Advanced Synthesis & Catalysis

Accepted Article

Title: Copper(I)-catalyzed alkyl- and arylsulfenylation of 3,4-dihalo-2(5H)-furanones (X=Br, Cl) with sulfoxides under mild conditions

Authors: Liang Cao, Shi-He Luo, Han-Qing Wu, Liu-Qing Chen, Kai Jiang, Zhi-Feng Hao, and zhao-yang wang

To be cited as: *Adv. Synth. Catal.* 10.1002/adsc.201700600

Link to VoR: http://dx.doi.org/10.1002/adsc.201700600

10.1002/adsc.201700600

DOI: 10.1002/adsc.201((will be filled in by the editorial staff))

Copper(I)-catalyzed alkyl- and arylsulfenylation of 3,4-dihalo-2(5*H*)-furanones (X=Br, Cl) with sulfoxides under mild conditions

Liang Cao,[a] Shi-He Luo,*[a] Han-Qing Wu,[a] Liu-Qing Chen,[a] Kai Jiang,[a] Zhi-Feng Hao,[b] and Zhao-Yang Wang*[a]

[a] School of Chemistry and Environment, South China Normal University; Key Laboratory of Theoretical Chemistry of Environment, Ministry of Education, Guangzhou 510006, People's Republic of China. E-mail: wangzy@scnu.edu.cn, pinky_r@163.com; Fax: (+86)-020-3931-0187; Tel: (+86)-020-3931-0258.

[b] School of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou 510006, People's Republic of China

Received: ((will be filled in by the editorial staff))

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201######.((Please delete if not appropriate))

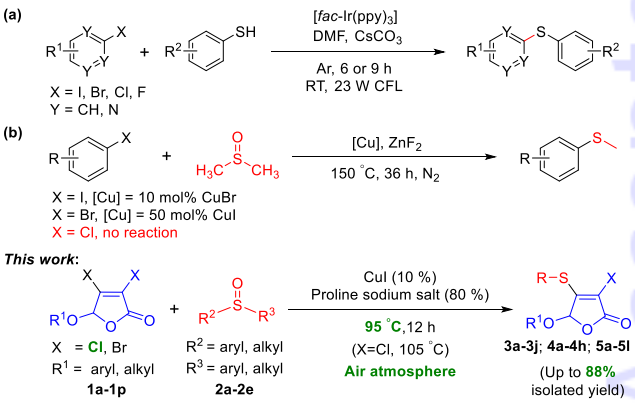
Abstract. An efficient copper(I)/proline sodium salt catalyzed alkyl- and arylsulfenylation of C_{sp2}-X 3,4-dihalo-2(5*H*)-furanone compounds with sulfoxides is described. For inexpensive C_{sp2}-Cl compounds, there is also a satisfactory reactivity with the moderate yields. This transformation provides a novel approach for the utilization of sulfoxides (not only DMSO) as sulfur source with mild temperature without the need for an anaerobic atmosphere. More importantly, both sulfoxide and proline sodium salt can play a dual role in this reaction.

Keywords: copper(I)-catalyzed; C-S bond formation; C_{sp2}-X (X=Br, Cl) compounds; sulfoxides; 2(5*H*)-furanones

Introduction

The formation of alkyl and aryl C-S bonds is becoming one of the research hotspots because alkyl and aryl sulfides are valuable building blocks for the synthesis of biologically and pharmaceutically active molecules and organic materials.[1,2] Traditionally, transition-metal-catalyzed cross-coupling reactions of thiols (thiophenols) with halides are important methods for the synthesis of alkyl and aryl sulfides.[1,3] Even for the direct alkyl- and arylsulfenylation *via* the transition-metal-catalyzed selective functionalization of C-H bonds recently developed, thiols (thiophenols) as sulfur source are necessary for C-S bond formation.[4] However, these agents have obvious deficiencies, such as unpleasant odors, high toxicity and harsh conditions, including high catalyst loadings, specially designed ligands, high temperatures due to the fact that they easily bring the transition-metal catalysts deactivated. Thus, the development of more practical, environmentally friendly and atom-economical reagents for the construction of C-S bonds remains a challenge.

Dimethyl sulfoxide (DMSO), being a cheap and commercially available solvent, has been widely used in organic synthesis as an important source of different units, such as O,[5] CH,[6] CN,[7] CHO,[8] CH_2,[9] CH_3,[10] SCH_3,[11,12] $SOCH_3$[13] and SO_2CH_3.[14] Among them, using DMSO as a sulfenylating agent is more important in the viewpoint of atomic economy. However, the utilization of other sulfoxide compounds as alkyl- or arylsulfenylation agents in C-S bond formation has been less reported.[15]



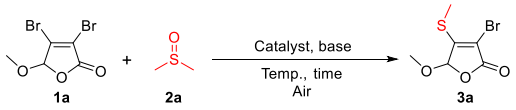
Scheme 1 An overview of previously reported alkyl- and arylsulfenylation methods *vs* our approach

On the other hand, in the traditional transition-metal-catalyzed cross-coupling reactions of C_{sp2}-X bonds with thiols (thiophenols) for the synthesis of alkyl and aryl sulfides, the C_{sp2}-X compounds are usually bromides and iodides; readily available, low-cost aryl chlorides are often not reactive enough.[1,16] To our delight, Fu and co-workers[17] recently

developed a simple and efficient visible-light photoredox arylation of thiols with aryl halides at room temperature (**Scheme 1a**). More importantly, aryl chlorides are also effective arylation reagents. For the reaction of C_{sp2}-X and sulfoxide, Cheng's group reported Cu(I)-mediated methylthiolation of aryl iodides and aryl bromides with DMSO using ZnF_2 at 150 °C (**Scheme 1b**).[18] However, inexpensive chlorides are not effective and other sulfoxides are not suitable, both making the applicability of the substrates seriously affected.

Herein, we chose 3,4-dihalo-2(5*H*)-furanones as non-aromatic C_{sp2}-X (X=Br, Cl) substrates instead of aryl halides to explore their reactions with different sulfoxides (**Scheme 1**). To our knowledge, the method for the reaction of alkyl- and arylsulfenylation by non-aromatic C_{sp2}-X compounds with sulfoxides has been not reported yet in the previous researches. More importantly, molecules possessing 2(5*H*)-furanone moiety, frequently found in natural products, have been considered as potential bactericides, anti-inflammatory agents, anticancer agents and anti-HIV agents, which makes the synthesis of 2(5*H*)-furanones with polyfunctional groups more challenging and practical.[19]

Table 1 Optimization of reaction conditions.[a]



Entry	Catalyst	Base (*x* mol%)	Temp. (°C)	Time (h)	Yield (%)
1	CuCl	Proline sodium salt (20%)	95	12	46
2	CuBr	Proline sodium salt (20%)	95	12	48
3	CuI	Proline sodium salt (20%)	95	12	55
4	Cu_2O	Proline sodium salt (20%)	95	12	35
5	CuO	Proline sodium salt (20%)	95	12	34
6	$Cu(OAc)_2$	Proline sodium salt (20%)	95	12	42
7	$CuSO_4 \cdot 5H_2O$	Proline sodium salt (20%)	95	12	41
8	$Cu(OTf)_2$	Proline sodium salt (20%)	95	12	42
9	$CuCl_2$	Proline sodium salt (20%)	95	12	17
10	$CuBr_2$	Proline sodium salt (20%)	95	12	12
11	-	Proline sodium salt (20%)	95	12	0
12	CuI	NaOH (20%)	95	12	0
13	CuI	K_3PO_4 (20%)	95	12	< 5
14	CuI	Na_2CO_3 (20%)	95	12	8
15	CuI	$NaHCO_3$ (20%)	95	12	9
16	CuI	K_2CO_3 (20%)	95	12	< 5
17	CuI	Proline sodium salt (40%)	95	12	61
18	CuI	Proline sodium salt (60%)	95	12	69
19	CuI	Proline sodium salt (80%)	95	12	77
20	CuI	Proline sodium salt (100%)	95	12	73
21	CuI	Proline sodium salt (80%)[b]	95	12	82
22	CuI	Proline sodium salt (80%)	95	12	25[c]
23	**CuI**	**Proline sodium salt (80%)**	**95**	**12**	**88**[d]
24	CuI	Proline sodium salt (80%)	95	12	87[e]
25	CuI	Proline sodium salt (80%)	85	12	80
26	CuI	Proline sodium salt (80%)	105	12	88
27	CuI	Proline sodium salt (80%)	95	10	83
28	CuI	Proline sodium salt (80%)	95	14	87

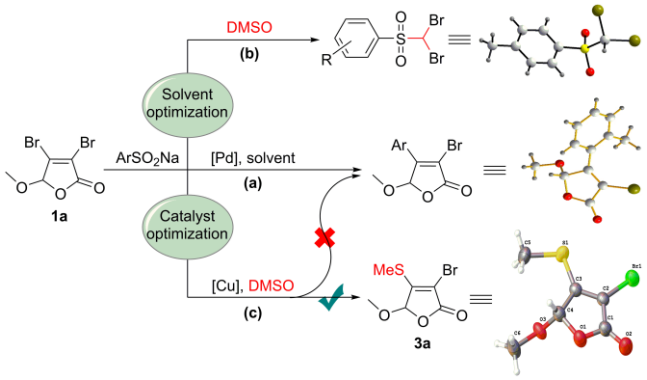
[a] *Reaction conditions:* all reactions were performed with **1a** (0.30 mmol), **2a** (1.0 mL) as a substrate and solvent, catalyst (10 mol%). Yield of isolated product **3a** is given.
[b] Proline sodium salt (80 mol%) was added in batches.
[c] DMSO:H_2O = 1:1.
[d] Using dried DMSO.
[e] Using dried DMSO under N_2 atmosphere.

Results and Discussion

For organic chemists, killing two birds with one stone in organic synthesis is usually welcome,[20] and many reactions simultaneously using solvent as a substrate have been developed recently.[21,22] Being interested in 2(5*H*)-furanone chemistry,[19,23] we surprisingly discovered that sodium arylsulfinates can react with solvent DMSO and 3,4-dibromo-5-methoxy-2(5*H*)-

10.1002/adsc.201700600

furanone (**1a**) to give arylsulfonyl dibromomethane (**Scheme 2b**)[24] when investigating the effect of solvents on the Pd-catalyzed desulfitative arylation of **1a** with sodium arylsulfinates (**Scheme 2a**).[25] And excitingly, the substitution of inexpensive Cu catalysts for Pd salts in optimizing catalyst fortunately gave an unexpected methylthiolation (**Scheme 2c**). Namely, sodium arylsulfinates did not work, and DMSO played a dual role also, but acting as a solvent and alkylsulfenylating reagent in this reaction.



Scheme 2 Reactions of **1a** with sodium arylsulfinates in different conditions

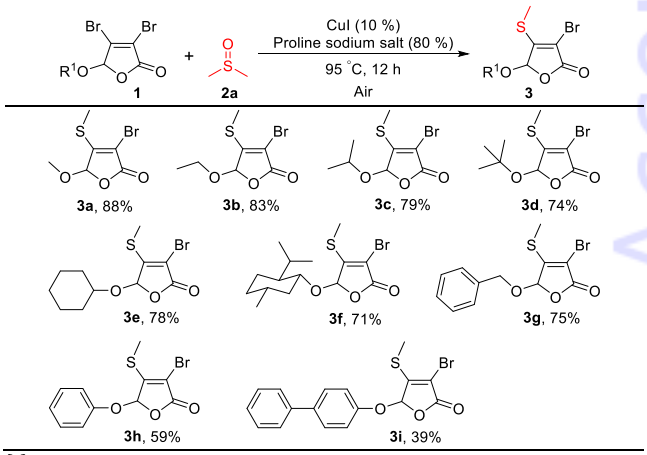
Once the product **3a** was confirmed by single-crystal X-ray diffraction analysis (**Scheme 2c**),[26] the reaction parameters, such as catalyst, base, temperature and time, were first examined using 3,4-dibromo-5-methoxy-2(5*H*)-furanone (**1a**) and DMSO (**2a**) as substrates. The obtained results are listed in **Table 1**.

Under the same conditions, the catalytic activity of Cu(I) compounds is much higher than that of Cu(II) compounds (**Table 1**, entries 1-10). Among the examined catalysts, CuI is the best and the isolated yield of target compound **3a** is 55% (entry 3). With CuI as the catalyst, some bases were further screened. Obviously, proline sodium salt as the base is greatly better than others (entry 3 *vs*. entries 12-16). However, even using proline sodium salt as the base, the reaction in the absence of the catalyst CuI did not give any target product **3a** (entry 11). These results clearly indicate that both CuI and proline sodium salt are necessary for this transformation, and proline sodium salt may not only simply act as a base but also a ligand for CuI. Then we also examined the effect of the amount of proline sodium salt on the reaction (entries 17-20). When proline sodium salt is 80 mol%, the yield is as high as 77%. In addition, it has been found that the addition of proline sodium salt in batches is better (entry 21).

Hoping to make the reaction more suitable and green, we tried to react it in the DMSO/H_2O system (v/v = 1/1), but the yield dropped significantly to 25% (**Table 1**, entry 22), indicating that the content of water in solvent DMSO largely impacts the reaction. This may be due to the fact that 2(5*H*)-furanone **1a** as a lactone is easily hydrolyzed in the environment of an alkaline aqueous solution, resulting in a decrease of **3a** yield. Thus, an improved reaction was carried out with dry DMSO (entry 23). It can be found that the yield is further increased to 88%. However, using dried DMSO under N_2 atmosphere, the effect is not significant (entry 24). Therefore, in the following experiments, the reaction was still carried out in an air atmosphere, only making the anhydrous treatment of DMSO. In addition, we did not notice any significant changes when altering the reaction temperature or time (entries 25-28 *vs*. entry 23). In a word, we can achieve the methylthiolation of **1a** in DMSO under the mild conditions, such as relatively lower temperature, simple solvent treatment and air atmosphere.

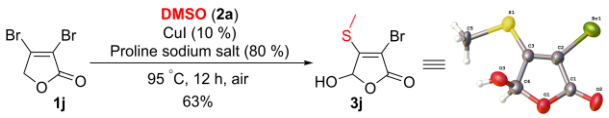
Under the optimized reaction conditions, we further studied the scope of the reaction with respect to 5-substituted 3,4-dibromo-2(5*H*)-furanones. The results are summarized in **Table 2**. As expected, all reactions proceeded smoothly with yields ranging from good to excellent. Especially, they tolerated various steric hindrance groups for 5-alkoxy. For example, 88% of **3a** (methoxy) was isolated while **3d** (*tert*-butoxy) was obtained in 74% yield (**3a** *vs*. **3d**). It is noteworthy that even for the larger menthoxy, the product **3f** was also successfully obtained and the yield is as high as 71%. In short, the substituted 2(5*H*)-furanones with 5-alkoxy as an electron-donating group can give the products in higher yields. On the contrary, those 3,4-dibromo-2(5*H*)-furanones possessing electron-withdrawing analogues, e.g. aryloxy (**3h** and **3i**), are slightly disadvantageous to the reaction, and their yields are obviously lower than that of the substituted 2(5*H*)-furanone with 5-benzyloxy (**3g**).

Table 2 Substrate scope of various 5-substituted 3,4-dibromo-2(5*H*)-furanones[a]



[a] *Reaction conditions:* all reactions were performed with **1** (0.30 mmol), **2a** (1.0 mL) as a substrate and solvent, CuI (10 mol%), proline sodium salt (80 mol%), under air atmosphere at 95 °C for 12 h. Yields of isolated products are given.

Even when 3,4-dibromo-2(5*H*)-furanone **1j** was used as the substrate, the effects of 5-substituted groups are similar with the above mentioned. However, the structure of compound **3j** characterized by single-crystal X-ray diffraction analysis is not wholly the same as anticipated (**Scheme 3**).[26] Perhaps there is an oxidation caused by the solvent DMSO[22] or oxygen in the air, a compound **3j** with a 5-hydroxy structure is obtained with the yield of 63%. Even so, the result further indicates that the methylthiolation reaction of DMSO **2a** occurs to the C-4 position halogen of 2(5*H*)-furanone indeed, which is confirmed by the X-ray diffraction of compound **3a** firstly.[26]

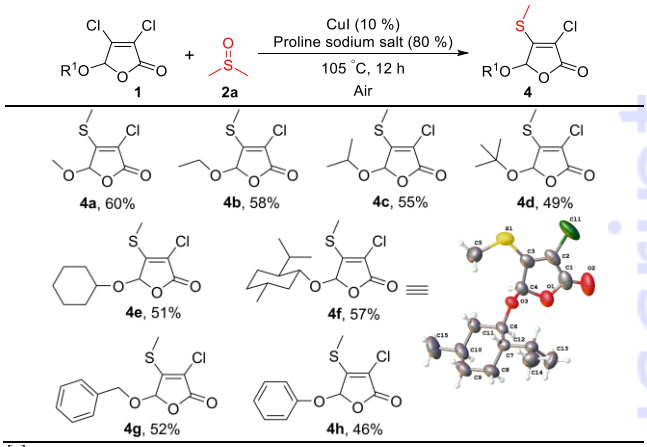


Scheme 3 Reaction of **1j** with DMSO in standard conditions

To further improve the practicability of this protocol, we also evaluated 3,4-dichloro-2(5*H*)-furanones using our procedure. Satisfyingly, 5-substituted 3,4-dichloro-2(5*H*)-furanones were also able to react with **2a** at 105 °C, affording the corresponding methyl sulfide in moderate to good yields (**Table 3**). Of course, for the alkylsulfenylation of 5-substituted 3,4-dihalo-2(5*H*)-furanones with DMSO, the yields of compounds **4** (X = Cl) is lower than those of compounds **3** (X = Br). Not only the structures of compounds **4a-4h** are well characterized by ^{1}H and ^{13}C NMR, MS (their spectra can be seen in **SI**), and elementary analysis, but also the structure of compound **4f** is confirmed using single-crystal X-ray diffraction analysis.[26] Thus, unlike other copper-catalyzed methodologies for the synthesis of methylthiolation from C_{sp2}-X (X = I, Br) compounds and DMSO,[1,16,18] the present method can well achieve the conversion of C_{sp2}-Cl compounds.

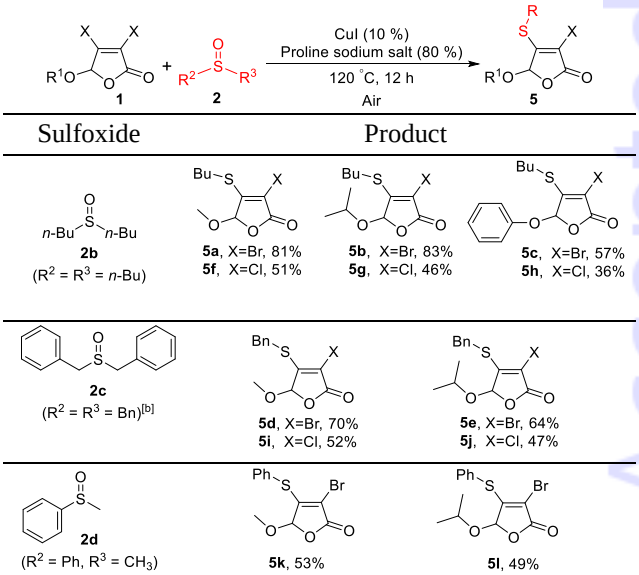
The utilization of sulfoxide compounds in organic synthesis is attracting the attention of chemists.[27] It can be delightedly found that, not only DMSO, the methodology developed herein also can be extended to other sulfoxides (**Table 4**). For the substrates dibutyl sulfoxide **2b** and dibenzyl sulfoxide **2c**, there is an alkylsulfenylation reaction resulting in the formation of compounds **5a-5j** in 36-83% yields. In general, other sulfoxides give the lower yields than DMSO, which may be in touch with the reaction mechanism. It is a pity that the substrate diphenyl sulfoxide cannot go through the arylsulfenylation to generate the corresponding product *via* this similar transformation. However, using unsymmetrical methyl phenyl sulfoxide **2d** as the substrate, the arylsulfenylation products **5k** and **5l** can be successfully obtained. It may be due to the greater steric hindrance of the phenylthio group, and their yields are lower than those of the alkylsulfenylation of the corresponding 5-substituted 3,4-dihalo-2(5*H*)-furanone substrates. Even so, the arylsulfenylation reaction still has moderate yields. These phenomena may be related to the reaction mechanism, which will be discussed in the following.

Table 3 Substrate scope of various 5-substituted 3,4-dichloro-2(5*H*)-furanones[a]



[a] *Reaction conditions:* all reactions were performed with **1** (0.30 mmol), **2a** (1.0 mL) as a substrate and solvent, CuI (10 mol%), proline sodium salt (80 mol%), under air atmosphere at 105 °C for 12 h. Yields of isolated products are given.

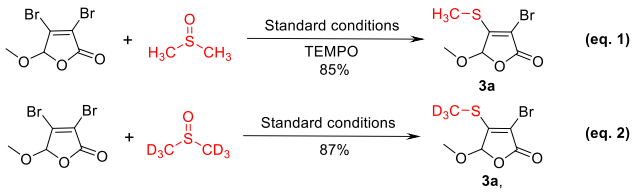
Table 4 Substrate scope of various sulfoxides[a]



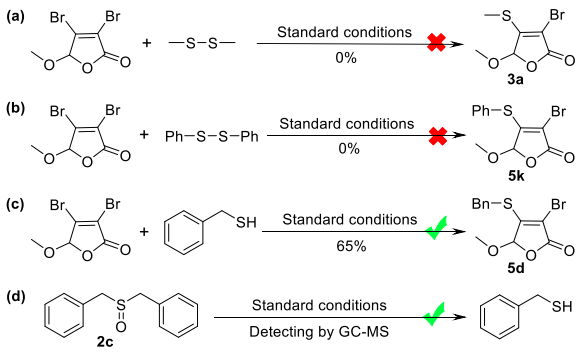
[a] *Reaction conditions:* all reactions were performed with **1** (0.30 mmol), **2** (1.0 mL, for **2b**: 5.1 mmol; **2c**: 5.2 mmol; **2d**: 8.5 mmol) as a substrate and solvent, CuI (10 mol%), proline sodium salt (80 mol%), under air atmosphere at 120 °C for 12 h. Yields of isolated products are given.

[b] For dibenzyl sulfoxide **2c** (m.p. 130-132 °C), the reaction temperature is 135 °C.

To gain insight into the reaction mechanism, several mechanistic experiments were carried out. Firstly, the radical scavenger 2,2,6,6-tetramethyl-piperidinooxy (TEMPO) was employed for this transformation. The yield of **3a** is not obviously changed (**eq. 1**). This result suggests that this reaction does not follow the radical pathway. Subsequently, a deuterium labelling experiment with d_6-DMSO was operated to explore the potential role of DMSO in the methylthiolation process (**eq. 2**). The deuterated product **3a** (its spectra of ^{1}H NMR and MS can be seen in **SI**, **Figs**. **S4** and **S5**) is generated from d_6-DMSO as desired, indicating that DMSO acts as a methylthiolation source indeed.

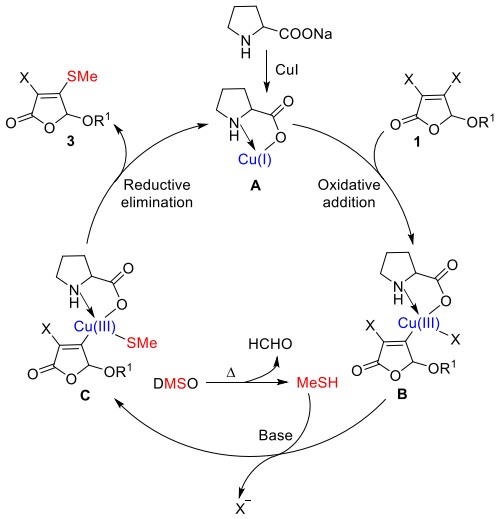


In order to further explain the mechanism, some control experiments were implemented (**Scheme 4**). According to the previous reports,[12,28] DMSO may go through thermal decomposition to generate dimethyl disulfide, methanethiol and formaldehyde. Perhaps one of these sulfur-containing organic compounds is an intermediate in this newly-developed transformation. Thus, investigating the reaction with dimethyl disulfide or diphenyl disulfide instead of DMSO, but no related products can be detected (**Scheme 4a** and **4b**). Fortunately, when using benzyl mercaptan as a substitute for DMSO, the product **5d** can be isolated in the yield of 65% (**Scheme 4c**). Only using dibenzyl sulfoxide **2c** as the reactant under the standard conditions (**Scheme 4d**), the existence of benzyl mercaptan and benzaldehyde can be detected by GC-MS (see their MS spectra in **SI**, **Figs. S6** and **S7**). These results indicate that thiol compounds (e.g. benzyl mercaptan) should be the reaction of intermediates.



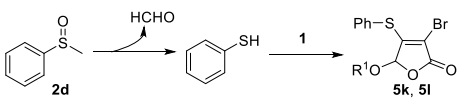
Scheme 4 Control experiments

Based on the above experimental results and previous reports,[12,28,29] a plausible mechanism using DMSO **2a** as an example is proposed in **Scheme 5**. First, CuI and proline sodium salt may form a complex **A**.[29] Then, the oxidative addition of **A** with 5-substituted 3,4-dihalo-2(5*H*)-furanones **1** gives intermediate **B**. Subsequently, in the presence of proline sodium salt as a base, intermediate **C** is formed by the exchange of intermediate **B** with methanethiol from the decomposition of DMSO under the heat.[12,28] In the end, the desired product **3** is produced by a reductive elimination of intermediate **C**, and the CuI complex **A** is regenerated.



Scheme 5 Plausible reaction mechanism

For other symmetrical sulfoxide substrates (e.g. **2b** and **2c**), the corresponding thiol compounds (e.g. butanethiol and benzyl mercaptan) are involved in this mechanism. However, diphenyl sulfoxide cannot yield thiophenol as the heat decomposition way of DMSO,[12,28] thus its arylsulfenylation failed. When the unsymmetrical methyl phenyl sulfoxide **2d** is used as the substrate, thiophenol can be formed according to the literature.[12,28] Therefore, there is a arylsulfenylation but not methylthiolation reaction (**Scheme 6**). If the mixture of two different sulfoxides (DMSO **2a**: dibenzyl sulfoxide **2c** = 1:1, molar ratio) reacted with **1a** under standard conditions, only the product **3a** was obtained in 82% yield. This indicates that methanethiol is more readily available under the same condition, which is consistent with the above-mentioned experimental results. In other words, these results also demonstrate the above reaction mechanism from another side.



Scheme 6 Arylsulfenylation of methyl phenyl sulfoxide **2d** under standard conditions

Conclusion

In summary, we have developed a general and efficient copper(I)-catalyzed alkyl- and arylsulfenylation of C_{sp2}-X (X=Br, Cl) compounds (not only 3,4-dihalo-2(5*H*)-furanones[30]) with various sulfoxides without the need for an anaerobic atmosphere for the first time. The protocol shows excellent reaction site selectivity, which can realize sulfenylation of 3,4-dihalo-2(5*H*)-furanones at the C-4 position, as well as good functional group tolerance especially for ester and ether (acetal). Thus, the low cost of the reagents and wide range of substrates make this method a powerful route for the synthesis of 2(5*H*)-furanone derivatives. Importantly, the method uses readily available C_{sp2}-X compounds, including low-reactive C_{sp2}-Cl compounds often believed before. The present discovery will be helpful for the development of novel reactions of C_{sp2}-X compounds (especially chlorides) with various sulfoxides (not only DMSO) under mild conditions by the synthetic strategy of killing two birds with one stone.

Experimental Section

General Procedure for Compounds 3a-5l

The mixture of **1** (0.30 mmol), CuI (10 mol %), and proline sodium salt (80%, adding in batches) in sulfoxide (1 mL) was stirred at *T* °C (oil bath temperature, designed as request, usually 95 °C) under air for 12 h. At ambient temperature, the reaction mixture was diluted with H_2O (15 mL) and extracted with EtOAc (3 × 15 mL). The organic extracts were dried over anhydrous Na_2SO_4. After filtration and evaporation of the solvents under reduced pressure, the crude product was purified by column chromatography on silica gel to afford desired product.

3-Bromo-5-methoxy-4-(methylthio)furan-2(5*H*)-one (3a): Yellow solid (63 mg, 88%); m.p. 86.7-87.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.58 (s, 3H, SCH_3), 3.52 (s, 3H, OCH_3), 5.89 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.2, 54.8, 101.8, 105.5, 160.0, 164.9; MS (EI, 70 eV), *m/z*: 240, 238 (M^+), 207, 178, 163, 151, 99, 84; Anal. Calcd for $C_6H_7BrO_3S$: C 30.14, H 2.95, Found: C 30.19, H 2.86.

3-Bromo-5-ethoxy-4-(methylthio)furan-2(5*H*)-one (3b): Yellow liquid (63 mg, 83%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.30 (t, *J* = 8.0 Hz, 3H, CH_3), 2.59 (s, 3H, SCH_3), 3.70-3.91 (m, 2H, OCH_2), 5.93 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.2, 15.0, 64.6, 101.3, 105.3, 160.3, 165.0; MS (EI, 70 eV), *m/z*: 254, 252 (M^+), 207, 178, 163, 151, 99, 84; Anal. Calcd for $C_7H_9BrO_3S$: C 33.22, H 3.58, Found: C 33.15, H 3.52.

3-Bromo-5-isopropoxy-4-(methylthio)furan-2(5*H*)-one (3c): Yellow liquid (63 mg, 79%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.28-1.33 (m, 6H, $2CH_3$), 2.58 (s, 3H, SCH_3), 4.08-4.20 (m, 1H, OCH), 5.95 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.2, 22.0, 23.2, 73.7, 100.5, 105.5, 160.4, 165.2; MS (EI, 70 eV), *m/z*: 268, 266 (M^+), 207, 178, 163, 151, 99, 84; Anal. Calcd for $C_8H_{11}BrO_3S$: C 35.97, H 4.15, Found: C 35.88, H 4.19.

3-Bromo-5-(*tert*-butoxy)-4-(methylthio)furan-2(5*H*)-one (3d): Yellow liquid (62 mg, 74%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.39 (s, 9H, $3CH_3$), 2.61 (s, 3H, SCH_3), 6.06 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.6, 28.6, 79.2, 97.7, 105.8, 160.5, 165.5; MS (EI, 70 eV), *m/z*: 282, 280 (M^+), 224, 207, 179, 153, 99, 84; Anal. Calcd for $C_9H_{13}BrO_3S$: C 38.45, H 4.66, Found: C 38.53, H 4.59.

3-Bromo-5-(cyclohexyloxy)-4-(methylthio)furan-2(5*H*)-one (3e): Yellow liquid (72 mg, 78%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.21-1.51 (m, 6H, $3CH_2$), 1.73-2.01 (m, 4H, $2CH_2$), 2.58 (s, 3H, SCH_3), 3.76-3.86 (m, 1H, OCH), 5.99 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.2, 23.9, 24.0, 25.2, 32.1, 33.2, 79.3, 100.4, 105.4, 160.6, 165.3; MS (EI, 70 eV), *m/z*: 308, 306 (M^+), 207, 178, 163, 151, 99, 83; Anal. Calcd for $C_{11}H_{15}BrO_3S$: C 43.01, H 4.92, Found: C 43.09, H 4.87.

3-Bromo-5-(*L*-menthoxy)-4-(methylthio)furan-2(5*H*)-one (3f): Yellow solid (78 mg, 71%); m.p. 107.3-109.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.80 (d, *J* = 8.0 Hz, 3H, CH_3), 0.90-0.95 (m, 7H, CH, $2CH_3$), 1.05-1.15 (m, 2H, CH_2), 1.33-1.40 (m, 2H, 2CH), 1.65-1.70 (m, 2H, CH_2), 2.21-2.28 (m, 2H, CH_2), 2.66 (s, 3H, SCH_3), 3.54-3.62 (ddd, J_1 = 4.0 Hz, J_2 = 4.0 Hz, J_3 = 4.0 Hz, 1H, OCH), 5.86 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.7, 15.9, 21.1, 22.1, 22.8, 25.1, 31.7, 33.9, 42.2, 48.1, 71.5, 102.4, 106.4, 159.9, 165.5; MS (EI, 70 eV), *m/z*: 364, 362 (M^+), 315, 207, 179, 138, 99, 81; Anal. Calcd for $C_{15}H_{23}BrO_3S$: C 49.59, H 6.38, Found: C 49.52, H 6.45.

5-(Benzyloxy)-3-bromo-4-(methylthio)furan-2(5*H*)-one (3g): Yellow liquid (71 mg, 75%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.49 (s, 3H, SCH_3), 4.70-4.87 (dd, J_1 = 12.0 Hz, J_2 = 12.0 Hz, 2H, OCH_2), 5.97 (s, 1H, CH); 7.34-7.42 (m, 5H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.2, 70.5, 99.9, 105.5, 128.8, 128.9, 134.9, 160.4, 165.0; MS (EI, 70 eV), *m/z*: 316, 314 (M^+), 208, 178, 151, 129, 107, 91; Anal. Calcd for $C_{12}H_{11}BrO_3S$: C 45.73, H 3.52, Found: C 45.82, H 3.47.

3-Bromo-4-(methylthio)-5-phenoxyfuran-2(5*H*)-one (3h): Yellow liquid (54 mg, 59%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.60 (s, 3H, SCH_3), 6.36 (s, 1H, CH), 7.13-7.19 (m, 3H, ArH), 7.34-7.40 (m, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.5, 99.4, 116.8, 117.2, 124.3, 130.0, 155.4, 160.0, 164.7; MS (EI, 70 eV), *m/z*: 302, 300 (M^+), 209, 179, 163, 151, 136, 99; Anal. Calcd for $C_{11}H_9BrO_3S$: C 43.87, H 3.01, Found: C 43.97, H 3.07.

5-([1,1'-Biphenyl]-4-yloxy)-3-bromo-4-(methylthio) furan-2(5*H*)-one (3i): Yellow liquid (44 mg, 39%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.63 (s, 3H, SCH_3), 6.39 (s, 1H, CH), 7.23 (d, *J* = 8.0 Hz, 2H, ArH), 7.35 (t, *J* = 8.0 Hz, 1H, ArH), 7.42-7.48 (m, 2H, ArH), 7.55 (d, *J* = 8.0 Hz, 2H, ArH), 7.59 (d, *J* = 8.0 Hz, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.6, 99.4, 105.8, 117.2, 126.9, 127.3, 128.7, 128.9, 137.5, 140.0, 154.9, 159.9, 164.6; MS (EI, 70 eV), *m/z*: 378, 376 (M^+), 207, 179, 169, 151, 141, 115; Anal. Calcd for $C_{17}H_{13}BrO_3S$: C 54.12, H 3.47, Found: C 54.19, H 3.38.

3-Bromo-5-hydroxy-4-(methylthio)furan-2(5*H*)-one (3j): Yellow liquid (42 mg, 63%); m.p. 137.6-138.0 °C; ^{1}H NMR (400 MHz, d_6-DMSO), δ: 2.60 (s, 3H, SCH_3), 6.38 (s, 1H, CH), 8.39 (s, 1H, OH); ^{13}C NMR (100 MHz, d_6-DMSO), δ: 13.2, 98.3, 103.0, 164.8, 165.5; MS (EI, 70 eV),

m/z: 182, 180 ([M-CO_2]$^+$), 151, 136, 101, 84; Anal. Calcd for $C_5H_5BrO_3S$: C 26.68, H 2.24, Found: C 26.61, H 2.32.

3-Chloro-5-methoxy-4-(methylthio)furan-2(5*H*)-one (4a): Yellow liquid (35 mg, 60%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.61 (s, 3H, SCH_3), 3.54 (s, 3H, OCH_3), 5.88 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.1, 55.0, 100.8, 117.1, 155.4, 164.4; MS (EI, 70 eV), *m/z*: 196, 194 (M$^+$), 163, 134, 119, 106, 91, 84; Anal. Calcd for $C_6H_7ClO_3S$: C 37.03, H 3.63, Found: C 37.10, H 3.59.

3-Chloro-5-ethoxy-4-(methylthio)furan-2(5*H*)-one (4b): Yellow liquid (36 mg, 58%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.30 (t, J = 8.0 Hz, 3H, CH_3), 2.61 (s, 3H, SCH_3), 3.71-3.93 (m, 2H, OCH_2), 5.92 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.1, 14.9, 64.8, 100.2, 116.9, 155.7, 164.6; MS (EI, 70 eV), *m/z*: 210, 208 (M$^+$), 163, 134, 119, 106, 91; Anal. Calcd for $C_7H_9ClO_3S$: C 40.29, H 4.35, Found: C 40.35, H 4.29.

3-Chloro-5-isopropoxy-4-(methylthio)furan-2(5*H*)-one (4c): Yellow liquid (37 mg, 55%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.28-1.33 (m, 6H, $2CH_3$), 2.60 (s, 3H, SCH_3), 4.09-4.19 (m, 1H, OCH), 5.94 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.1, 22.0, 23.2, 73.8, 99.4, 117.0, 155.8, 164.8; MS (EI, 70 eV), *m/z*: 224, 222 (M$^+$), 163, 134, 119, 106, 92; Anal. Calcd for $C_8H_{11}ClO_3S$: C 43.15, H 4.98, Found: C 43.20, H 4.87.

5-(*tert*-Butoxy)-3-chloro-4-(methylthio)furan-2(5*H*)-one (4d): Yellow liquid (35 mg, 49%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.36 (s, 9H, $3CH_3$), 2.61 (s, 3H, SCH_3), 5.95 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.1, 28.3, 64.8, 100.2, 116.9, 155.6, 164.6; MS (EI, 70 eV), MS (EI, 70 eV), *m/z*: 210, 208, 163, 134, 119, 106, 91; Anal. Calcd for $C_9H_{13}ClO_3S$: C 45.67, H 5.54, Found: C 45.72, H 5.49.

3-Chloro-5-(cyclohexyloxy)-4-(methylthio)furan-2(5*H*)-one (4e): Yellow liquid (40 mg, 51%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.23-1.45 (m, 6H, $3CH_2$), 1.73-2.01 (m, 4H, $2CH_2$), 2.60 (s, 3H, SCH_3), 3.78-3.85 (m, 1H, OCH), 5.98 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.1, 23.8, 23.9, 25.2, 32.0, 33.2, 79.3, 99.4, 116.9, 156.0, 164.8; MS (EI, 70 eV), *m/z*: 264, 262 (M$^+$), 180, 163, 134, 119, 106, 92; Anal. Calcd for $C_{11}H_{15}ClO_3S$: C 50.28, H 5.75, Found: C 50.35, H 5.69.

3-Chloro-5-(*L*-menthoxy)-4-(methylthio)furan-2(5*H*)-one (4f): Yellow solid (54 mg, 57%); m.p. 91.6-92.9 °C; ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.81 (d, J = 8.0 Hz, 3H, CH_3), 0.88-0.97 (m, 7H, CH, $2CH_3$), 0.99-1.18 (m, 2H, CH_2), 1.31-1.44 (m, 2H, 2CH), 1.63-1.70 (m, 2H, CH_2), 2.19-2.28 (m, 2H, CH_2), 2.60 (s, 3H, SCH_3), 3.53-3.61 (ddd, J_1 = 4.0 Hz, J_2 = 4.0 Hz, J_3 = 4.0 Hz, 1H, OCH), 5.80 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.7, 15.9, 20.8, 22.0, 23.0, 25.3, 31.6, 33.9, 42.1, 48.0, 84.5, 102.2, 124.0, 155.6, 164.1; MS (EI, 70 eV) *m/z*: 320, 318 (M$^+$), 271, 207, 163, 138, 107, 95; Anal. Calcd for $C_{15}H_{23}ClO_3S$: C 56.50, H 7.27, Found: C 56.45, H 7.32.

5-(Benzyloxy)-3-chloro-4-(methylthio)furan-2(5*H*)-one (4g): Yellow liquid (42 mg, 52%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.51 (s, 3H, SCH_3), 4.69-4.90 (dd, J_1 = 12.0 Hz, J_2 = 12.0 Hz, 2H, OCH_2), 5.95 (s, 1H, CH), 7.35-7.40 (m, 5H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.2, 70.6, 98.9, 117.0, 128.8, 128.9, 134.9, 155.9, 164.5; MS (EI, 70 eV), *m/z*: 272, 270 (M$^+$), 207, 164, 134, 106, 91; Anal. Calcd for $C_{12}H_{11}ClO_3S$: C 53.24, H 4.10, Found: C 53.18, H 4.20.

3-Chloro-4-(methylthio)-5-phenoxyfuran-2(5*H*)-one (4h): Yellow liquid (35 mg, 46%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 2.62 (s, 3H, SCH_3), 6.35 (s, 1H, CH), 7.13-7.20 (m, 3H, ArH), 7.34-7.40 (m, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.4, 98.4, 116.9, 124.4, 130.0, 155.4, 155.5, 164.1; MS (EI, 70 eV), *m/z*: 258, 256 (M$^+$), 163, 135, 119, 107, 92; Anal. Calcd for $C_{11}H_9ClO_3S$: C 51.47, H 3.53, Found: C 51.52, H 3.48.

3-Bromo-4-(butylthio)-5-methoxyfuran-2(5*H*)-one (5a): Yellow liquid (68 mg, 81%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.95 (t, J = 8.0 Hz, 3H, CH_3), 1.41-1.51 (m, 2H, CH_2), 1.64-1.72 (m, 2H, CH_2), 3.12 (t, J = 8.0 Hz, 2H, SCH_2), 3.51 (s, 3H, OCH_3), 5.88 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.5, 21.7, 30.1, 31.6, 54.8, 102.0, 105.6, 160.0, 165.0; MS (EI, 70 eV), *m/z*: 282, 280 (M$^+$), 163, 141, 113, 85, 57; Anal. Calcd for $C_9H_{13}BrO_3S$: C 38.45, H 4.66, Found: C 38.52, H 4.58.

3-Bromo-4-(butylthio)-5-isopropoxyfuran-2(5*H*)-one (5b): Yellow liquid (77 mg, 83%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.94 (t, J = 8.0 Hz, 3H, CH_3), 1.29 (t, J = 8.0 Hz, 6H, CH_3), 1.41-1.50 (m, 2H, CH_2), 1.63-1.70 (m, 2H, CH_2), 3.05-3.20 (m, 2H, SCH_2), 4.08-4.18 (m, 1H, CH), 5.93 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.5, 21.7, 22.0, 23.2, 30.0, 31.6, 73.6, 100.6, 105.7, 160.3, 165.3; MS (EI, 70 eV), *m/z*: 310, 308 (M$^+$), 250, 163, 141, 113, 85, 57; Anal. Calcd for $C_{11}H_{17}BrO_3S$: C 42.73, H 5.54, Found: C 42.81, H 5.42.

3-Bromo-4-(butylthio)-5-phenoxyfuran-2(5*H*)-one (5c): Yellow liquid (59 mg, 57%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.91 (t, J = 8.0 Hz, 3H, CH_3), 1.39-1.48 (m, 2H, CH_2), 1.65-1.74 (m, 2H, CH_2), 3.05-3.21 (m, 2H, SCH_2), 6.34 (s, 1H, CH), 7.13-7.19 (m, 3H, ArH), 7.34-7.40 (m, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.4, 21.6, 30.4, 31.5, 99.6, 106.0, 116.8, 124.3, 130.0, 155.5, 159.8, 164.7; MS (EI, 70 eV), *m/z*: 344, 342 (M$^+$), 249, 195, 165, 94, 77; Anal. Calcd for $C_{14}H_{15}BrO_3S$: C 48.99, H 4.41, Found: C 48.91, H 4.50.

4-(Benzylthio)-3-bromo-5-methoxyfuran-2(5*H*)-one (5d): Yellow liquid (66 mg, 70%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 3.52 (s, 3H, OCH_3), 4.29-4.42 (m, 2H, SCH_2), 5.73 (s, 1H, CH), 7.34-7.42 (m, 5H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 34.8, 55.0, 101.8, 105.9, 128.3, 128.7, 129.1, 134.9, 159.3, 164.7; MS (EI, 70 eV), *m/z*: 316, 314 (M$^+$), 282, 203, 163, 91, 65; Anal. Calcd for $C_{12}H_{11}BrO_3S$: C 45.73, H 3.52, Found: C 45.80, H 3.43.

4-(Benzylthio)-3-bromo-5-isopropoxyfuran-2(5*H*)-one (5e): Yellow liquid (66 mg, 64%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.30-1.35 (m, 6H, $2CH_3$), 4.09-4.17 (m, 1H, OCH), 4.33-4.45 (m, 2H, SCH_2), 5.90 (s, 1H, CH), 7.33-7.42 (m, 5H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 22.2, 23.3, 34.7, 73.7, 100.7, 106.2, 128.3, 128.8, 129.1, 134.7, 159.7, 165.1; MS (EI, 70 eV), *m/z*: 344, 342 (M$^+$), 282, 203, 163, 91, 65; Anal. Calcd for $C_{14}H_{15}BrO_3S$: C 48.99, H 4.41, Found: C 48.92, H 4.48.

4-(Butylthio)-3-chloro-5-methoxyfuran-2(5*H*)-one (5f): Yellow liquid (36 mg, 51%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.95 (t, J = 4.0 Hz, 3H, CH_3), 1.45-1.51 (m, 2H, CH_2), 1.65-1.72 (m, 2H, CH_2), 3.14 (t, J = 8.0 Hz, 2H, SCH_2), 3.53 (s, 3H, OCH_3), 5.85 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.5, 21.6, 30.0, 31.8, 55.0, 101.0,

117.1, 155.3, 164.5; MS (EI, 70 eV), *m/z*: 238, 236 (M^+), 204, 148, 133, 119, 103, 91, 57; Anal. Calcd for $C_9H_{13}ClO_3S$: C 45.67, H 5.54, Found: C 45.73, H 4.45.

4-(Butylthio)-3-chloro-5-isopropoxyfuran-2(5*H*)-one (5g): Yellow liquid (36 mg, 46%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.95 (t, J = 8.0 Hz, 3H, CH_3), 1.30 (t, J = 8.0 Hz, 6H, $2CH_3$), 1.42-1.51 (m, 2H, CH_2), 1.64-1.72 (m, 2H, CH_2), 3.07-3.23 (m, 2H, SCH_2), 4.08-4.18 (m, 1H, OCH), 5.92 (s, 1H, CH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.5, 21.7, 22.0, 23.2, 29.9, 31.8, 73.7, 99.7, 117.2, 155.6, 164.9; MS (EI, 70 eV), *m/z*: 266, 264 (M^+), 204, 148, 133, 113, 92, 57; Anal. Calcd for $C_{11}H_{17}ClO_3S$: C 49.90, H 6.47, Found: C 49.98, H 6.41.

4-(Butylthio)-3-chloro-5-phenoxyfuran-2(5*H*)-one (5h): Yellow liquid (33 mg, 36%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.92 (t, J = 8.0 Hz, 3H, CH_3), 1.40-1.48 (m, 2H, CH_2), 1.65-1.74 (m, 2H, CH_2), 3.08-3.24 (m, 2H, SCH_2), 6.33 (s, 1H, CH), 7.12-7.19 (m, 3H, ArH), 7.34-7.40 (m, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 13.4, 21.6, 30.3, 31.7, 98.7, 116.9, 124.3, 130.0, 155.2, 155.6, 164.2; MS (EI, 70 eV), *m/z*: 300, 298 (M^+), 205, 149, 121, 57; Anal. Calcd for $C_{14}H_{15}ClO_3S$: C 56.28, H 5.06, Found: C 56.17, H 5.14.

4-(Benzylthio)-3-chloro-5-methoxyfuran-2(5*H*)-one (5i): Yellow liquid (42 mg, 52%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 3.52 (s, 3H, OCH_3), 4.30-4.43 (m, 2H, SCH_2), 5.72 (s, 1H, CH), 7.34-7.42 (m, 5H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 34.7, 55.1, 100.8, 117.5, 128.3, 128.7, 129.1, 135.0, 154.7, 164.2; MS (EI, 70 eV), *m/z*: 272, 270 (M^+), 238, 119, 103, 91, 65; Anal. Calcd for $C_{12}H_{11}ClO_3S$: C 53.24, H 4.10, Found: C 53.18, H 4.16.

4-(Benzylthio)-3-chloro-5-isopropoxyfuran-2(5*H*)-one (5j): Yellow liquid (42 mg, 47%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 1.29-1.35 (m, 6H, $2CH_3$), 4.08-4.16 (m, 1H, OCH), 4.34-4.46 (m, 2H, SCH_2), 5.87 (s, 1H, CH), 7.30-7.41 (m, 5H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 22.2, 23.2, 34.6, 73.9, 99.7, 117.8, 128.3, 128.8, 129.1, 134.8, 155.0, 164.7; MS (EI, 70 eV), *m/z*: 300, 298 (M^+), 238, 203, 119, 91, 65; Anal. Calcd for $C_{14}H_{15}ClO_3S$: C 56.28, H 5.06, Found: C 56.34, H 4.98.

3-Bromo-5-methoxy-4-(phenylthio)furan-2(5*H*)-one (5k): Yellow liquid (48 mg, 53%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 3.16 (s, 3H, OCH_3), 5.37 (s, 1H, CH), 7.42-7.52 (m, 3H, ArH), 7.59-7.65 (m, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 56.1, 102.5, 106.2, 125.4, 129.5, 130.7, 135.8, 159.5, 164.9; MS (EI, 70 eV), *m/z*: 302, 300 (M^+), 161, 133, 109, 89, 77; Anal. Calcd for $C_{11}H_9BrO_3S$: C 43.87, H 3.01, Found: C 43.92, H 3.09.

3-Bromo-5-isopropoxy-4-(phenylthio)furan-2(5*H*)-one (5l): Yellow liquid (48 mg, 49%); ^{1}H NMR (400 MHz, $CDCl_3$), δ: 0.70 (d, J = 8.0 Hz, 3H, CH_3), 1.11 (d, J = 8.0 Hz, 3H, CH_3), 3.47-3.56 (m, 1H, OCH); 5.60 (s, 1H, CH), 7.42-7.50 (m, 3H, ArH), 7.56-7.64 (m, 2H, ArH); ^{13}C NMR (100 MHz, $CDCl_3$), δ: 20.9, 22.9, 73.9, 100.6, 106.5, 125.9, 129.6, 130.4, 135.5, 159.8, 165.2; MS (EI, 70 eV), *m/z*: 330, 328 (M^+), 269, 161, 134, 109, 77; Anal. Calcd for $C_{13}H_{13}BrO_3S$: C 47.43, H 3.98, Found: C 47.51, H 3.92.

Acknowledgements

Financial support from the Guangdong Natural Science Foundation (No. 2014A030313429), Guangdong Provincial Science and Technology Project (No. 2017A010103016), the Guangzhou Science and Technology Project Scientific Special (General Items, No. 201607010251) and Applied Science and Technology Research and Development Special Foundation of Guangdong Province (No. 2016B090930004) is greatly appreciated.

References

[1] A. N. Desnoyer, J. A. Love, *Chem. Soc. Rev.*, **2017**, *46*, 197-238.

[2] a) F.-G. Sun, M. Li, C.-F. He, B. Wang, B. Li, X.-W. Sui, Z.-H. Gu, *J. Am. Chem. Soc.*, **2016**, *138*, 7456-7459; b) L. Yao, Q. Zhu, L. Wei, Z.-F. Wang, C.-J. Wang, *Angew. Chem. Int. Ed*., **2016**, *55*, 5829-5833; c) T. Tamai, K. Fujiwara, S. Higashimae, A. Nomoto, A. Ogawa, *Org. Lett.*, **2016**, *18*, 2114-2117; d) R. M. P. Dias, A. C. B. Burtoloso, *Org. Lett.*, **2016**, *18*, 3034-3037; e) S.-F. Li, Z.-W. Lu, L. Meng, J. Wang, *Org. Lett.*, **2016**, *18*, 5276-5279; f) F.-H. Xiao, S.-Q. Chen, C. Li, H.-W. Huang, G.-J. Deng, *Adv. Synth. Catal.*, **2016**, *358*, 3881-3886; g) J.-X. Li, C.-S. Li, S.-R. Yang, Y.-N. An, W.-Q. Wu, H.-F. Jiang, *J. Org. Chem.*, **2016**, *81*, 2875-2887; h) J.-X. Li, C.-S. Li, S.-R. Yang, Y.-N. An, W.-Q. Wu, H.-F. Jiang, *J. Org. Chem.*, **2016**, *81*, 7771-7783; i) S. Song, Y.-Q. Zhang, A. Yeerlan, B.-C. Zhu, J.-Z. Liu, N. Jiao, *Angew. Chem. Int. Ed*., **2017**, *56*, 2487-2491; j) P. Wang, S. Tang, P.-F. Huang, A.-W. Lei, *Angew. Chem. Int. Ed.*, **2017**, *56*, 3009-3013.

[3] a) I. P. Beletskaya, V. P. Ananikov, *Chem. Rev.*, **2011**, *111*, 1596-1636; b) C.-F. Lee, Y.-C. Liu, S. S. Badsara, *Chem. Asian J.*, **2014**, *9*, 706-722; c) A. Sujatha, A. M. Thomas, A. P. Thankachan, G. Anilkumar, *ARKIVOC*, **2015**, 1-28; d) A. Ghaderi, *Tetrahedron*, **2016**, *72*, 4758-4782; e) M. Jouffroy, C. B. Kelly, G. A. Molander, *Org. Lett.*, **2016**, *18*, 876-879.

[4] a) C. Shen, P.-F. Zhang, Q. Sun, S.-Q. Bai, T. S. A. Hor, X.-G. Liu, *Chem. Soc. Rev.*, **2015**, *44*, 291-314; b) T. Gensch, F. J. R. Klauck, F. Glorius, *Angew. Chem. Int. Ed.*, **2016**, *55*, 11287-11291; c) Z.-H. Yang, Y.-L. An, Y. Chen, Z.-Y. Shao, S.-Y. Zhao, *Adv. Synth. Catal.*, **2016**, *358*, 3869-3875.

[5] a) R. N. Reddi, P. K. Prasad, A. Sudalai, *Angew. Chem. Int. Ed.*, **2015**, *54*, 14150-14153; b) T. Jiang, X. Quan, C. Zhu, P. G. Andersson, J. E. Bäckvall, *Angew. Chem. Int. Ed*. **2016**, *55*, 5824-5828; c) N. García, R. Rubio-Presa, P. García-García, M. A. Fernández-Rodríguez, M. R. Pedrosa, F. J. Arnáiz, R. Sanz, *Green Chem.*, **2016**, *18*, 2335-2340; d) J.-G. Sun, W.-Z. Weng, P. Li, B. Zhang, *Green Chem*., **2017**, *19*, 1128-1133.

[6] a) Y.-H. Lv, Y. Li, T. Xiong, W.-Y. Pu, H.-W. Zhang, K. Sun, Q. Liu, Q. Zhang, *Chem. Commun*., **2013**, *49*, 6439-6411; b) Z.-G. Zhang, Q. Tian, J.-J. Qian, Q.-F. Liu, T.-X. Liu, L. Shi, G.-S. Zhang, *J. Org. Chem.*, **2014**, *79*, 8182-8188; c) J.-J. Qian, Z.-G. Zhang, Q.-F. Liu, T.-X. Liu, G.-S. Zhang, *Adv. Synth. Catal.*, **2014**, *356*, 3119-3124.

[7] X.-Y. Ren, J.-B. Chen, F. Chen, J. Cheng, *Chem. Commun.*, **2011**, *47*, 6725-6727.

[8] H. Cao, S. Lei, N.-Y. Li, L.-B. Chen, J.-Y. Liu, H.-Y. Cai, S.-X. Qiu, J.-W. Tan, *Chem. Commun.*, **2015**, *51*, 1823-1825.

[9] a) O. P. S. Patel, D. Anand, R. K. Maurya, P. P. Yadav, *J. Org. Chem.*, **2016**, *81*, 7626-7634; b) P. Liu, Z.-Y. Shen, Y. Yuan, P.-P. Sun, *Org. Biomol. Chem.*, **2016**, *14*, 6523-6530.

[10] Z.-J. Li, X.-S. Cui, L. Niu, Y.-M. Ren, M.-H. Bian, X.-B. Yang, B. Yang, Q.-Q. Yan, J.-C. Zhao, *Adv. Synth. Catal.*, **2017**, *359*, 246-249.

[11] a) P. J. A. Joseph, S. Priyadarshini, M. L. Kantam, B. Sreedhar, *Tetrahedron*, **2013**, *69*, 8276-8283; b) H.-Y. Li, L.-J. Xing, M.-M. Lou, H. Wang, R.-H. Liu, B. Wang, *Org. Lett.*, **2015**, *17*, 1098-1101; c) Y.-F. Xu, T.-T. Cong, P. Liu, P.-P. Sun, *Org. Biomol. Chem.*, **2015**, *13*, 9742-9745; d) K. Ghosh, S. Ranjit, D. Mal, *Tetrahedron Lett.*, **2015**, *56*, 5199-5202; e) Z.-Y. An, Y. She, X.-D. Yang, X.-B. Pang, R.-L. Yan, *Org. Chem. Front.*, **2016**, *3*, 1746-1749; f) A. A. Pereira, A. S. Pereira, A. C. de Mello, A. G. Carpanez, B. A. C. Horta, G. W. Amarante, *Eur. J. Org. Chem.*, **2017**, 1578-1582.

[12] a) X.-F. Gao, X.-J. Pan, J. Gao, H.-F. Jiang, G.-Q. Yuan, Y.-W. Li, *Org. Lett.*, **2015**, *17*, 1038-1041; b) G. Shukla, A. Srivastava, A. Nagaraju, K. Raghuvanshi, M. S. Singh, *Adv. Synth. Catal.*, **2015**, *357*, 3969-3976; c) P. Sharma, S. Rohilla, N. Jain, *J. Org. Chem.*, **2015**, *80*, 4116-4122.

[13] M. M. D. Pramanik, N. Rastogi, *Chem. Commun.*, **2016**, *52*, 8557-8560.

[14] a) G.-Q. Yuan, J.-H. Zheng, X.-F. Gao, X.-W. Li, L.-B. Huang, H.-J. Chen, H.-F. Jiang, *Chem. Commun.*, **2012**, *48*, 7513-7515; b) X.-F. Gao, X.-J. Pan, J. Gao, H.-W. Huang, G.-Q. Yuan, Y.-W. Li, *Chem. Commun.*, **2015**, *51*, 210-212; c) J.-Y. Chen, X.-L. Chen, X. Li, L.-B. Qu, Q. Zhang, L.-K. Duan, Y.-Y. Xia, X. Chen, K. Sun, Z.-D. Liu, Y.-F. Zhao, *Eur. J. Org. Chem.*, **2015**, 314-319; d) A.-L. Shao, M. Gao, S.-T. Chen, T. Wang, A.-W. Lei, *Chem. Sci.*, **2017**, *8*, 2175-2178.

[15] a) T.-Z. Jia, M.-N. Zhang, I. K. Sagamanova, C. Y. Wang, P. J. Walsh, *Org. Lett.*, **2015**, *17*, 1168-1171; b) X.-F. Wu, K. Natte, *Adv. Synth. Catal.*, **2016**, *358*, 336-352; c) X.-J. Li, Y. Sun, X. Huang, L. Zhang, L. Kong, B. Peng, *Org. Lett.*, **2017**, *19*, 838-841; d) D. Kaldre, B Maryasin, D Kaiser, O. Gajsek, L. Gonzáez, N. Maulide, *Angew. Chem. Int. Ed.*, **2017**, *56*, 2212-2215.

[16] C. F. Lee, Y.-C. Liu, S. S. Badsara, *Chem. Asian J.*, **2014**, *9*, 706-722.

[17] M. Jiang, H.-F. Li, H.-J. Yang, H. Fu, *Angew. Chem. Int. Ed.*, **2017**, *56*, 874-879.

[18] F. Luo, C.-D. Pan, L.-P. Li, F. Chen, J. Cheng, *Chem. Commun.*, **2011**, *47*, 5304-5306.

[19] a) J. Luo, H.-F. Wang, X. Han, L.-W. Xu, J. Kwiatkowski, K.-W. Huang, Y.-X. Lu, *Angew. Chem. Int. Ed.*, **2011**, *50*, 1861-1864; b) W. Kaplan, H. R. Khatri, P. Nagorny, *J. Am. Chem. Soc.*, **2016**, *138*, 7194-7198; c) J. Zhu, Y.-J. Cheng, X.-K. Kuang, L.-J. Wang, Z.-B. Zheng, Y. Tang, *Angew. Chem. Int. Ed.*, **2016**, *55*, 9224-9228; d) T. J. Greshock, K. P. Moore, R. T. McClain, A. Bellomo, C. K. Chung, S. D. Dreher, P. S. Kutchukian, Z.-W. Peng, I. W. Davies, P. Vachal, M. Ellwart, S. M. Manolikakes, P. Knochel, P. G. Nantermet, *Angew. Chem. Int. Ed.*, **2016**, *55*, 13714-13718; e) A. Manchoju, S. V. Pansare, *Org. Lett.*, **2016**, *18*, 5952-5955; f) M. J. Goldfogel, C. C. Roberts, R. S. Manan, S. J. Meek, *Org. Lett.*, **2017**, *19*, 90-93; g) R. Wehlauch, S. M. Grendelmeier, H. Miyatake-Ondozabal, A. H. Sandtorv, M. Scherer, K. Gademann, *Org. Lett.*, **2017**, *19*, 548-551; h) B. Zhou, Q.-F. Liu, S. Dalal, M. B. Cassera, J.-M. Yue, *Org. Lett.*, **2017**, *19*, 734-737; i) X.-Y. Li, C.-H. Han, H.-Q. Yao, A.-J. Lin, *Org. Lett.*, **2017**, *19*, 778-781.

[20] a) P. G. Janson, I. Ghoneim, N. O. Ilchenko, K. J. Szabó, *Org. Lett.*, **2012**, *14*, 2882-2885; b) G. Fumagalli, S. Boyd, M. F. Greaney, *Org. Lett.*, **2013**, *15*, 4398-4401; c) A. Yoshimura, V. V. Zhdankin, *Chem. Rev.*, **2016**, *116*, 3328-3435; d) P. Ricci, T. Khotavivattana, L. Pfeifer, M. Médebielle, J. R. Morphy, V. Gouverneur, *Chem. Sci.*, **2017**, *8*, 1195-1199; e) C. J. Teskey, S. M. A. Sohel, D. L. Bunting, S. G. Modha, M. F. Greaney, *Angew. Chem. Int. Ed.*, **2017**, *56*, 5263-5266.

[21] a) T. Wu, X. Mu, G.-S. Liu, *Angew. Chem. Int. Ed.*, **2011**, *50*, 12578-12581; b) K. D. Hesp, R. J. Lundgren, M. Stradiotto, *J. Am. Chem. Soc.*, **2011**, *133*, 5194-5197; c) X.-S. Wu, Y. Zhao, H.-B. Ge, *J. Am. Chem. Soc.*, **2015**, *137*, 4924-4927; d) X.-W. Lan, N.-X. Wang, W. Zhang, J.-L. Wen, C.-B. Bai, Y.-L. Xing and Y.-H. Li, *Org. Lett.*, **2015**, *17*, 4460-4463.

[22] a) R.-S. Xu, J.-P. Wan, H. Mao, Y.-J. Pan, *J. Am. Chem. Soc.*, **2010**, *132*, 15531-15533; b) Y.-F. Liang, X.-Y. Li, X.-Y. Wang, M.-C. Zou, C.-H. Tang, Y.-J. Liang, S. Song, N. Jiao, *J. Am. Chem. Soc.*, **2016**, *138*, 12271-12277.

[23] a) Y.-H. Tan, J.-X. Li, F.-L. Xue, J. Qi, Z.-Y. Wang, *Tetrahedron*, **2012**, *68*, 2827-2843; b) J.-P. Huo, P. Peng, G.-H. Deng, W. Wu, J.-F. Xiong, M.-L. Zhong, Z.-Y. Wang, *Macromol. Rapid Commun.*, **2013**, *34*, 1779-1784; c) J.-P. Huo, J.-C. Luo, W. Wu, J.-F. Xiong, G.-Z. Mo, Z.-Y. Wang, *Ind. Eng. Chem. Res.*, **2013**, *52*, 11850-11857.

[24] J. Shi, X.-D. Tang, Y.-C. Wu, J.-F. Fang, L. Cao, X.-Y. Chen, Z.-Y. Wang, *RSC Adv.*, **2016**, *6*, 25651-25655.

[25] J. Shi, X.-D. Tang, Y.-C. Wu, H.-N. Li, L.-J. Song, Z.-Y. Wang, *Eur. J. Org. Chem.*, **2015**, 1193-1197.

[26] CCDC-1544747 (for **3a**), CCDC-1544748 (for **3j**), and CCDC-1544749 (for **4f**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

[27] a) F. Gelat, J. F. Lohier, A. C. Gaumont, S. Perrio, *Adv. Synth. Catal.*, **2015**, *357*, 2011-2016; b) J. A. Fernández-Salas, A. P Pulis, D. J. Procter, *Chem. Commun.*, **2016**, *52*, 12364-12367; c) A. U. Meyer, A. Wimmer, B. König, *Angew. Chem. Int. Ed.*, **2017**, *56*,

409-412; d) L. Shang, Y.-H. Chang, F. Luo, J.-N. He, X. Huang, L. Zhang, L.-C. Kong, K.-X. Li, B. Peng, *J. Am. Chem. Soc*., **2017**, *139*, 4211-4217.

[28] V. J. Traynelis, W. L. Hergenrother, *J. Org. Chem.*, **1964**, *29*, 221-222.

[29] a) G. D. Allred, L. S. Liebeskind, *J. Am. Chem. Soc*., **1996**, *118*, 2748-2749; b) W. Zhu, D.-W. Ma, *J. Org. Chem*., **2005**, *70*, 2696-2700; c) J. Kim, S. Chang, *Chem. Commun.*, **2008**, *26*, 3052-3054; d) D.-W. Ma, Q. Cai, *Acc. Chem. Res*., **2008**, *41*, 1450-1460.

[30] To further investigate the versatility of copper(I)-catalyzed sulfenylation of C_{sp2}-X compounds, we also simply applied this method into the synthesis of aryl methyl sulfides. When using different halogenated benzene derivatives **6a**-**6c** and DMSO as starting materials, the expected products **7a**-**7c** can be obtained (the corresponding discussions on these preliminary observations, the characterization data and spectra of the products **7a**-**7c** can be seen in **SI**).

10.1002/adsc.201700600

FULL PAPER

Copper(I)-catalyzed alkyl- and arylsulfenylation of 3,4-dihalo-2(5*H*)-furanones (X=Br, Cl) with sulfoxides under mild conditions

Adv. Synth. Catal. **2017**, *359*, 1 – 11

Liang Cao,[a] Shi-He Luo,*[a] Han-Qing Wu,[a] Liu-Qing Chen,[a] Kai Jiang,[a] Zhi-Feng Hao,[b] Zhao-Yang Wang*[a]