Organic LETTERS

Letter

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Rh(II)-Catalyzed [2,3]-Sigmatropic Rearrangement of Sulfur Ylides Derived from Cyclopropenes and Sulfides

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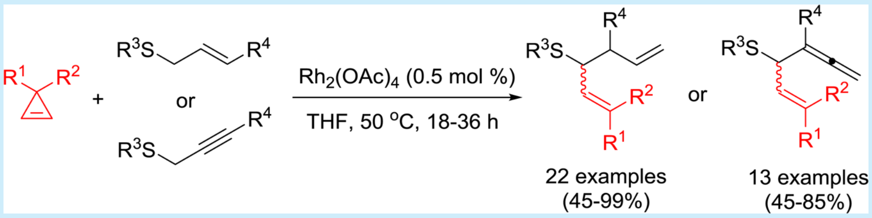
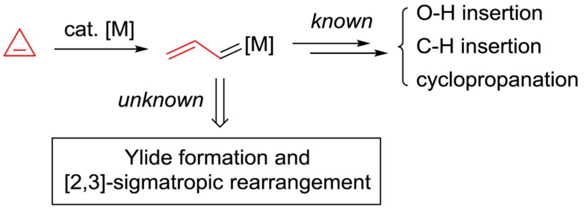
S *Supporting Information*



ABSTRACT: A new type of $Rh_2(OAc)_4$-catalyzed [2,3]-sigmatropic rearrangement of sulfur ylides is reported. A series of cyclopropenes were successfully employed for [2,3]-sigmatropic rearrangement by a reaction with either allylic or propargylic sulfides. Under the optimized conditions, the reaction afforded the products in moderate to excellent yields. In these transformations, the vinyl metal carbenes generated in situ from the cyclopropenes were effectively trapped by sulfides, resulting in the formation of corresponding products upon [2,3]-sigmatropic rearrangements.

Cyclopropenes have diverse reactivity due to the high strain of the small ring, which makes this type of unique compound an excellent three-carbon structure unit for organic synthesis.[1] Among the various transformations, the generation of vinyl metal carbene intermediates from cyclopropenes under transition-metal-catalyzed conditions has attracted considerable attention in recent years. The metal carbene species generated through ring-opening undergoes typical carbene transformations, such as cyclopropanations,[2] C−H bond insertions,[3] O−H bond insertions,[4] and other related rearrangement reactions (Scheme 1).[5] Recently, we have reported a Rh(III)-catalyzed synthesis of 2*H*-chromenes from cyclopropenes and *N*-phenoxyacetamides that involves C−H bond activation and the migratory insertion of the vinyl rhodium carbene generated from cyclopropene.[6]

Scheme 1. Transformations of Vinyl Metal Carbene Generated from Cyclopropene



On the other hand, the [2,3]-sigmatropic rearrangement of sulfur ylide is an efficient method to build C−C and C−S bonds simultaneously, which represents a unique transformation in organic synthesis.[7] The key intermediate, the sulfur ylide, can be formed either by deprotonation of sulfonium salt[8] or through the reaction of sulfide with carbene. Diazo compounds are the commonly used carbene precursors in the catalytic sulfur ylide [2,3]-sigmatropic rearrangement, a transformation known as the Doyle−Kirmse reaction.[9] In 2012, we demonstrated that *N*-tosylhydrazones could be utilized as the precursors of diazo compounds in the Doyle−Kirmse reaction.[10] In addition, other carbene precursors, such as enyne carbonyl compounds[11] and terminal alkynes,[12] are also demonstrated to participate in such transformations.

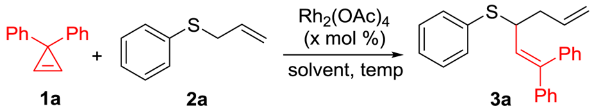
As the continuation of our interest in the exploration of cyclopropenes as vinyl metal carbene precursors, we report herein the Rh(II)-catalyzed [2,3]-sigmatropic rearrangement of sulfur ylides derived from cyclopropenes and sulfides. This reaction represents the first example of using cyclopropenes as the carbene precursors in [2,3]-sigmatropic rearrangement of sulfur ylides.

At the outset of this study, we employed 3,3-diphenylcyclopropene **1a** and allyl phenyl sulfide **2a** as the model substrate with $Rh_2(OAc)_4$ as the catalyst to optimize the reaction conditions (Table 1). Upon examining the solvents, THF was proved to be suitable for this transformation, which afforded the desired product **3a** in moderate yield (Table 1, entries 1−4). Reducing the amount of solvent improved the yield (Table 1, entry 5). Then, a higher yield of 90% could be obtained by increasing the amount of **2a** (Table 1, entry 6). To our delight, reducing the

Received: May 26, 2015

DOI: 10.1021/acs.orglett.5b01542

Table 1. Optimization of Reaction Conditions[a]



entry	solvent (mL)	1a/2a	$Rh_2(OAc)_4$ (mol %)	temp (°C)	time (h)	yield[b] (%)
1	toluene (0.2)	1:1.5	2.0	70	12	54
2	DCE (0.5)	1:1.5	2.0	70	12	56
3	THF (0.5)	1:1.5	2.0	70	12	68
4	hexane (0.5)	1:1.5	2.0	70	12	53
5	THF (0.2)	1:1.5	2.0	70	12	75
6	THF (0.2)	1:3.0	2.0	70	12	90
7	THF (0.2)	1:3.0	0.5	70	12	91
8	THF (0.2)	1:3.0	0	70	12	13
9	THF (0.2)	1:3.0	0.5	50	18	99
10	THF (0.2)	1:3.0	0.5	30	36	99

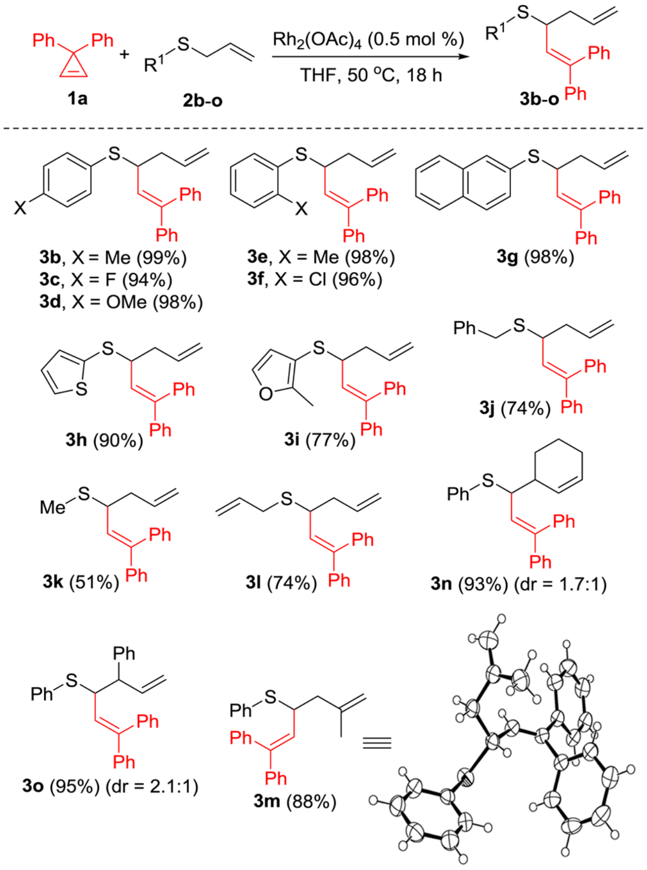
[a] Reaction conditions are as follows if not otherwise noted: **1a** (0.30 mmol), **2a**, and $Rh_2(OAc)_4$ were stirred at the indicated temperature. [b] All of the yields refer to the isolated yields by column chromatography. DCE = 1,2-dichloroethane.

amount of Rh catalyst to 0.5 mol % did not affect the outcome of the reaction (Table 1, entry 7). Interestingly, 13% yield of the desired product **3a** could be obtained in the absence of the Rh catalyst (Table 1, entry 8). This should be attributed to the formation of free carbene through thermal rearrangement under the heating conditions (70 °C). Finally, lowering the reaction temperature could further improve the yield, although the reaction needed longer time under such conditions (Table 1, entries 9 and 10).

With the optimized conditions, the scope of allylic sulfides was then examined. As shown in Scheme 2, aryl allyl sulfides were reacted smoothly with cyclopropene **1a**, affording the corresponding products in excellent yields (**3b**–**f**). In these reactions, the electronic nature of the substituents (**3b**–**d**) and steric effects at *ortho* positions (**3e**, **f**) have no significant impact on the outcome. It is noteworthy that naphthyl and heteroaryl substrates **2g**–**i** were also tolerated, giving the corresponding products **3g**–**i** in good to excellent yields. Next, a series of alkyl substituted allyl sulfides were subjected to the reaction. To our delight, the desired products **3j**–**l** were also obtained in moderate to good yields when the benzyl, methyl and allyl substituted sulfides were used as the substrates. Additionally, substituted allyl phenyl sulfides were also the suitable substrates for this reaction. 2-Methyl-substituted allyl phenyl sulfide **2m** afforded the corresponding products **3m** in 88% yield. The structure of **3m** was unambiguously confirmed by X-ray diffraction. We assume that all of the products have the same constitution based on the comparison of their NMR spectra. It is worth mentioning that the desired products **3n** and **3o** were obtained in 93% and 95% yields as 1.7:1 and 2.1:1 mixtures of diastereomers.

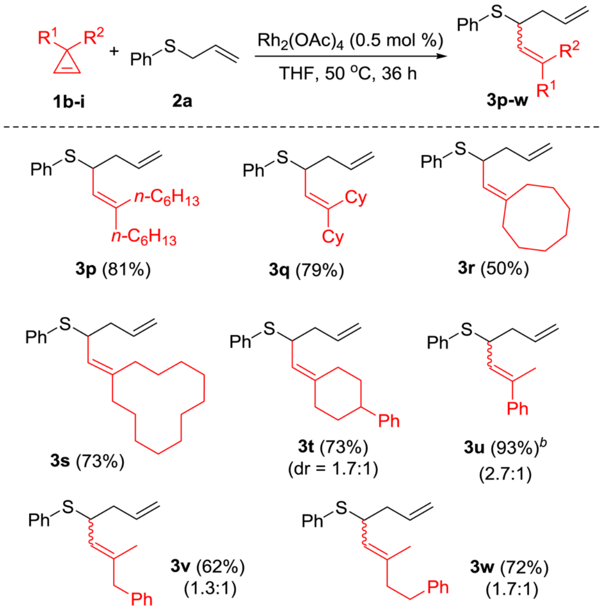
Next, we examined the scope of cyclopropenes. A series of 3,3-disubstituted cyclopropenes **1b**–**i** were examined (Scheme 3). For cyclopropenes **1b**–**e** the reaction all gave the corresponding products in good yields, but prolonging the reaction time was necessary in these cases. However, phenyl-substituted spiro cyclopropene **1f** produced a 1.7:1 mixture of diastereomers in 73% yield. On the other hand, the reaction of cyclopropenes **1g**–**i**, which bears two different substituents, afforded the mixture of

Scheme 2. Scope of Allylic Sulfides[a]



[a] Reaction conditions: **1a** (0.30 mmol), **2b**–**o** (0.90 mmol), and $Rh_2(OAc)_4$ (0.5 mol %) in THF (0.2 mL) at 50 °C for 18 h. All the yields refer to the isolated yields by column chromatography.

Scheme 3. Scope of Cyclopropenes[a]

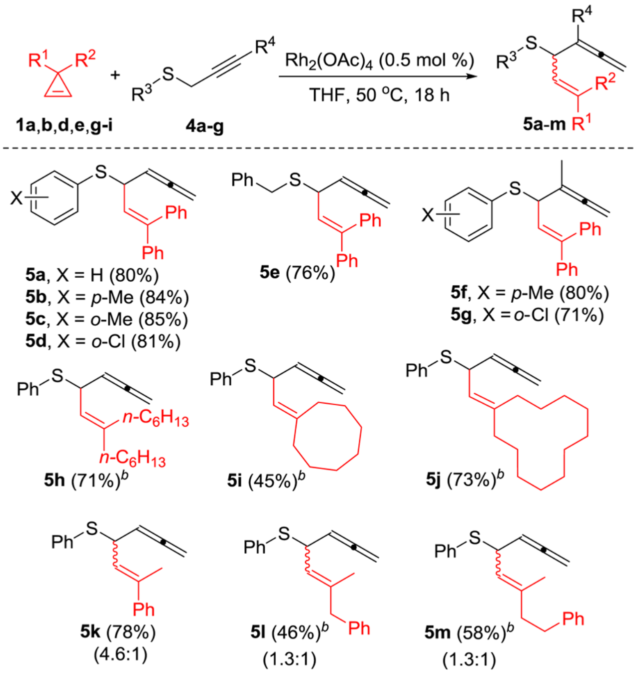


[a] Reaction conditions: **1b**–**i** (0.30 mmol), **2a** (0.90 mmol), and $Rh_2(OAc)_4$ (0.5 mol %) in THF (0.2 mL) at 50 °C. All of the yields refer to the isolated yields by column chromatography. [b] The reaction time is 18 h.

E- and *Z*-isomeric products **3u−w** in an essentially nonselective manner.

Encouraged by these results, we further turned our attention to explore the reaction of cyclopropenes with propargylic sulfides. Gratifyingly, various allenyl-substituted sulfides **5a−m** were obtained as the anticipated products (Scheme 4). Aryl propargyl sulfides were reacted smoothly with cyclopropene **1a**, affording the corresponding products in good yields (**5a−d**). Benzyl propargyl sulfide was also the suitable substrate for the reaction (**5e**). It is worth mentioning that the desired disubstituted allene products **5f** and **5g** were also obtained in 80% and 71% yields. Next, the scope of the cyclopropenes was examined by using phenyl propargyl sulfide **4a** as the substrate. Allene products **5h−j** were obtained as single stereoisomers in moderate to good yields, and cyclopropene **1g−i** afforded the mixture of *E*- and *Z*-isomeric products **5k−m**.

Scheme 4. Reactions of Cyclopropenes and Aryl Propargylic Sulfides[a]



[a] Reaction conditions: **1a,b,d,e,g−i** (0.30 mmol), **4a−g** (0.90 mmol), and Rh$_2$(OAc)$_4$ (0.5 mol %) in THF (0.2 mL) at 50 °C. All of the yields refer to the isolated yields by column chromatography. [b] The reaction time is 36 h.

Unexpectedly, the reaction of cyclopropene **1a** with 2-thienyl propargyl sulfide **4h** failed to give the desired allene product **5n**; instead, a cyclic product **6a** was isolated in 54% yield (Scheme 5, eq 1). This product is likely to be formed by ring closure of intermediate allene product **5n** under Lewis acid conditions. 2-Naphthyl propargyl sulfide **4i** also afforded the similar ring-closure product **6b** in 64% yield (Scheme 5, eq 2).

Finally, we attempted the asymmetric catalysis of this [2,3]-sigmatropic rearrangement of sulfur ylides with chiral Rh(II) catalysts. Cyclopropene **1a** and phenyl allyl sulfide **2a** were chosen as the substrates, and a series of commercially available chiral Rh(II) catalysts were screened (Table 2). All of the catalysts afforded the products in excellent yields. However, the enantioselectivities were only low to moderate (Table 2, entries 1−6). Lowering the reaction temperature did not significantly improve the result (Table 2, entry 7).

Scheme 5. Reactions of Cyclopropene 1a with Aryl Propargylic Sulfides 4h and 4i

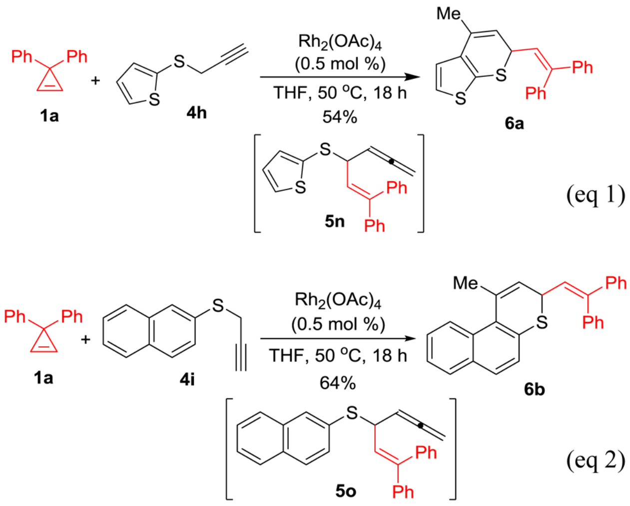
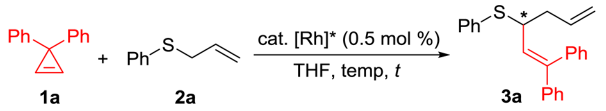


Table 2. Asymmetric [2,3]-Sigmatropic Rearrangement of Sulfur Ylides[a]

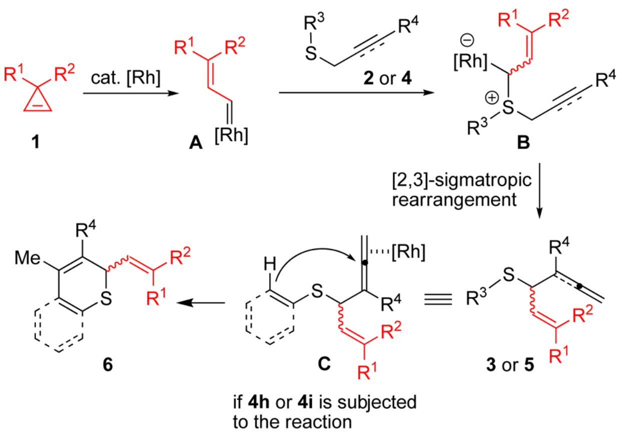


entry	cat. [Rh]*	temp (°C)	time (h)	yield[b] (%)	ee[c] (%)
1	Rh$_2$(*S*-TBSP)$_4$	50	18	96	15
2	Rh$_2$(*S*-DOSP)$_4$	50	18	94	16
3	Rh$_2$(4*S*-MEAZ)$_4$	50	18	89	33
4	Rh$_2$(5*S*-MEPY)$_4$	50	18	94	48
5	Rh$_2$(4*S*-MEOX)$_4$	50	18	98	29
6	Rh$_2$(4*S*-MPPIM)$_4$	50	18	82	16
7	Rh$_2$(5*S*-MEPY)$_4$	30	36	93	53

[a] Reaction conditions: **1a** (0.30 mmol), **2a** (0.90 mmol), and catalyst (0.5 mol %) in THF (0.2 mL). [b] All of the yields refer to the isolated yields by column chromatography. [c] Enantiomeric excess values were determined by chiral HPLC; Chiracel OD; hexane.

A plausible mechanism is proposed in Scheme 6. Cyclopropene **1** is activated by rhodium catalyst, which generates intermediate **A** through ring-opening of the cyclopropene

Scheme 6. Proposed Reaction Mechanism



moiety. The vinyl rhodium carbene **A** in situ generated from cyclopropenes is trapped by sulfide **4**, resulting in the formation of intermediate **B**. Then the allene product **5** is formed through typical [2,3]-sigmatropic rearrangement of sulfur ylide. In the case when the R^3 group is electron-rich aromatic or heteroaryl ring, subsequent ring closure of C occurs to lead to the final ring-closure product **6**, as shown in Scheme 5, eqs 1 and 2.

In summary, a new type of $Rh_2(OAc)_4$-catalyzed [2,3]-sigmatropic rearrangement of sulfur ylides has been developed. A series of cyclopropenes have been successfully used for the [2,3]-sigmatropic rearrangement by reaction with either allylic or propargylic sulfides, and the corresponding sulfide products can be obtained in good to excellent yields. The results significantly extend the chemistry of vinyl metal carbenes that are generated in situ from the cyclopropenes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experiment details, characterization data, X-ray crystallographic data for **3m**, and ^1H and ^{13}C NMR spectra for all products. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b01542.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This project was supported by the 973 program (2012CB821600) and the NSFC (Grant Nos. 21272010 and 21332002).

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