A facile stereoselective synthesis of 1,3-dienyl and 1,4-dienyl sulfides by hydrostannylation-Stille tandem reaction of acetylenic sulfides

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1,3-Dienyl and 1,4-dienyl sulfides can be stereoselectively synthesised in one pot under mild conditions in good yields by the palladium-catalysed hydrostannylation of acetylenic sulfides, followed by Stille coupling with alkenyl or allylic halides, respectively.

Keywords: hydrostannylation, Stille coupling, acetylenic sulfide, tandem reaction, stereoselective synthesis

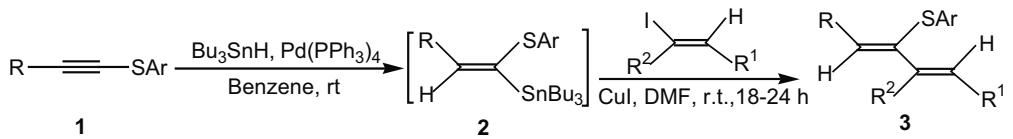
The stereocontrolled synthesis of conjugated dienes has received much attention in organic chemistry because of their appearance in a wide variety of biologically active molecules and as key synthetic intermediates.[1-3] Conjugated dienes are usually prepared by utilising either a Wittig-type approach[4,5] or through transition-metal-catalysed coupling reactions of stereodefined vinyl halides with vinyl organometallic compounds.[6,7] Recently, Kasatkin and Whitby reported the insertion of 1-lithio-1-halobutadiene into organozirconocenes providing a stereocontrolled synthesis of (*E,Z*)-1,3-dienes.[8] Molander and Yokoyama reported one-pot stereoselective synthesis of trisubstituted 1,3-dienes via sequential Suzuki-Miyaura cross-coupling with alkenyl- and alkyltrifluoroborates.[9]

The 1,4-diene framework constitutes an important structural assembly in many molecules of biological importance[10-12] in addition to its application in organic synthesis[13-16] and for these reasons the synthesis of 1,4-dienes has also attracted much interest.[17] Many methods can be used for the stereocontrolled synthesis of 1,4-dienes.[18-22] Very recently, Kabalka and Al-Masum reported a new route to 1,4-pentadienes via microwave-enhanced palladium-catalysed cross-coupling reactions of potassium vinyltrifluoroborates and allyl acetates.[23]

The stereocontrolled synthesis of 1,3-dienes and 1,4-dienes containing metal or heteroatom functional groups is also of considerable interest in organic synthesis because many useful functional group transformations can be achieved by the introduction and removal of metal or heteroatom functions. Heteroatom-substituted 1,3-dienes are also useful precursors for the construction of highly functionalised ring systems in Diels–Alder reactions.[24,25] The stereoselective synthesis of 1,3-dienylsilanes,[26-29] 1,3-dienyl selenides,[30-33] 1,3-dienylstannanes[34-36] and 1,3-dienyl sulfones[37-39] have already been described in the literature. 1,3-Dienyl sulfides serve as valuable versatile intermediates since vinyl sulfides are synthetically equivalent to carbonyls and can be stereospecifically converted into alkenes by nickel-catalysed cross-coupling reactions with Grignard reagents.[40] In addition, 1,3-dienyl sulfides play a very important role in Diels–Alder reactions, where they impart an added level of reactivity and regioselectivity to such cycloadditions.[41-44] Due to their synthetic utility, a variety of methods have been developed for their preparation.[45-49] However, the stereoselective synthesis of polysubstituted 1,3-dienyl sulfides has received less attention.[50] Allred and Liebeskind reported that α-(tributylstannyl)thiophene and iodoolefins were successfully Stille-coupled to afford different products containing a sulfur-substituted 1,3-diene structural skeleton.[51] Recently, Jin *et al.* have developed a convergent approach for the stereoselective synthesis of (*Z,Z*)-2-alkoxy-3-alkyl(aryl)thiobuta-1,3-dienes by Negishi coupling between an α-alkyl(aryl)thiovinylzinc chloride and an α-bromovinyl ether.[52] The tandem reaction has recently been of interest for organic synthesis because it offers a convenient and economical method by which to prepare target organic molecules.[53-55] The palladium-catalysed hydrostannylation of alkynes and the Stille coupling reaction are acknowledged as useful tools for constructing complex organic molecules. However, to the best of our knowledge, there have been no reports on palladium-catalysed tandem hydrostannylation-Stille coupling reactions of tributyltin hydride with acetylenic sulfides and organic halides to date. Here we report that 1,3-dienyl and 1,4-dienyl sulfides can be stereoselectively synthesised in one pot under mild conditions in good yields by the palladium-catalysed hydrostannylation of acetylenic sulfides, followed by Stille coupling with alkenyl or allylic halides, respectively.

Palladium-catalysed hydrostannylation of alkynes provides a simple, general route for the synthesis of vinylstannanes.[56] In 1991, Magriotis reported that the palladium-catalysed hydrostannylation of phenylthioalkynes with Bu_3SnH was highly regio- and stereoselective, giving (*E*)-α-stannylvinyl sulfides in high yields.[57] (*E*)-α-Stannylvinyl sulfides are difunctional reagents in which two synthetically versatile groups are linked to the same olefinic carbon atom and they can be considered both as vinylstannanes and as vinyl sulfides. Vinylstannanes can undergo the Stille-coupling reaction with organic halides.[58,59] Considering the fact that both the hydrostannylation and Stille reactions were catalysed by tetrakis(triphenylphosphine)palladium [$Pd(PPh_3)_4$], we tried to combine the two reactions, in one pot, to synthesise stereoselectively 1,3-dienyl sulfides (Scheme 1).

We found that, after the hydrostannylation reaction of acetylenic sulfides **1** with Bu_3SnH using 5 mol% $Pd(PPh_3)_4$ in benzene at room temperature for 4 h, solvent removal under



1 **2** **3**

Scheme 1

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reduced pressure and stirring of the residue with DMF, alkenyl iodides and 75 mol% CuI at room temperature for 18-24 h, the 1,3-dienyl sulfides **3** were obtained in good yields. The experimental results are summarised in Table 1. As shown in Table 1, the hydrostannylation-Stille tandem reaction of Bu_3SnH with a variety of acetylenic sulfides and alkenyl iodides proceeded smoothly under very mild conditions to afford stereoselectively the corresponding 1,3-dienyl sulfides **3**. The Stille-coupling reaction of the intermediates **2** with alkenyl bromides was very slow under the same reaction conditions; only traces of coupled products were obtained after 24 h of reaction time. The Stille-coupling reaction of the intermediates **2** with alkenyl chlorides did not occur at all.

It is well documented that the Stille-coupling reaction of vinylstannanes with organic halides in the presence of a palladium catalyst occurs with retention of configuration.[58,59] The (1*E*)-configuration of the compounds **3a, 3e, 3f, 3i** has been proved by their ^{1}H NMR spectra which show a doublet at δ = 6.08–6.89 with a coupling constant of 14.8–15.6 Hz, and this is also the evidence of the retention of the *E*-configuration of the starting alkenyl iodides. In addition, the (3*Z*)-configuration of the compound **3f** was confirmed by the NOESY in the ^{1}H NMR spectrum. An enhancement of the allylic protons was observed as the vinylic proton (δ = 6.25) of **3f** was irradiated. There was no correlation between the vinylic proton (δ = 6.25) and aromatic protons. Correlation between the allylic protons and aromatic protons was observed and correlation between the vinylic proton (δ = 6.25) and another vinylic proton (δ = 6.30) was also observed. The NOE results indicate that **3f** has the expected (3*Z*)-configuration and the cross-coupling reaction of (*E*)-α-stannylvinyl sulfides **2** with alkenyl iodides occurs with the retention of configuration of both the starting compounds **2** and the alkenyl iodides.

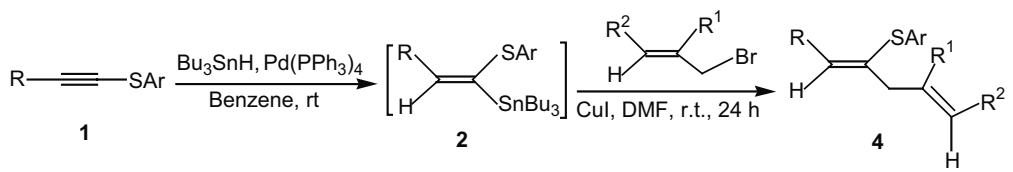
We have also investigated a one-pot stereoselective synthesis of 1,4-dienyl sulfides by the hydrostannylation-Stille tandem reaction of Bu_3SnH with acetylenic sulfides and allylic bromides (Scheme 2). We observed that, after the hydrostannylation reaction of acetylenic sulfides **1** with Bu_3SnH using 5 mol% $Pd(PPh_3)_4$ in benzene at room temperature for 4 h, solvent removal under reduced pressure and stirring of the residue with DMF, allylic bromides and 75 mol% CuI at room temperature for 24 h, the desired (*Z*)-2-arylsulfanyl-substituted 1,4-dienes **4** were obtained in good yields. The experimental results are summarised in Table 2. From Table 2, we can see that the hydrostannylation-Stille tandem reaction of Bu_3SnH with a variety of acetylenic sulfides and allylic bromides could also proceed smoothly under very mild conditions to give stereoselectively the corresponding (*Z*)-2-arylsulfanyl-substituted 1,4-dienes **4**. When allylic bromides were replaced by allylic chlorides, no Stille reaction was observed.

In summary, we have developed an efficient and stereoselective one-pot method for the synthesis of 1,3-dienyl and 1,4-dienyl sulfides. The present method has the advantages of readily available starting materials, straightforward and simple procedures, mild reaction conditions and good yields. The procedure should find wide application to the synthesis of a large array of naturally occurring substances having the 1,3- or 1,4-diene system.

Table 1 Synthesis of 1,3-dienyl sulfides **3a–i**[a]

Entry	R	Ar	R^1	R^2	Product	Yield[b]/%
1	*n*-C_4H_9	Ph	*n*-C_4H_9	H	**3a**	73
2	CH_3OCH_2	Ph	*n*-C_4H_9	H	**3b**	70
3	*n*-C_4H_9	4-ClC_6H_4	CH_3OCH_2	H	**3c**	72
4	*n*-C_4H_9	4-ClC_6H_4	—$(CH_2)_4$—		**3d**	77
5	Ph	Ph	CH_3OCH_2	H	**3e**	62
6	*n*-C_4H_9	4-$CH_3C_6H_4$	CH_3OCH_2	H	**3f**	71
7	Ph	Ph	—$(CH_2)_4$—		**3g**	63
8	*n*-C_4H_9	4-$CH_3C_6H_4$	—$(CH_2)_4$—		**3h**	79
9	*n*-C_4H_9	4-ClC_6H_4	Ph	H	**3i**	64

[a]1.0 mmol acetylenic sulfide, 1.05 mmol Bu_3SnH, 0.05 mmol $Pd(PPh_3)_4$, 1.1 mmol alkenyl iodide, and 0.75 mmol CuI at room temperature.
[b]Isolated yield based on the **1** used.



Scheme 2

Table 2 Synthesis of 1,4-dienyl sulfides **4a–j**[a]

Entry	R	Ar	R^1	R^2	Product	Yield[b]/%
1	*n*-C_4H_9	Ph	H	H	**4a**	68
2	*n*-C_4H_9	4-$CH_3C_6H_4$	H	H	**4b**	73
3	$MeOCH_2$	Ph	H	H	**4c**	65
4	Ph	4-$CH_3C_6H_4$	H	H	**4d**	61
5	*n*-C_4H_9	Ph	Me	H	**4e**	74
6	*n*-C_4H_9	4-$CH_3C_6H_4$	Me	H	**4f**	70
7	Ph	4-$CH_3C_6H_4$	Me	H	**4g**	64
8	$MeOCH_2$	Ph	Me	H	**4h**	67
9	*n*-C_4H_9	Ph	H	Ph	**4i**	58
10	Ph	4-$CH_3C_6H_4$	H	Ph	**4j**	61

[a]1.0 mmol acetylenic sulfide, 1.05 mmol Bu_3SnH, 0.05 mmol $Pd(PPh_3)_4$, 1.1 mmol allylic bromide, and 0.75 mmol CuI at room temperature.
[b]Isolated yield based on the **1** used.

Experimental

^{1}H NMR spectra were recorded on a Bruker AC-P400 (400 MHz) spectrometer with TMS as an internal standard using $CDCl_3$ as the solvent. ^{13}C NMR (100 MHz) spectra were recorded on a Bruker AC-P400 (400 MHz) spectrometer using $CDCl_3$ as the solvent. IR spectra were determined on an FTS-185 instrument as neat films. Mass spectra were obtained on a Finnigan 8239 mass spectrometer. Microanalyses were measured using a Yanaco MT-3 CHN microelemental analyser. All reactions were carried out in pre-dried glassware (150 °C, 4 h) and cooled under a stream of dry Ar. Benzene was distilled from sodium prior to use. DMF was dried by distillation over calcium hydride.

General procedure for one-pot synthesis of 1,3-dienyl sulfides **3a–i**
A 25 mL, two-necked, round-bottom flask equipped with a magnetic stirring bar under argon atmosphere, was charged sequentially with acetylenic sulfide (1.0 mmol), benzene (4 mL), $Pd(PPh_3)_4$ (0.05 mmol) and Bu_3SnH (1.05 mmol). The mixture was stirred at room temperature for 4 h, then the solvent was removed under reduced pressure and the residue was dissolved in DMF (8 mL). Alkenyl iodide (1.1 mmol) and CuI (0.75 mmol) were added and the mixture was stirred for 18–24 h at room temperature and monitored by TLC (SiO_2) for the disappearance of the intermediate **2**. The reaction mixture was diluted with diethyl ether (30 mL), filtered and then treated with 20% aqueous KF (10 mL) for 30 min before being dried and concentrated. The residue was purified by column chromatography on silica gel, eluting either with a mixture of diethyl ether and petroleum or just petroleum.

(5Z,7E)-6-Phenylthiododeca-5,7-diene (**3a**): Oil. IR (film): ν (cm^{-1}) 3059, 2958, 1584, 1478, 1465, 1439, 1378, 961, 737; ^{1}H NMR ($CDCl_3$): δ 7.26–7.08 (m, 5H), 6.16 (t, *J* = 7.2 Hz, 1H), 6.08 (d, *J* = 14.8 Hz, 1H), 6.01–5.92 (m, 1H), 2.46–2.40 (m, 2H), 2.04–1.97 (m, 2H), 1.41–1.15 (m, 8H), 0.89–0.79 (m, 6H); ^{13}C NMR ($CDCl_3$): δ 141.5, 137.0, 133.4, 130.9, 130.2, 128.7, 127.1, 124.8, 32.0, 31.4, 30.0, 22.4, 22.3, 22.0, 14.0, 13.9; MS (EI): *m/z* (%) 275 (M^+ + 1, 100), 219 (11.3), 149 (12.5), 109 (3.8). Anal. Calcd for $C_{18}H_{26}S$: C, 78.77; H, 9.55. Found: C, 78.59; H, 9.28%.

(2Z,4E)-1-Methoxy-3-phenylthionona-2,4-diene (**3b**): Oil. IR (film): ν (cm^{-1}) 3058, 2957, 1643, 1583, 1478, 1440, 1376, 1119, 961, 739; ^{1}H NMR ($CDCl_3$): δ 7.26–7.11 (m, 5H), 6.21 (t, *J* = 6.0 Hz, 1H), 6.11–6.05 (m, 2H), 4.29 (d, *J* = 6.4 Hz, 2H), 3.34 (s, 3H), 2.06–2.00 (m, 2H), 1.27–1.14 (m, 4H), 0.81 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 135.9, 135.7, 133.5, 130.6, 129.3, 128.8, 127.7, 125.4, 70.5, 58.3, 32.0, 31.2, 22.0, 13.9; MS (EI): *m/z* (%) 262 (M^+, 18.9), 249 (39), 233 (21.5), 221 (37), 169 (68), 147 (83), 135 (94), 109 (100). Anal. Calcd for $C_{16}H_{22}OS$: C, 73.23; H, 8.45. Found: C, 73.01; H, 8.33%.

(2E,4Z)-1-Methoxy-4-(4-chlorophenylthio)nona-2,4-diene (**3c**): Oil. IR (film): ν (cm^{-1}) 2957, 2925, 1645, 1598, 1476, 1380, 1092, 1011, 962, 814; ^{1}H NMR ($CDCl_3$): δ 7.17 (d, *J* = 8.8 Hz, 2H), 7.08 (d, *J* = 8.8 Hz, 2H), 6.35–6.28 (m, 2H), 6.05–6.01 (m, 1H), 3.92 (d, *J* = 5.6 Hz, 2H), 3.25 (s, 3H), 2.46–2.40 (m, 2H), 1.41–1.19 (m, 4H), 0.87 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 144.9, 135.2, 132.2, 130.8, 130.0, 128.9, 128.3, 128.2, 72.3, 57.9, 31.2, 30.1, 22.4, 13.9; MS (EI): *m/z* (%) 297 (M^+ + 1, ^{35}Cl, 11.4), 296 (M^+, ^{35}Cl, 2.1), 267 (36), 265 (100), 209 (12.5). Anal. Calcd for $C_{16}H_{21}OSCl$: C, 64.74; H, 7.13. Found: C, 64.58; H, 6.89%.

(Z)-1-(Cyclohex-1-enyl)-1-(4-chlorophenylthio)hex-1-ene (**3d**): Oil. IR (film): ν (cm^{-1}) 3019, 2926, 1631, 1574, 1474, 1389, 1092, 1011, 812, 742; ^{1}H NMR ($CDCl_3$): δ 7.16 (d, *J* = 8.8 Hz, 2H), 7.04 (d, *J* = 8.8 Hz, 2H), 6.23–6.17 (m, 2H), 2.43–2.39 (m, 2H), 2.21–2.17 (m, 2H), 2.07–2.01 (m, 2H), 1.64–1.58 (m, 2H), 1.52–1.48 (m, 2H), 1.42–1.21 (m, 4H), 0.88 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 137.0, 136.3, 135.0, 134.1, 130.5, 128.7, 128.3, 128.1, 31.5, 30.4, 28.9, 27.1, 25.9, 22.9, 22.4, 14.0; MS (EI): *m/z* (%) 307 (M^+ + 1, ^{35}Cl, 100), 308 (M^+, ^{37}Cl, 19), 306 (M^+, ^{35}Cl, 58), 279 (7.4), 237 (17.4), 163 (8.5). Anal. Calcd for $C_{18}H_{23}SCl$: C, 70.45; H, 7.55. Found: C, 70.18; H, 7.23%.

(1Z,3E)-1-Phenyl-2-phenylthio-5-methoxypenta-1,3-diene (**3e**): Oil. IR (film): ν (cm^{-1}) 3057, 2926, 1580, 1478, 1439, 1383, 1116, 1039, 977, 746; ^{1}H NMR ($CDCl_3$): δ 7.67 (d, *J* = 7.6 Hz, 2H), 7.31–7.06 (m, 9H), 6.46 (d, *J* = 15.2 Hz, 1H), 6.24–6.20 (m, 1H), 3.95 (d, *J* = 5.6 Hz, 2H), 3.22 (s, 3H). ^{13}C NMR ($CDCl_3$): δ 139.6, 136.0, 133.3, 130.2, 129.9, 129.0, 128.3, 128.2, 127.5, 125.5, 72.3, 57.9; MS (EI): *m/z* (%) 282 (M^+, 7.8), 251 (100), 142 (17.4). Anal. Calcd for $C_{18}H_{18}OS$: C, 76.56; H, 6.42. Found: C, 76.43; H, 6.14%.

(2E,4Z)-1-Methoxy-4-(p-tolylthio)nona-2,4-diene (**3f**): Oil. IR (film): ν (cm^{-1}) 3020, 2924, 1646, 1599, 1492, 1379, 1123, 1087, 962, 804; ^{1}H NMR ($CDCl_3$): δ 7.07 (d, *J* = 8.0 Hz, 2H), 7.01 (d, *J* = 8.0 Hz, 2H), 6.30 (d, *J* = 15.6 Hz, 1H), 6.25 (t, *J* = 7.2 Hz, 1H), 6.08–6.04 (m, 1H), 3.91 (d, *J* = 5.6 Hz, 2H), 3.22 (s, 3H), 2.47–2.41 (m, 2H), 2.27 (s, 3H), 1.41–1.26 (m, 4H), 0.88 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 144.0, 134.9, 132.9, 132.8, 130.7, 129.5, 128.0, 127.3, 72.4, 57.7, 31.3, 30.1, 22.4, 20.9, 13.9; MS (EI): *m/z* (%) 277 (M^+ + 1, 44), 276 (M^+, 7.3), 275 (29), 245 (100), 189 (24). Anal. Calcd for $C_{17}H_{24}OS$: C, 73.86; H, 8.75. Found: C, 73.63; H, 8.61%.

(Z)-1-(Cyclohex-1-enyl)-1-phenylthio-2-phenylethene (**3g**): Oil. IR (film): ν (cm^{-1}) 3057, 3020, 2928, 1626, 1583, 1491, 1477, 1440, 739, 690; ^{1}H NMR ($CDCl_3$): δ 7.59 (d, *J* = 7.6 Hz, 2H), 7.34–7.15 (m, 8H), 7.04 (s, 1H), 6.35–6.31 (m, 1H), 2.31–2.25 (m, 2H), 2.07–2.02 (m, 2H), 1.61–1.56 (m, 2H), 1.49–1.44 (m, 2H); ^{13}C NMR ($CDCl_3$): δ 137.1, 136.3, 132.2, 129.8, 129.6, 128.6, 128.4, 127.9, 127.4, 125.4, 27.6, 26.0, 22.9, 22.1; MS (EI): *m/z* (%) 292 (M^+, 86), 183 (79), 141 (100), 115 (47). Anal. Calcd for $C_{20}H_{20}S$: C, 82.14; H, 6.89. Found: C, 82.24; H, 6.63%.

(Z)-1-(Cyclohex-1-enyl)-1-(p-tolylthio)hex-1-ene (**3h**): Oil. IR (film): ν (cm^{-1}) 3022, 2926, 1632, 1598, 1492, 1448, 1087, 802; ^{1}H NMR ($CDCl_3$): δ 7.04–6.98 (m, 4H), 6.26–6.22 (m, 1H), 6.15 (t, *J* = 7.6 Hz, 1H), 2.44–2.40 (m, 2H), 2.27 (s, 3H), 2.21–2.17 (m, 2H), 2.05–2.01 (m, 2H), 1.61–1.57 (m, 2H), 1.51–1.46 (m, 2H), 1.42–1.20 (m, 4H), 0.87 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 136.2, 135.4, 134.8, 134.5, 134.0, 129.4, 127.8, 127.4, 31.7, 30.3, 27.2, 25.9, 23.0, 22.5, 22.3, 21.0, 14.0; MS (EI): *m/z* (%) 287 (M^+ + 1, 100), 217 (14.1), 161 (8.7). Anal. Calcd for $C_{19}H_{26}S$: C, 79.66; H, 9.15. Found: C, 79.44; H, 9.01%.

(1E,3Z)-1-Phenyl-3-(4-chlorophenylthio)octa-1,3-diene (**3i**): Oil. IR (film): ν (cm^{-1}) 3059, 3025, 2956, 2927, 1624, 1594, 1493, 1389, 1092, 958, 814, 692; ^{1}H NMR ($CDCl_3$): δ 7.42–7.09 (m, 9H), 6.89 (d, *J* = 15.6 Hz, 1H), 6.83 (d, *J* = 15.6 Hz, 1H), 6.42 (t, *J* = 7.6 Hz, 1H), 2.49–2.44 (m, 2H), 1.45–1.25 (m, 4H), 0.88 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 145.5, 137.0, 135.4, 130.8, 129.4, 129.0, 128.6, 128.1, 127.6, 126.6, 31.3, 30.4, 22.5, 14.0; MS (EI): *m/z* (%) 329 (M^+ + 1, ^{35}Cl, 100), 330 (M^+, ^{37}Cl, 17), 328 (M^+, ^{35}Cl, 54), 273 (20.4), 185 (9.6), 129 (13.3). Anal. Calcd for $C_{20}H_{21}SCl$: C, 73.03; H, 6.44. Found: C, 72.82; H, 6.16%.

General procedure for one-pot synthesis of 1,4-dienyl sulfides (**4a–j**)
A 25 mL, two-necked, round-bottom flask, equipped with a magnetic stirring bar under argon atmosphere, was charged sequentially with acetylenic sulfide (1.0 mmol), benzene (4 mL), $Pd(PPh_3)_4$ (0.05 mmol) and Bu_3SnH (1.05 mmol). The mixture was stirred at room temperature for 4 h. The solvent was removed under reduced pressure and the residue was dissolved in DMF (8 mL). Then allylic bromide (1.1 mmol) and CuI (0.75 mmol) were added and the mixture was stirred at room temperature for 24 h and monitored by TLC (SiO_2) for the disappearance of the intermediate **2**. The reaction mixture was diluted with diethyl ether (30 mL), filtered and then treated with 20% aqueous KF (10 mL) for 30 min before being dried and concentrated. The residue was purified by column chromatography on silica gel, eluting either with a mixture of diethyl ether and petroleum or just petroleum.

(4Z)-4-Phenylthionona-1,4-diene (**4a**): Oil. IR (film): ν (cm^{-1}) 3074, 3023, 2957, 1715, 1639, 1583, 1477, 740, 690; ^{1}H NMR ($CDCl_3$): δ 7.37–7.10 (m, 5H), 5.91 (t, *J* = 7.2 Hz, 1H), 5.85–5.76 (m, 1H), 5.02–4.93 (m, 2H), 2.89 (d, *J* = 6.8 Hz, 2H), 2.37–2.32 (m, 2H), 1.43–1.26 (m, 4H), 0.90 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 137.4, 136.0, 135.3, 131.3, 129.7, 128.8, 126.0, 116.4, 41.8, 31.6, 29.7, 22.4, 14.0; MS (EI): *m/z* (%) 231 (M^+–1, 4.7), 57 (54), 43 (68), 41 (100). Anal. Calcd for $C_{15}H_{20}S$: C, 77.53; H, 8.68. Found: C, 77.31; H, 8.52%.

(4Z)-4-(p-Tolylthio)nona-1,4-diene (**4b**): Oil. IR (film): ν (cm^{-1}) 3076, 2957, 1716, 1639, 1491, 1457, 913, 807; ^{1}H NMR ($CDCl_3$): δ 7.18 (d, *J* = 8.0 Hz, 2H), 7.07 (d, *J* = 8.0 Hz, 2H), 5.84 (t, *J* = 7.2 Hz, 1H), 5.81–5.77 (m, 1H), 5.01–4.93 (m, 2H), 2.85 (d, *J* = 6.8 Hz, 2H), 2.38–2.34 (m, 2H), 2.31 (s, 3H), 1.41–1.23 (m, 4H), 0.91 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 136.2, 136.1, 136.0, 131.9, 131.3, 130.4, 129.6, 116.2, 41.5, 31.6, 29.6, 22.4, 21.1, 14.0; MS (EI): *m/z* (%) 246 (M^+, 8.4), 244 (19), 124 (47), 91 (77), 57 (80), 41 (100). Anal. Calcd for $C_{16}H_{22}S$: C, 77.99; H, 9.00. Found: C, 77.83; H, 8.81%.

(4Z)-4-Phenylthio-6-methoxyhexa-1,4-diene (**4c**): Oil. IR (film): ν (cm^{-1}) 3075, 2957, 1715, 1639, 1583, 1477, 1191, 1116, 742, 691; ^{1}H NMR ($CDCl_3$): δ 7.35–7.19 (m, 5H), 5.99 (t, *J* = 6.0 Hz, 1H), 5.84–5.75 (m, 1H), 5.05–4.94 (m, 2H), 4.23 (d, *J* = 6.0 Hz, 2H), 3.36 (s, 3H), 2.90 (d, *J* = 6.8 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ 135.8, 135.1, 133.9, 131.8, 130.7, 129.0, 126.8, 117.1, 70.1, 58.2, 41.3; MS (EI): *m/z* (%) 220 (M^+, 4.6), 176 (43), 147 (100), 109 (44), 77 (42), 45 (88). Anal. Calcd for $C_{13}H_{16}OS$: C, 70.87; H, 7.32. Found: C, 70.71; H, 7.04%.

(1Z)-1-Phenyl-2-(p-tolylthio)penta-1,4-diene (**4d**): Oil. IR (film): ν (cm^{-1}) 3077, 2956, 1715, 1638, 1598, 1491, 1444, 808, 693; ^{1}H NMR ($CDCl_3$): δ 7.56 (d, *J* = 7.6 Hz, 2H), 7.38–7.23 (m, 5H), 7.09 (d, *J* = 8.0 Hz, 2H), 6.72 (s, 1H), 5.89–5.83 (m, 1H), 5.08–4.98 (m, 2H),

2.97 (d, J = 6.8 Hz, 2H), 2.32 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 137.3, 136.7, 135.7, 134.6, 133.2, 132.1, 131.2, 129.7, 129.2, 128.0, 127.1, 116.8, 42.0, 21.1; MS (EI): *m/z* (%) 266 (M^+, 3.8), 265 (M^+–1, 11), 128 (36), 115 (56), 91 (100), 77 (46). Anal. Calcd for $C_{18}H_{18}S$: C, 81.15; H, 6.81. Found: C, 80.93; H, 6.64%.

(4Z)-2-Methyl-4-phenylthionona-1,4-diene (**4e**): Oil. IR (film): ν (cm^{-1}) 3074, 2957, 1713, 1651, 1583, 1477, 739, 690; ^{1}H NMR ($CDCl_3$): δ 7.28–7.14 (m, 5H), 5.92 (t, J = 7.2 Hz, 1H), 4.79 (s, 1H), 4.60 (s, 1H), 2.84 (s, 2H), 2.40–2.34 (m, 2H), 1.66 (s, 3H), 1.43–1.32 (m, 4H), 0.91 (t, J = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 142.8, 138.1, 135.4, 130.7, 129.9, 128.8, 126.0, 112.9, 45.8, 31.6, 29.7, 22.4, 21.7, 14.0; MS (EI): *m/z* (%) 246 (M^+, 3.5), 229 (100), 228 (77), 186 (51), 110 (46), 77 (42). Anal. Calcd for $C_{16}H_{22}S$: C, 77.99; H, 9.00. Found: C, 77.81; H, 8.84%.

(4Z)-2-Methyl-4-(p-tolylthio)nona-1,4-diene (**4f**): Oil. IR (film): ν (cm^{-1}) 3073, 2958, 1713, 1650, 1583, 1491, 890, 807; ^{1}H NMR ($CDCl_3$): δ 7.18 (d, J = 8.0 Hz, 2H), 7.07 (d, J = 8.0 Hz, 2H), 5.85 (t, J = 7.2 Hz, 1H), 4.79 (s, 1H), 4.59 (s, 1H), 2.80 (s, 2H), 2.40–2.34 (m, 2H), 2.32 (s, 3H), 1.65 (s, 3H), 1.42–1.31 (m, 4H), 0.91 (t, J = 7.2 Hz, 3H); ^{13}C NMR ($CDCl_3$): δ 142.9, 137.0, 136.1, 131.4, 131.2, 130.5, 129.5, 112.9, 45.5, 31.6, 29.6, 22.4, 21.7, 21.1, 14.0; MS (EI): *m/z* (%) 260 (M^+, 3.8), 259 (10), 242 (98), 240 (67), 91 (100). Anal. Calcd for $C_{17}H_{24}S$: C, 78.40; H, 9.29. Found: C, 78.14; H, 9.10%.

(1Z)-1-Phenyl-2-(p-tolylthio)-4-methylpenta-1,4-diene (**4g**): Oil. IR (film): ν (cm^{-1}) 3075, 2957, 1713, 1650, 1598, 1492, 808, 693; ^{1}H NMR ($CDCl_3$): δ 7.58 (d, J = 7.6 Hz, 2H), 7.38–7.23 (m, 5H), 7.08 (d, J = 8.0 Hz, 2H), 6.73 (s, 1H), 4.84 (s, 1H), 4.66 (s, 1H), 2.92 (s, 2H), 2.32 (s, 3H), 1.64 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 142.3, 136.8, 133.6, 131.9, 131.3, 130.1, 129.5, 129.1, 128.8, 127.6, 126.7, 112.9, 45.6, 21.4, 20.7; MS (EI): *m/z* (%) 280 (M^+, 100), 226 (23), 157 (47), 115 (37), 91 (35). Anal. Calcd for $C_{19}H_{20}S$: C, 81.38; H, 7.19. Found: C, 81.24; H, 6.93%.

(4Z)-2-Methyl-4-phenylthio-6-methoxyhexa-1,4-diene (**4h**): Oil. IR (film): ν (cm^{-1}) 3074, 2957, 1716, 1650, 1583, 1476, 1439, 1194, 743, 691; ^{1}H NMR ($CDCl_3$): δ 7.32–7.19 (m, 5H), 6.00 (t, J = 6.0 Hz, 1H), 4.82 (s, 1H), 4.60 (s, 1H), 4.25 (d, J = 6.0 Hz, 2H), 3.38 (s, 3H), 2.86 (s, 2H), 1.66 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 142.1, 135.1, 133.9, 132.5, 130.9, 128.9, 126.8, 113.6, 70.2, 58.2, 45.3, 21.7; MS (EI): *m/z* (%) 234 (M^+, 7.8), 203 (25), 177 (27), 147 (57), 93 (100), 77 (54). Anal. Calcd for $C_{14}H_{18}OS$: C, 71.75; H, 7.74. Found: C, 71.50; H, 7.52%.

(1E,4Z)-1-Phenyl-4-phenylthionona-1,4-diene (**4i**): Oil. IR (film): ν (cm^{-1}) 3083, 2923, 1723, 1650, 1481, 1464, 963, 808, 694; ^{1}H NMR ($CDCl_3$): δ 7.37–7.15 (m, 10H), 6.27 (d, J = 16.0 Hz, 1H), 6.20 (dt, J = 16.0, 6.4 Hz, 1H), 5.97 (t, J = 7.2 Hz, 1H), 3.04 (d, J = 6.4 Hz, 2H), 2.41–2.34 (m, 2H), 1.42–1.25 (m, 4H), 0.91 (t, J = 7.2 Hz, 3H);^{13}C NMR ($CDCl_3$): δ 139.3, 137.4, 135.2, 131.5, 129.8, 129.1, 128.9, 128.5, 127.7, 127.1, 126.1, 116.4, 41.0, 31.6, 29.7, 22.4, 14.0; MS (EI): *m/z* (%) 308 (M^+, 36), 218 (51), 115 (100), 109 (52), 77 (48). Anal. Calcd for $C_{21}H_{24}S$: C, 81.76; H, 7.84. Found: C, 81.50; H, 7.73%.

(1Z,4E)-1,5-Diphenyl-2-(p-tolylthio)penta-1,4-diene (**4j**): Oil. IR (film): ν (cm^{-1}) 3080, 2921, 1718, 1492, 1445, 965, 808, 693; ^{1}H NMR ($CDCl_3$): δ 7.59–7.56 (m, 2H), 7.38–7.16 (m, 10H), 7.12 (d, J = 8.0 Hz, 2H), 6.77 (s, 1H), 6.28 (d, J = 16.0 Hz, 1H), 6.22 (dt, J = 16.0, 5.6 Hz, 1H), 3.12 (d, J = 5.6 Hz, 2H), 2.34 (s, 3H); ^{13}C NMR ($CDCl_3$): δ 139.7, 137.4, 136.7, 135.0, 133.4, 132.4, 132.0, 131.2, 129.8, 129.3, 128.5, 128.1, 127.5, 127.2, 126.2, 116.9, 41.4, 21.2; MS (EI): *m/z* (%) 342 (M^+, 100), 225 (92), 210 (94), 115 (53), 91 (88), 77 (22). Anal. Calcd for $C_{24}H_{22}S$: C, 84.16; H, 6.47. Found: C, 84.01; H, 6.22%.

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References

1 K. Mori, *The total synthesis of natural products: the synthesis of insect pheromones*, J. ApSimon, (ed.)Vol. 4, Wiley, New York, 1981.
2 Y.Z. Huang, L. Shi, J. Yang and J. Zhang, *Tetrahedron Lett.*, 1987, **28**, 2159.
3 X. Zeng, M. Qian, Q. Hu and E.-I. Negishi, *Angew. Chem. Int. Ed.*, 2004, **43**, 2259.
4 R. Ideses and A. Shani, *Tetrahedron*, 1989, **45**, 3523.
5 J.B. Baudin, G. Hareau, S.A. Julia, R. Lorne and O. Ruel, *Bull. Soc. Chim. France*, 1993, **130**, 856.
6 E. Negishi, T. Takahashi, S. Baba, D.E. Van Horn and N. Okukado, *J. Am. Chem. Soc.*, 1987, **109**, 2393.
7 K.S. Chan and C.C. Mak, *Tetrahedron*, 1994, **50**, 2003.
8 A. Kasatkin and R.J. Whitby, *J. Am. Chem. Soc.*, 1999, **121**, 7039.
9 G.A. Molander and Y. Yokoyama, *J. Org. Chem.*, 2006, **71**, 2493.
10 S. Durand, J.-L. Parrain and M. Santelli, *J. Chem. Soc., Perkin Trans. 1*, 2000, 253.
11 O. Andrey, C. Glanzmann, Y. Landais and L. Parra-Rapado, *Tetrahedron*, 1997, **53**, 2835.
12 K.C. Nicolaou, J.Y. Ramphal, N.A. Petasis and C.N. Serhan, *Angew. Chem., Int. Ed. Engl.*, 1991, **30**, 1100.
13 D. Basavaiah, D.S. Sharada, N. Kumaragurubaran and R.M. Reddy, *J. Org. Chem.*, 2002, **67**, 7135.
14 N. Tsukada, T. Sato and Y. Inoue, *Chem. Commun.*, 2001, 237.
15 E. Klaps and W. Schmid, *J. Org. Chem.*, 1999, **64**, 7537.
16 H. Matsushita and E. Negishi, *J. Am. Chem. Soc.*, 1981, **103**, 2882.
17 S. Okamoto, Y. Takayama, Y. Gao and F. Sato, *Synthesis*, 2000, 975.
18 K.C. Nicolaou, P.E. Hernandez, T. Ladduwhetty, J.L. Randall, S.E. Webber, W.S. Li and N.A. Petasis, *J. Org. Chem.*, 1983, **48**, 5404.
19 J.S.R. Zilenovski and S.S. Hall, *J. Org. Chem.*, 1979, **44**, 1159.
20 Y. Yamamoto, H. Yatagai, A. Sonoda and S. Murahashi, *J. Chem. Soc., Chem. Commun.*, 1976, 452.
21 H. Yatagai, *J. Org. Chem.*, 1980, **45**, 1640.
22 H. Matsushita and E.I. Negishi, *J. Am. Chem. Soc.*, 1981, **103**, 2882.
23 G. Kabalka and W.M. Al-Masum, *Org. Lett.*, 2006, **8**, 11.
24 A. Padwa, B. Harrison, S.S. Murphree and P.E. Yeske, *J. Org. Chem.*, 1989, **54**, 4232.
25 M. Yoshimatsu and J. Hasegawa, *J. Chem. Soc., Perkin Trans. 1*, 1997, 211.
26 T.Y. Luh and K.T. Wong, *Synthesis*, 1993, 349.
27 E. Negishi and F.T. Luo, *J. Org. Chem.*, 1983, **48**, 1560.
28 Z.J. Ni, P.F. Yang, D.K.P. Ng, Y.L. Tzeng and T.Y. Luh, *J. Am. Chem. Soc.*, 1990, **112**, 9356.
29 M. Cai, W. Hao, H. Zhao and C. Song, *J. Organomet. Chem.*, 2003, **679**, 14.
30 L. Hevesi, B. Hermans and C. Allard, *Tetrahedron Lett.*, 1994, **35**, 6729.
31 L.S. Zhu, Z.Z. Huang and X. Huang, *Tetrahedron*, 1996, **52**, 9819.
32 Y. Ma and X. Huang, *J. Chem. Soc. Perkin Trans. 1*, 1997, 2953.
33 M. Cai, J. Huang and C. Peng, *J. Organomet. Chem.*, 2003, **681**, 98.
34 F. Suzenet, E. Blart and J.P. Quintard, *Synlett*, 1998, 879.
35 B.H. Lipshutz and C. Lindsley, *J. Am. Chem. Soc.*, 1997, **119**, 4555.
36 J.F. Betzer, F. Delaloge, B. Muller and A. Pancrazi, *J. Org. Chem.*, 1997, **62**, 7768.
37 O.S. Andell and J.E. Backvall, *Tetrahedron Lett.*, 1985, **26**, 4555.
38 T.G. Back and S. Collins, *J. Org. Chem.*, 1981, **46**, 3249.
39 M.-Z. Cai, G.-Q. Chen, W.-Y. Hao and D. Wang, *J. Organomet. Chem.*, 2007, **692**, 1125.
40 T.Y. Luh and Z.J. Ni, *Synthesis*, 1990, 89.
41 B.M. Trost and A.V. Lavoie, *J. Am. Chem. Soc.*, 1983, **105**, 5057.
42 T.H. Chan and C.V.C. Prasad, *J. Org. Chem.*, 1987, **52**, 110.
43 P.G. McDougal, Y.-I. Oh and D. VanDerveer, *J. Org. Chem.*, 1989, **54**, 91.
44 L.E. Overman, C.B. Petty, T. Ban and G.T. Huang, *J. Am. Chem. Soc.*, 1983, **105**, 6335.
45 Y. Ikeda, K. Furata, N. Meguriya, N. Ikeda and H. Yamamoto, *J. Am. Chem. Soc.*, 1982, **104**, 7663.
46 R.J. Pariza and P.L. Fuchs, *J. Org. Chem.*, 1985, **50**, 4252.
47 S.-S.P. Chou, S.-Y. Liou, C.-Y. Tsai and A.-J. Wang, *J. Org. Chem.*, 1987, **52**, 4468.
48 W.H. Pearson, K.-C. Lin and Y.-F. Poon, *J. Org. Chem.*, 1989, **54**, 5814.
49 P.A. Grieco, S.A. May and M.D. Kaufman, *Tetrahedron Lett.*, 1998, **39**, 7047.
50 A. Tsirk, S. Gronowitz and A.-B. Hornfeldt, *Tetrahedron*, 1998, **54**, 9529.
51 G.D. Allred and L.S. Liebeskind, *J. Am. Chem. Soc.*, 1996, **118**, 2748.
52 M. Su, Y. Kang, W. Yu, Z. Hua and Z. Jin, *Org. Lett.*, 2002, **4**, 691.
53 G.H. Posner, *Chem. Rev.*, 1986, **86**, 831.
54 L.F. Tietze and U. Beifuss, *Angew. Chem. Int. Ed. Engl.*, 1993, **32**, 131.
55 L.F. Tietze, *Chem. Rev.*, 1996, **96**, 115.
56 B.M. Trost and C.J. Li, *Synthesis*, 1994, 1267.
57 P.A. Magriotis, J.T. Brown and M.E. Scott, *Tetrahedron Lett.*, 1991, **32**, 5047.
58 J.K. Stille, *Angew. Chem. Int. Ed.Engl.*, 1986, **25**, 508.
59 T.N. Mitchell, *J. Organomet. Chem.*, 1986, **304**, 1.