillation (200−210 °C/3 Torr) gave **1a** in 86% yield as a colorless solid (GC yield; >99%). The following symmetrical conjugate diynes were prepared by literature procedures: 1,4-di(4-methoxyphenyl)-1,3-butadiyne (**3b**),[42] 1,4-di(4-acetylphenyl)-1,3-butadiyne (**3c**),[43] and 7,9-hexadecadiyne (**4**).[44]

1,4-Di(2-thienyl)-1,3-butadiyne (3d): isolated in 20% yield as a light sensitive pale yellow solid; GC yield was 70%; mp 92−93 °C; IR (neat) 3106, 2141, 1408, 714 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.00 (dd, J = 5.1, 3.7 Hz, 2 H), 7.32 (dd, J = 5.1, 1.2 Hz, 2 H), 7.34 (dd, J = 3.7, 1.2 Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 76.63, 77.77, 121.95, 127.20, 128.90, 134.39. Anal. Calcd for $C_{12}H_6S_2$: C, 67.25; H, 2.28. Found: C, 67.12; H, 2.69.

General Procedure for Synthesis of Aryl Triflates 8. To a solution of a phenol in pyridine was added triflic anhydride (1.2 molar amounts) dropwise at 0 °C. After being warmed to room temperature and stirred for 1 h, the mixture was extracted with diethyl ether. The organic layer was separated, and the aqueous layer was extracted with diethyl

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[31] Homo-coupling of aryl- and alkenylsilanes in the presence of a copper salt will be described in due course: Nishihara, Y.; Ikegashira, K.; Toriyama, F.; Mori, A.; Hiyama, T. *Bull. Chem. Soc. Jpn.*, in press.

[32] Chatt, J.; Mann, F. G. *J. Chem. Soc.* **1939**, 1622.

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[41] Liu, Q.; Burton, D. J. *Tetrahedron Lett.* **1997**, *38*, 4371.

[42] Galamb, V.; Gopal, M.; Alper, H. *Organometallics* **1983**, *2*, 801.

[43] Akiyama, T.; Amino, M.; Saitou, T.; Utsunomiya, K.; Seki, K.; Ikoma, Y.; Kajitani, M.; Sugiyama, T.; Shimizu, K.; Sugimori, A. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 2351.

ether. The combined organic layers were washed with two portions of water, 3 M hydrochloric acid, and brine and dried over $MgSO_4$. Filtration and concentration, followed by removal of the solvent under reduced pressure, gave analytically pure triflates **8a**−**8f** and **8i**−**8m** in yields ranging from 58% to 95%.

Cyclic enol triflate **8g** was prepared from 4-*tert*-butylcyclohexanone with LDA, followed by addition of $PhN(SO_2CF_3)$[47], and 1-naphthyl trifluoromethanesulfonate (**8h**) was purchased from Aldrich Chemical Co., Inc. and used without further purification. Aryl triflates **8a**−**8f** and **8i**−**8m** were prepared according to the previously described procedures:[45,46] 4-acetylphenyl trifluoromethanesulfonate (**8a**),[45] phenyl trifluoromethanesulfonate (**8b**),[48,49] 4-cyanophenyl trifluoromethanesulfonate (**8c**),[49] 2-methoxyphenyl trifluoromethanesulfonate (**8e**),[49] 4-methoxyphenyl trifluoromethanesulfonate (**8f**),[46] 4-(1,1-dimethylethyl)-1-cyclohexen-1-yl trifluoromethanesulfonate (**8g**),[50] 2-naphthyl trifluoromethanesulfonate (**8i**),[51] 2-pyridyl trifluoromethanesulfonate (**8j**),[52] 2-quinolyl trifluoromethanesulfonate (**8k**),[46] 4-acetylphenyl methanesulfonate (**14**).[53]

Spectroscopic data and physical properties of triflates (**8d**, **8l**, and **8m**), nonaflate **12**, and tosylate **13** are listed below.

2,4-Difluorophenyl trifluoromethanesulfonate (8d): isolated in 88% yield as a colorless liquid; IR (neat) 3132, 3097, 3075, 1624, 1608, 1509, 1306, 745, 688 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.92−7.07 (m, 2 H), 7.30−7.38 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 106.02 (dd, J_{C-F} = 27, 22 Hz), 112.08 (dd, J_{C-F} = 23, 4 Hz), 118.72 (q, J_{C-F} = 318 Hz), 124.43 (d, J_{C-F} = 10 Hz), 133.25 (dd, J_{C-F} = 14, 5 Hz), 154.07 (dd, J_{C-F} = 254, 13 Hz), 161.61 (dd, J_{C-F} = 251, 10 Hz);HRMS calcd for $C_7H_3F_5O_3S$ 261.9723, found M$^+$, 261.9746.

4-Pentylphenyl trifluoromethanesulfonate (8l): isolated in 92% yield as a colorless liquid; bp 165 °C/5 Torr; IR (neat) 2961, 2934, 2861, 1501, 1142, 845 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.89 (t, J = 7.0 Hz, 3 H), 1.27−1.39 (m, 4 H), 1.60 (quintet, J = 7.8 Hz, 2 H), 2.60 (t, J = 7.5 Hz, 2 H), 7.15, (d, J = 9.0 Hz, 2 H), 7.22 (d, J = 9.0 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.85, 22.45, 30.96, 31.38, 35.24, 118.80 (q, J_{C-F} = 319 Hz), 120.94, 129.98, 143.49, 147.67; HRMS calcd for $C_{12}H_{15}F_3O_3S$ 296.0693, found M$^+$, 296.0686.

3,4-Difluorophenyl trifluoromethanesulfonate (8m): isolated in 64% yield as a colorless liquid; IR (neat) 3098, 1626, 1294, 781 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.05−7.11 (m, 1 H), 7.15−7.23 (m, 1 H), 7.27−7.32 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 111.89 (d, J_{C-F} = 21 Hz), 117.85 (dd, J_{C-F} = 7, 4 Hz), 118.20 (d, J_{C-F} = 20 Hz), 118.68 (q, J_{C-F} = 319 Hz), 144.40 (dd, J = 7, 4 Hz), 150.05 (dd, J_{C-F} = 249, 13 Hz), 150.26 (dd, J_{C-F} = 253, 14 Hz); HRMS calcd for $C_7H_3F_5O_3S$ 261.9723, found M$^+$, 261.9711.

4-Acetylphenyl nonafluorobutanesulfonate (12): isolated in 71% yield as white solid; mp 41−42 °C; IR (KBr) 1694, 1266 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.63 (s, 3 H), 7.38 (d, J = 9.0 Hz, 2 H), 8.05 (d, J = 9.0 Hz, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.46, 105−120 (m), 121.54, 130.50, 136.81, 152.66, 195.98; ^{19}F NMR (188 MHz, $CDCl_3$) δ −126.32 (m), −121.35 (m), −109.13 (m), −81.10 (t, J_{F-F} = 10 Hz); HRMS calcd for $C_{12}H_7F_9O_4S$ 417.9920, found M$^+$, 417.9926.

4-Acetylphenyl (4-toluenesulfonate) (13): isolated in 71% yield as white solid; mp 74−75 °C; IR (KBr) 3062, 3048, 2919, 1682, 1269 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.41 (s, 3 H), 2.53 (s, 3 H), 7.05 (d, J = 8.6 Hz, 2 H), 7.29 (d, J = 8.2 Hz, 2 H), 7.67 (d, J = 8.2 Hz, 2 H), 7.86 (d, J = 8.6 Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 21.60, 26.48, 122.36, 128.33, 129.84, 129.94, 131.98, 135.58, 145.71, 152.86, 196.54; HRMS calcd or $C_{15}H_{14}O_4S$ 290.0612, found M$^+$, 290.0612.

General Procedure for Synthesis of Unsymmetrical Disubstituted Ethynes: Formation of 1-[4-(Phenylethynyl)phenyl]ethanone (11a).[54] To a solution of CuCl (10 mg, 0.1 mmol, 2 mol %) and tetrakis(triphenylphosphine)palladium (58 mg, 0.05 mmol, 1 mol %) in DMF (25 mL) were added 1-phenyl-2-trimethylsilylethyne (**1a**) (984 μL, 6.0 mmol) and 4-acetylphenyl trifluoromethanesulfonate (**8a**) (945 μL, 5.0 mmol) at room temperature. The reaction mixture was stirred for 24 h at 80 °C, quenched with 3 M HCl, and extracted with diethyl ether (25 mL × 2). The combined ethereal layer was washed with aqueous $NaHCO_3$ and brine and dried over $MgSO_4$. Filtration and evaporation afforded a brown oil. Column chromatography (silica gel, hexane−diethyl ether = 1:1, R_f = 0.56) gave a brown powder. Bulb-to-bulb distillation (200−210 °C/5 Torr) gave **11a** (979 mg, 89% yield) as colorless solid. The GC yield was 97%.

The following unsymmetrical disubstituted ethynes were prepared by literature procedures: 1-{4-[(4-methoxyphenyl)-ethynyl]phenyl}ethanone (**11b**),[55] 1-methoxy-4-(phenylethynyl)benzene (**11c**),[56] 4-[(4-methoxyphenyl)ethynyl]benzonitrile (**11d**),[57] 1-[4-(2-thienylethynyl)phenyl]ethanone (**11h**),[58] 1-(phenylethynyl)naphthalene (**11n**),[59] 2-(phenylethynyl)naphthalene (**11o**),[59] 2-(phenylethynyl)pyridine (**11p**),[60] 2-(phenylethynyl)-quinoline (**11q**).[61]

2,4-Difluoro-1-[(4-methoxyphenyl)ethynyl]benzene (11e): isolated in 79% yield as colorless solid; GC yield was 82%; mp 65−66 °C; IR (KBr) 2844, 2150, 1615, 1510, 1248, 818 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.83 (s, 3 H), 6.83−6.91 (m, 4 H), 7.44−7.51 (m, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.29, 80.33, 94.15, 104.19 (dd, J_{C-F} = 26, 25 Hz), 108.53 (d, J_{C-F} = 20 Hz), 111.46 (dd, J_{C-F} = 22, 4 Hz), 113.99, 114.76, 133.10, 134.00 (dd, J_{C-F} = 10, 3 Hz), 159.86, 162.38 (dd, J_{C-F} = 250, 11 Hz), 162.75 (dd, J_{C-F} = 252, 12 Hz); HRMS calcd for $C_{15}H_{10}F_2O$ 244.0700, found M$^+$, 244.0703.

4-[(2-Methoxyphenyl)ethynyl]methoxybenzene (11f): isolated in 40% yield as a yellow liquid; GC yield was 49%; IR (KBr) 2838, 2216, 1607, 1489, 834 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.82 (s, 3 H), 3.91 (s, 3 H), 6.85−6.96 (m, 4 H), 7.26−7.32 (m, 1 H), 7.47−7.53 (m, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.26, 55.81, 84.26, 93.39, 110.59, 112.68, 113.82, 115.64, 120.44, 129.39, 133.07, 133.40, 159.44, 159.69; HRMS calcd for $C_{16}H_{14}O_2$ 238.0994, found M$^+$, 238.0993.

1-{4-[(4-Cyanophenyl)ethynyl]phenyl}ethanone (11g): isolated in 65% yield as colorless solid; GC yield was 98%; mp 128−129 °C; IR (KBr) 3080, 3050, 2226, 1688, 1603, 828 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.63 (s, 3 H), 7.60−7.66 (m, 6 H), 7.94−8.00 (m, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 26.55, 92.58, 111.98, 118.26, 126.88, 128.27, 128.47, 131.85, 132.04, 132.13, 133.83, 136.81, 197.05. Anal. Calcd for $C_{17}H_{11}NO$: C, 83.25; H, 4.52; N: 5.71. Found: C, 83.63; H, 4.57; N, 5.49.

4-(2-Thienylethynyl)benzonitrile (11i): isolated in 52% yield as colorless solid; GC yield was 79%; mp 134−135 °C; IR (KBr) 3100, 2228, 2203, 1603, 839 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 6.45−6.60 (m, 2 H), 7.26−7.42 (m, 2 H), 7.48−7.70 (m, 3 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 87.13, 91.43, 111.54, 118.46, 122.13, 127.34, 127.89, 128.53, 131.74, 132.05, 133.01.

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Anal. Calcd for $C_{13}H_7N$: C, 74.61; H, 3.37; N: 6.69. Found: C, 74.95; H, 3.57; N, 6.73.

4-{[4-*tert*-Butyl(dimethylsiloxy)phenyl]ethynyl}-benzonitrile (11j): isolated in 71% yield as colorless solid; GC yield was 82%; mp 77−78 °C; IR (KBr) 2959, 2930, 2889, 2861, 2230, 2211, 1597, 1512, 1287, 839 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.22 (s, 6 H), 0.98 (s, 9 H), 6.83 (d, $J = 8.8$ Hz, 2 H), 7.42 (d, $J = 8.8$ Hz, 2 H), 7.56 (d, $J = 8.8$ Hz, 2 H), 7.62 (d, $J = 8.8$ Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 4.41, 18.22, 25.61, 86.82, 94.12, 111.06, 114.90, 118.61, 120.37, 128.64, 131.85, 132.00, 133.33, 156.75; HRMS calcd for $C_{21}H_{23}ONSi$ 333.1549, found M$^+$, 333.1555.

1-{4-[1-(Octynyl)phenyl]}ethanone (11k): isolated in 65% yield as a pale yellow oil; GC yield was 87%; bp 190−200 °C/5 Torr; IR (neat) 2226, 1686, 1601, 841 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.91 (t, $J = 6.5$ Hz, 3 H), 1.28−1.66 (m, 8 H), 2.43 (t, $J = 7.0$ Hz, 2 H), 2.58 (s, 3 H), 7.46 (d, $J = 8.0$ Hz, 2 H), 7.87 (d, $J = 8.0$ Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 13.63, 19.12, 22.18, 25.90, 28.19, 28.24, 30.96, 79.80, 93.87, 127.69, 128.72, 131.16, 135.25, 196.32. Anal. Calcd for $C_{16}H_{20}O$: C, 84.16; H, 8.83. Found: C, 83.93; H, 8.87.

4-{[4-(1,1-Dimethylethyl)-1-cyclohexen-1-yl]ethynyl}-methoxybenzene (11l): isolated in 90% yield as a colorless solid; GC yield was >99%; mp 85−86 °C; IR (KBr) 2953, 2874, 2841, 1509, 830 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.88 (s, 9 H), 1.10−1.38 (m, 2 H), 1.77−2.00 (m, 2 H), 2.08−2.40 (m, 3 H), 3.80 (s, 3 H), 6.25 (brs, 1 H), 6.82 (d, $J = 8.8$ Hz, 2 H), 7.36 (d, $J = 8.8$ Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 23.87, 27.14, 27.50, 30.86, 32.21, 43.30, 55.26, 86.89, 89.62, 113.91, 115.99, 120.70, 132.87, 134.79, 159.28. Anal. Calcd for $C_{19}H_{24}O$: C, 85.03; H, 9.01. Found: C, 84.72; H, 8.97.

4-{[4-(1,1-Dimethylethyl)-1-cyclohexen-1-yl]ethynyl}-benzonitrile (11m): isolated in 44% yield as colorless solid; GC yield was 86%; mp 138−140 °C; IR (KBr) 2926, 2885, 2224, 2209, 1601, 1501, 839 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.89 (s, 9 H), 1.09−1.39 (m, 2 H), 1.78−2.03 (m, 2 H), 2.12−2.34 (m, 3 H), 6.26 (brs, 1 H), 7.47 (d, $J = 8.6$ Hz, 2 H), 7.58 (d, $J = 8.6$ Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 23.71, 27.10, 27.65, 30.46, 32.19, 43.15, 85.63, 95.67, 110.85, 118.64, 120.03, 128.86, 131.86, 131.92, 137.57. Anal. Calcd for $C_{19}H_{21}N$: C, 86.65; H, 8.04; N: 5.32. Found: C, 86.86; H, 7.89; N, 5.25.

Reaction of Alkynylsilane (1b) with Aryl Chloride (15a) Leading to 11b. To a solution of CuCl (2.3 mg, 0.020 mmol, 10 mol %) and $PdCl_2$(dppb) (14 mg, 0.020 mmol, 10 mol %) in DMF (2.0 mL) were added [(4-methoxyphenyl)ethynyl]-trimethylsilane (**1b**) (52 mg, 0.25 mmol) and 4-acetylphenyl chloride (**15a**) (30 μL, 0.23 mmol) at room temperature. The reaction mixture was stirred for 48 h at 120 °C, and the GC yield was calculated using an authentic sample of **11b** to be 86%.

1,2-Bis(4-cyanophenyl)ethyne (17).[62] To a solution of CuCl (9 mg, 0.1 mmol, 20 mol %) and $Pd(PPh_3)_4$ (51 mg, 0.05 mmol 10 mol %) in DMF (4 mL) were added 4-cyanophenyl trifluoromethanesulfonate (**8c**) (167 μL, 1.0 mmol) and bis(trimethylsilyl)ethyne (**16**) (100 μL, 0.44 mmol) at room temperature. The reaction mixture was stirred for 12 h at 80 °C before being quenched with 3 M HCl and extracted with dichloromethane (25 mL × 2). The combined layers were washed with aqueous $NaHCO_3$ and brine and dried over $MgSO_4$. Filtration and evaporation gave a brown oil, which was purified by column chromatography (silica gel, hexane: dichloromethane = 1:1; $R_f = 0.25$). The residue was bulb-to-bulb distilled (200−210 °C/5 Torr) to give **17** (81.4 mg, 40% yield) as colorless solid. The GC yield was 86%.

One-Pot Synthesis of 11g from (Trimethylsilyl)ethyne. To a solution of $Pd(PPh_3)_4$ (122 mg, 0.1 mmol, 10 mol %) in DMF (4 mL) and Et_3N (1 mL) were added 4-acetylphenyl trifluoromethanesulfonate (**8a**) (200 μL, 1.05 mmol) and (1-trimethylsilyl)ethyne (**18**) (150 μL, 1.06 mmol) at room temperature. The mixture was stirred for 6 h at 60 °C. Then, 4-cyanophenyl trifluoromethanesulfonate (**8c**) and CuCl (10 mg, 0.1 mmol 10 mol %) were added to the reaction mixture at 60 °C, and the resulting mixture was stirred for 12 h at 80 °C and the GC yield was calculated using an authentic sample of **11g** to be 94%. 1,2-Difluoro-4-[(4-pentylphenyl)ethynyl]-benzene (**11r**) was reported in the literature.[63]

General Procedure for Synthesis of 1-Chloroalkynes (19a−19d). To a solution of a terminal alkyne (1.0 mmol) in THF (2.0 mL) was added butyllithium (1.1 mmol, 1.59 M hexane solution) dropwise at −78 °C. The reaction mixture was stirred for 30 h at −78 °C and then treated with *N*-chlorosuccinimide (1.3 mmol) at −78 °C. The reaction mixture was warmed to room temperature under stirring for 1 h, quenched with H_2O, and extracted with diethyl ether. The organic layer was separated, and the aqueous layer was extracted with diethyl ether. The combined ethereal layers were washed with brine and dried over $MgSO_4$. Filtration and concentration in vacuo, followed by purification with column chromatography, gave **19a−19d**.

The following 1-chloroalkynes were prepared by literature procedures:[64] 1-chloro-2-(4-chlorophenyl)ethyne (**19b**),[65] 1-chloro-2-(4-methoxyphenyl)ethyne (**19c**),[65] 1-chloro-2-phenylethyne, (**19d**).[64,66]

1-Chloro-2-(4-acetylphenyl)ethyne (19a): isolated in 30% yield as a yellow liquid; IR (neat) 2222, 1690, 1603 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.57 (s, 3 H), 7.50 (d, $J = 8.5$ Hz, 2 H), 7.88 (d, $J = 8.5$ Hz, 2 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 26.51, 68.68, 71.53, 126.89, 128.17, 132.06, 136.50, 197.08; HRMS calcd for $C_{10}H_7ClO$ 178.0185, found M$^+$, 178.0185.

General Procedure for Synthesis of Unsymmetrical Conjugate Diynes: Formation of 1-(4-Methoxyphenyl)-4-phenyl-1,3-butadiyne (20c). To a solution of CuCl (2.4 mg, 0.02 mmol, 10 mol %) in DMF (1.5 mL) were added 1-chloro-2-phenylethyne (**19d**) (50 mg, 0.37 mmol) and [(4-methoxyphenyl)ethynyl]trimethylsilane (**1b**) (50 μL, 0.24 mmol) at room temperature. The reaction mixture was stirred for 48 h at 120 °C, quenched with 3 M HCl, and then extracted with diethyl ether (25 mL × 2). The combined ethereal layer was washed with aqueous $NaHCO_3$ and brine and dried over $MgSO_4$. Filtration and evaporation provided brown oily substances. Column chromatography (silica gel, hexane:dichloromethane = 10:1) gave **20c** (36 mg, 65% yield) as a colorless solid. The GC yield was 90%; mp 96−97 °C; IR (KBr) 3076, 3056, 3035, 2216, 1599, 1506, 828 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 3.83 (s, 3 H), 6.86 (d, $J = 9.0$ Hz, 2 H), 7.30−7.58 (m, 7 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 55.32, 72.73, 74.17, 81.01, 81.81, 113.71, 114.17, 122.02, 128.40, 129.01, 132.42, 134.12, 160.38; HRMS calcd for $C_{17}H_{12}O$ 232.0888, found M$^+$, 232.0896.

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Supporting Information Available: Experimental data for **2e−2f**, **20a**, **20b**, and **20d−20h** and ^{1}H and ^{13}C NMR spectra of compounds **1f**, **2c**, **2e−2g**, **8d**, **8l**, **8m**, **11e**, **11f**, **11j**, **12**, **13**, **19a**, and **20a−20h**. This material is available free of charge via the Internet at http://pubs.acs.org.

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