Organic reactions mediated by electrochemically generated ArS+.

Matsumoto, Kouichi; Suga, Seiji; Yoshida, Jun-ichi


© The Royal Society of Chemistry 2011; この論文は出版社版ではありません。引用の際には出版社版をご確認ご利用ください。This is not the published version. Please cite only the published version.
Organic reactions mediated by electrochemically generated \( \text{ArS}^+ \)

Kouichi Matsumoto, a Seiji Suga b and Jun-ichi Yoshida a

5 Low-temperature electrochemical oxidation of \( \text{ArSSAr} \) was carried out to generate a pool of \( \text{ArS}^+ \). Spectroscopic studies (\(^1\)H NMR and CSI-MS) of the resulting solution revealed the accumulation of \( \text{ArS(ArSSAr)}^+ \). The resulting \( \text{ArS}^+ \) pool reacted with alkenes and alkynes to give diarylthio-substituted products. \( \text{ArS}^+ \) pool rapidly reacted with thiaoacetals to give the corresponding alkoxy carbeneium ion pools, which reacted with various carbon nucleophiles (indirect cation pool method). The reaction of the alkoxy carbeneium ion pools with stilbene derivatives in the presence of \( \text{ArSSAr} \) gave thiocroman derivatives. In addition to such stoichiometric reactions, a catalytic amount of \( \text{ArS}^+ \) serves as an initiator and a chain carrier of some cationic chain reactions involving intramolecular carbon-carbon bond formation. In-situ generation of \( \text{ArS}^+ \) by electrochemical oxidation of \( \text{ArSSAr} \) with a catalytic amount of electricity in the presence of a substrate is also effective for such cationic chain reactions.

1 Introduction

Organic electrochemistry 1 provides a straightforward, efficient, and tunable method for making and modifying organic molecules under mild conditions. The advantages of this method lie in its ability to oxidize or reduce organic compounds of a wide range of oxidation and reduction potentials selectively generating highly reactive intermediates that are useful in organic synthesis. 2 It is also noteworthy that electrochemical processes are applicable to organic compounds bearing a variety of functional groups, because they usually proceed without using strong acids or bases. Based on such features, many synthetic transformations that are unique to electrochemistry have been developed so far. Thus, the electrochemical method opens new possibilities of synthesizing organic molecules of interesting functions and biological activities.

In general, the electrochemical methods are mainly classified into the following three types (Scheme 1): 3 the direct method, the in-cell indirect method, and the ex-cell indirect method. In the direct electrochemical method, substrate A undergoes the electron transfer directly on the surface of the electrode to give product B. In the in-cell indirect electrochemical method, a mediator X undergoes the electron transfer on the surface of the electrode, and the resulting reactive species Y reacts with substrate A in situ to give product B, regenerating X. In the ex-cell indirect electrochemical method, 4 the direct electrochemical reaction of X is carried out to generate and accumulate reactive species Y in the first step. In the next step, Y is reacted with substrate A in the absence of electricity to give product B.

We have developed the ‘cation pool’ method in which highly reactive onium ions and carbocations are generated and accumulated by low-temperature electrochemical oxidation. 5 In the next step, the resulting reactive cations are reacted with carbon nucleophiles to obtain the corresponding carbon-carbon bond formation products. We also developed the ‘cation flow’ method, in which reactive cations are generated and reacted with nucleophile in a flow system. 6 Recently, we have shown that a similar method can be applied to generation and reaction of highly reactive reagents 7 and catalysts. This approach widens the scope of the ex-cell indirect electrochemical method. In this perspective article, we overview our recent studies on a new ex-cell indirect electrochemical method using \( \text{ArS}^+ \) generated by low-temperature electrochemical oxidation of \( \text{ArSSAr} \).

Department of Synthetic Chemistry and Biological Chemistry, Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8510, Japan. E-mail: yoshida@schem.kyoto-u.ac.jp; Fax: (+81) 75-383-2727; Tel (+81) 75-383-2766

a Current address: Faculty of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, Osaka 577-8502, Japan. E-mail: kmatsuom@chem.kindai.ac.jp; Fax: (+81) 6-6730-5890 ext4126; Tel (+81) 6-6730-2721

b Current address: Division of Chemistry and Biochemistry, Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama 700-8530, Japan. E-mail: suga@cc.okayama-u.ac.jp; Fax: (+81) 86-251-8081; Tel (+81) 86-251-8081

Kouichi Matsumoto was born in 1982 in Nara, Japan. He received his Ph.D. from Kyoto University in 2010 under the supervision of Prof. Jun-ichi Yoshida. In 2010 he joined the group of Prof. Shigenori Kashimura at Kinki University as an Assistant Professor. His current research interests include electro-organic chemistry.

Seiji Suga was born in 1963 in Hiroshima. He received his Ph.D. from Nagoya University under the supervision of Prof. Ryoji Noyori. He became a postdoctoral fellow (JSPS Postdoctoral Fellowships for Research Abroad) with Prof. Jack E. Baldwin at Oxford University. In 1996 he joined the group of Prof. Jun-ichi Yoshida at Kyoto University as Instructor, and was promoted to Lecturer (1999) and Associate Professor (2004). In 2008 he was appointed as Professor at Okayama University. His current research interests include electron-transfer reactions and synthetic processes of organic compounds.
2 Generation of "ArS" by low-temperature electrochemical oxidation of ArSSAr and its characterization by spectroscopic studies

"ArS" is considered to be a highly electrophilic reagent, although some doubts have been advanced of its existence in this form in the solution phase. Extensive studies on the chemical methods for generating "ArS" have been reported in the literature, which include chemical oxidation of ArSSAr and the reactions of Ar-S-X with Lewis acids. The electrochemical oxidation of ArSSAr serves as a useful method for generating "ArS" (Scheme 2). The radical cation of ArSSAr produced by one electron oxidation of ArSSAr undergoes the cleavage of the sulfur-sulfur bond to give ArS+ and ArS-. ArS+ is further oxidized to give ArS++. Thus, the electrochemical generation, in principle, does not produce any by-products, and therefore is superior to the chemical generation, which uses toxic oxidizing reagents and produces byproducts derived from them.

Scheme 1. Classification of electrochemical methods.

Scheme 2. Electrochemical oxidation of ArSSAr.

The nature and the reactivity of electrochemically generated "ArS" depend on the electrolysis conditions (solvent, supporting electrolyte and temperature etc.). Simonet and co-workers assumed that ArS+ is electrochemically generated as an intermediate in CH2Cl2, whereas they assumed that ArSSAr2+ is generated in CH2CN. On the other hand, Tsuchida and co-workers reported the synthesis of oligo(p-phenylene sulfide) (OPS) under acidic conditions. Presumably electrochemically generated ArS+ reacted with ArSSAr via Friedel-Crafts type reactions. In this case, ArS(ArSSAr)+ is suggested as an intermediate. Thus, there are several arguments on the chemistry of ArS++. Therefore, the characterization of electrochemically generated ArS++ has received significant research interest.

The electrochemical oxidation of ArSSAr (oxidation potential: 1.47 V (Ar = p-FC6H4)) is usually carried out in an H-type cell equipped with a carbon felt anode and a platinum plate cathode (Fig. 1). In the anodic chamber is placed a solution of ArSSAr (0.4 mmol) in 0.3 M Bu4NBF4/CH2Cl2 (8 mL). In the cathodic chamber are placed 0.3 M Bu4NBF4/CH2Cl2 (8 mL) and trifluoromethanesulfonic acid (TFOH) (0.27 mmol) to facilitate the reduction of protons in the cathodic process. The constant current electrolysis (8 mA) is carried out at −78 °C with magnetic stirring.

Jun-ichi Yoshida was born in Osaka, Japan in 1952. He graduated from Kyoto University in 1975, where he received his doctor’s degree under the supervision of Prof. Makoto Kamada in 1981. In 1979 Yoshida joined the faculty at Kyoto Institute of Technology as an Assistant Professor. In the meantime, he visited University of Wisconsin during 1982-1983, where he joined the research group of Prof. B. M. Trost. In 1985 he moved to Osaka City University, where he was promoted to an Associate Professor in 1992. In 1994 he was appointed as a full Professor of Kyoto University. Awards: the Progress Award of Synthetic Organic Chemistry, Japan (1987), the Chemical Society of Japan Award for Creative Work (2001), Nagoya Silver Medal (2006), Humboldt Research Award (2007), Green and Sustainable Chemistry Award (2010), and Dogane Award (2010). His research interests include integrated synthetic reactions on the basis of reactive intermediates, organic electron transfer reactions, organometallic reactions, and microreactors.

Jun-ichi Yoshida

Fig. 1 An electrochemical apparatus consisting of an H-type divided cell and DC power supply for generation of "ArS" by the oxidation of ArSSAr at −78 °C.

1H NMR (−80 °C) spectrum of the anodic solution obtained by the electrochemical oxidation of ArSSAr (Ar = p-FC6H4) in Bu4NBF4/CD2Cl2-CH2Cl2 at −78 °C (0.67 F/mol) showed a spectrum similar to that of ArS(ArSSAr)+ generated by the reaction of ArSSAr and SbCl5. CSI-MS (cold-spray ionization mass spectroscopy) (6) (spray temperature: 0 °C) provided strong evidence for the formation of ArS(ArSSAr)+ (m/z = 381) (Fig. 2). Therefore, it was concluded that ArS(ArSSAr)+ was the species that was generated and accumulated by the low temperature electrolysis of ArSSAr in Bu4NBF4/CH2Cl2. In fact, 0.67 F/mol is the theoretical amount of electricity to convert ArSSAr to ArS(ArSSAr)+.


3 Stoichiometric reactions

3.1 Reactions with alkenes and alkynes

The electrochemically generated ArS(ArSSAr)\(^{+}\)BF\(_4\)\(^{-}\) rapidly reacts with an alkene even at low temperatures.\(^{17}\) For example, the reaction of ArS(ArSSAr)\(^{+}\)BF\(_4\)\(^{-}\) with 1-methylcyclohexene at \(-78^\circ C\) followed by quenching with MeOH as a nucleophile afforded adduct 1 (Markovnikov product) in 68% yield (Scheme 3). Presumably, the reaction proceeded by initial formation of an episulfonium ion intermediate.\(^{18}\) A MeO group was introduced on the tertiary carbon, suggesting that MeOH attacked a partially developed carbocationic center. It is also noteworthy that the \(\textit{anti}\) addition product was obtained exclusively. These observations are quite similar to those obtained for \(\text{ArS}^-\) generated by other methods in the absence of ArSSAr.\(^{11}\) The use of H\(_2\)O as a quenching nucleophile led to the formation of 2 in a similar manner (Scheme 3).

![Scheme 3](image)

**Scheme 3.** The reactions of ArS(ArSSAr)\(^{+}\)BF\(_4\)\(^{-}\) (Ar = p-FC\(_6\)H\(_4\)) with 1-methylcyclohexene followed by addition of a quenching nucleophile.

However, the use of ketene silyl acetal 3 as a quenching nucleophile led to \(\textit{anti}\) addition of two ArS groups to give compound 5. No appreciable carbon–carbon bond formation took place.\(^{19}\) The formation of 5 indicated that ArSSAr attacked the episulfonium ion as a nucleophile. Use of an allylsilane, such as 4 as a quenching nucleophile also gave rise to the formation of 5. Et\(_3\)N was also found to be an effective quenching nucleophile (Scheme 4). Diarylthio-substituted compounds were obtained in good yields (6-9). The stereoselectivity of the reactions was high, and \(\textit{anti}\) addition products were obtained. Although several methods for this type of transformation have been reported in the literature,\(^{20}\) the present method serves as an alternative convenient way to access such compounds.

![Scheme 4](image)

**Scheme 4.** The reactions of ArS(ArSSAr)\(^{+}\)BF\(_4\)\(^{-}\) (Ar = p-FC\(_6\)H\(_4\)) with alkenes at \(-78^\circ C\) using Et\(_3\)N as a quenching nucleophile.

Although the reaction mechanism has not yet been fully clarified, the following mechanistic arguments seem to be reasonable (Scheme 5). In the first step, episulfonium ion intermediate\(^{19}\) 10 is generated by the reaction of ArS(ArSSAr)\(^{+}\) with an alkene. Nucleophilic attack of ArSSAr on 10 opens the three-membered ring to give sulfonium ion intermediate 11. There is an equilibrium between 10 and 11. A hard quenching nucleophile such as MeOH or H\(_2\)O selectively attacks 10 to give the corresponding product 12 (pathway I). On the other hand, a soft quenching nucleophile such as ketene silyl acetal 3, allylsilane 4, and Et\(_3\)N selectively attacks 11 to cleave the S–S bond giving diarylthio-substituted compound 13 as the final product (pathway II).

![Scheme 5](image)

**Scheme 5.** Plausible reaction mechanism (Nu = nucleophile).

It is interesting that the reactions of ArS(ArSSAr)\(^{+}\)BF\(_4\)\(^{-}\) with alkenes at higher temperatures give thiofluorinated product exclusively.\(^{21,22}\) For example, thiofluorinated compound 14 was obtained exclusively in the reaction with 1-octene at 0 °C, whereas the reaction at \(-78^\circ C\) gave diarylthio-substituted compound 7 as shown in Scheme 6.\(^{23}\) In this case, a fluoride ion, which is derived from the anionic part of supporting electrolyte (BF\(_4\)\(^{-}\)), attacked the episulfonium ion intermediate 10 as a nucleophile before a quenching reagent was added to the reaction mixture (Scheme 5).
transferred to another location to be used in the subsequent reaction with a nucleophile before it decomposes, has been developed. However, there is another way to solve the problem, which is based on the ex-cell indirect electrochemical method. In this method, a highly reactive reagent is once generated and accumulated electrochemically and is subsequently allowed to react with a precursor to generate an organic cation rapidly. Because the process of generating an organic cation takes place in a homogeneous solution, it could be completed in a short period. Therefore, the decomposition of unstable organic cations might be avoided. For example, the combination of thioacetics as precursors and ArS(ArSSAr) as a cation-generating reagent seems to be suitable for rapid generation of alkoxy carbene ions, because ArS(ArSSAr) is considered to be highly thiophilic.

Thus, ArS(ArSSAr) is generated by the electrochemical oxidation of ArSSAr (Ar = p-FC₆H₄) in Bu₄NBF₄/CH₂Cl₂ at –78 °C (step 1) (Scheme 8). The resulting solution is reacted with a thioacetal 20 to generate the corresponding alkoxycarbene ion 21 (step 2). This process requires only 5 min at –78 °C. In the third step, allytrimethylsilane (2 equiv) is added to obtain the final product 22 in 90% yield (step 3).

The formation of 21 was confirmed by NMR spectroscopy at –80 °C (Scheme 8). A solution obtained by the reaction of 20 with the electrochemically generated ArS(ArSSAr)BF₄⁻ (Ar = p-FC₆H₄) exhibited signals at 9.53 and 4.92 ppm due to the methine proton and methyl protons, respectively (¹H NMR), and a signal at 230.6 ppm due to the methine carbon (¹³C NMR). These chemical shifts were quite similar to those obtained by the direct electrochemical oxidation of CsH₅CH(OMe)SiMe₃ (9.55, 4.95 and 231.0 ppm). Such similarity in chemical shifts indicated that the sulfur-containing by-products, such as PhSSAr and ArSSAr, which should be present in the solution, did not change the nature of alkoxycarbene ion 21 appreciably.

The detailed mechanism for the reaction of 20 with ArS(ArSSAr)⁺ (step 2) has not been clarified as yet, but 21 seems to be generated according to Scheme 9. Although the possibility of a single electron-transfer mechanism cannot be ruled out, ionic mechanism seems to be more plausible. In the ionic mechanism, ArS(ArSSAr)⁺ acted as a thiophilic Lewis acid.

3.2 Reactions with thioacetics followed by reactions with carbon nucleophiles (indirect cation pool method)

In the “cation pool” method, carbocations stabilized by a neighboring heteroatom such as nitrogen (N-acyliminium ions), 24 oxygen (alkoxycarbene ions) 25 and aryl groups (diaryl carbene ions) 26 are generated and accumulated by low-temperature electrochemical oxidation of corresponding carbanions, α-silyl ethers and diarylmethanes, respectively in the absence of nucleophiles. In the next step, the accumulated organic cations are subjected to reactions with carbon nucleophiles to give the corresponding carbon-carbon bond formation products.

The first generation of the “cation pool” method uses the direct electrochemical method. Because direct electrochemical reactions take place only on the surface of the electrode, the electrochemical generation of a cation pool on a preparative scale usually takes several hours. Therefore, the applicability of the “cation pool” method using the direct electrochemical method strongly depends on the stability of the cation that is accumulated. Therefore, highly unstable cations might decompose during the course of the accumulation. The “cation pool” method suffers from this problem.

To solve the problem, the “cation flow” method, 5 in which an unstable organic cation is generated in a flow system and
The reactions of thioacetals with conventional Lewis acids such as BF₃·OEt₂ and SnCl₄ do not give the corresponding alkoxycarbenium ions under similar conditions. Presumably such Lewis acids are not strong enough to generate alkoxycarbenium ions in a significant concentration. The equilibrium between 20 and 21 lies to 20 in such cases. In fact, Denmark and co-workers could not observe an alkoxycarbenium ion in low-temperature ¹H NMR studies of a mixture of an acetal and a conventional Lewis acid, but they observed a Lewis acid–acetal complex.

Much lower reactivity of BF₃·OEt₂ was confirmed by the following experiments. The reaction of thioacetal 20 with BF₃·OEt₂ in 5 min followed by treatment with allyltrimethylsilane in 1 min at −78 °C did not give 22 in an appreciable amount (Scheme 10).

![Scheme 10](image)

The stereochemistry of the present reaction is interesting. The reaction with cis-stilbene gave 34 in 65% as a mixture of 33 and 32, while the reaction with trans-stilbene gave 34 in 70% as a mixture of 33 and 32.

![Fig. 4](image)

### 3.3 Reactions with thioacetals followed by reactions with alkenes. Synthesis of thiochromans

A pool of the alkoxycarbenium ion prepared by the “indirect cation pool” method reacts with stilbene derivatives to give thiochroman derivatives 34 (Scheme 12). In this case ArSSAr, which is present in the solution, participates in the reaction.

![Scheme 12](image)
two diastereomers (d.r. = 2.6:1). The reaction of trans-stilbene exhibited similar diastereoselectivity (70%, d.r. = 2.8:1). The diastereoselectivity indicates that the reaction proceeds by a step-wise mechanism rather than a concerted mechanism. The mechanism shown in Scheme 13 seems to be reasonable. Alkoxycarbenium ion 21 adds to the carbon-carbon double bond of stilbene to generate cation 35. Cation 35 reacts with ArSSAr to give intermediate 36. The elimination of MeO group in 36 generates cation 37, which cyclizes to give 34.

Scheme 13. The plausible reaction mechanism.

Various alkoxycarbenium ion pools (R = Ph, p-ClC₆H₄, PhCH₂CH₂, cyclohexyl) generated and accumulated from the corresponding thioacetals are effective for synthesizing substituted thiocromans (38-41) (Fig. 5).

Fig. 5 Synthesis of thiocroman derivatives by the reaction of alkoxycarbenium ion pools with cis-stilbene and ArSSAr (Ar = p-FC₆H₄).

Because compounds having the thiocroman skeleton show interesting biological activities, several methods for synthesizing the thiocromane derivatives have been developed. 33 For example, Ishibashi and co-workers reported the method based on the reaction of phenylthionium ion with olefins. 34 Ishino and co-workers have developed the method based on intermolecular cycloaddition of α,β-unsaturated aldehydes and thiophenols. 35 Although these literature methods are based on the coupling of two different components, the present method is based on the coupling of three components, an alkoxycarbenium ion, a stilbene derivative, and ArSSAr, and therefore the present method serves as a more flexible way for constructing a thiocroman skeleton.

4 Catalytic reactions

A chain reaction is a sequence of the reaction, where a reactive product or by-product causes the next sequence to take place. 66 Radical chain reactions 37 are extensively studied so far. However, cationic chain reactions are not so popular in organic chemistry.

Doyle and co-workers reported the first example of cationic chain reactions via hydride transfer. 68 INIFER (INIFER-initiator transfer) method developed by Kennedy and Smith is also recognized as a cationic chain reaction. 69 However, to the best of our knowledge, a cationic chain reaction mediated by organic cations such as ArS⁺ had not been developed when we initiated our studies on reactions using a catalytic amount of ArS⁺ as an initiator and a chain carrier.

4.1 Cation chain reactions of involving cyclization of dienes

We have already discussed the addition of ArSSAr to alkenes using a stoichiometric amount of ArS(ArSSAr)₄. 70 The reaction proceeds by adding a soft quenching nucleophile such as Et₃N (Scheme 4). If ArSSAr plays a role as a soft nucleophile, the last step regenerates ArS⁺, which causes the next sequence to take place (Scheme 5, soft nucleophile = ArSSAr). If we use B(C₆F₅)₄ as a counter anion of ArS(ArSSAr)₄, this is the case. For example, (Z)-1-phenylpropene reacts with ArSSAr in the presence of a catalytic amount of ArS(ArSSAr)₄B(C₆F₅)₄ to give diarylthio-substituted product 9 (Ar = p-FC₆H₄; 70%), 42 (Ar = p-MeOC₆H₄; 59%) (Scheme 14). 40 The reaction of (E)-1-phenylpropene also gives the corresponding diarylthio-substituted compounds (43 (Ar = p-FC₆H₄; 79%), 44 (Ar = p-MeOC₆H₄; 77%)). It is important to note that the use of B(C₆F₅)₄ as a counter anion is essential for the success of this catalytic process. Therefore, Bu₃NB(C₆F₅)₄ as a supporting electrolyte should be used for the electrochemical oxidation of ArSSAr to generate ArS(ArSSAr)₄B(C₆F₅)₄.

Scheme 14. The reaction of 1-phenylpropene with ArSSAr in the presence of a catalytic amount of ArS(ArSSAr)₄B(C₆F₅)₄. 70

With this information in hand, the cyclization reaction of non-conjugate dienes using a catalytic amount of ArS(ArSSAr)₄B(C₆F₅)₄ in the presence of ArSSAr has been developed (Scheme 15). For example, 1-phenyl-1,2-dimethyl-1,6-diene 45 reacted with 0.2 equiv of ArS(ArSSAr)₄B(C₆F₅)₄ in the presence of ArSSAr (Ar = p-MeOC₆H₄). The cyclized product 46 was obtained in 77% yield as a mixture of two diastereomers, although compound 47 that would be formed via another mode of cyclization, was not obtained. 81,82 The observed cyclization mode is consistent with the nucleophilicity parameters reported by Mayr and co-
workers. According to their parameters, trialkyl-substituted alkenes are more nucleophilic than \( \beta \)-methylstyrene.

To the best of our knowledge, the present reaction is the first example that the addition of organic disulfide to non-conjugate dienes involving intramolecular carbon-carbon bond formation.

\[
\text{ArSSAr} + \underbrace{\text{BuNB(C}_6\text{F}_3)_4}_{(0.2 \text{ equiv})}\rightarrow \text{ArS(ArSSAr)}^+\text{B(C}_6\text{F}_5)_4^-;
\]

\[
\text{Scheme 15. ArS(ArSSAr)}^+\text{B(C}_6\text{F}_5)_4^- \text{ initiated addition of ArSSAr to dienes via intramolecular C-C bond formation.}
\]

The reaction seems to proceed by a mechanism shown in Scheme 16. The \( \text{ArS}^+ \) (= ArS(ArSSAr)) reacts with the more nucleophilic carbon-carbon double bond in 45 to give episulfonium ion 48. The other carbon-carbon double bond attacks the episulfonium ion carbon to give cyclized cation 50, which reacts with ArSSAr to give 46. The final step regenerates \( \text{ArS}^+ \), which causes the next sequence to take place.

\[
\text{Scheme 16. Mechanism of } \text{ArS}^+ (= \text{ArS(ArSSAr)}) \text{ initiated addition of ArSSAr to dienes via intramolecular C-C bond formation.}
\]

The benzylic ArS group in 46 could be selectively removed by the electrochemical reduction, which gave 51 as a single diastereomer (Scheme 17). This stereochemical information suggests that the cyclization proceeds by transition state 49 (Scheme 16), where a carbon-carbon double bond attacks the episulfonium ion from the back side.

\[
\text{Scheme 17. Electroreductive removal of benzylic ArS from product 46} (\text{Ar} = \text{p-MeOCH}_3\text{H}_2).
\]

The stereochemistry of the carbon-carbon double bond in 45 does not affect the diastereoselectivity of the cyclization (Scheme 18).

\[
\text{Scheme 18. Stereoselectivity of the reaction of 45} (\text{Ar} = \text{p-MeOCH}_3\text{H}_2).
\]

Other non-conjugate dienes such as 52, 54, and 56 also reacted in a similar manner to give the corresponding cyclized products (53, 55, and 57) (Scheme 19).

\[
\text{Scheme 19. Cation chain reactions of various dienes} (\text{Ar} = \text{p-MeOCH}_3\text{H}_2).
\]

The reaction of a catalytic amount of ArS(ArSSAr)\(^+\)B(C\(_6\)F\(_5\))\(^-\) with 54 in the presence of ArSSAr followed by addition of allyltrimethylsilane instead of Et\(_3\)N led to the selective formation of olefinic product 58 (Scheme 20). Presumably, \( \text{ArS}^+ \) that remained in the solution reacted with allyltrimethylsilane to produce highly reactive Me\(_3\)Si\(^+\). Me\(_3\)Si\(^+\) reacted with 55 to cleave C-S bond generating the tertiary carbocation. \( \beta \)-Proton elimination gave 58. The resulting proton reacted with allyltrimethylsilane to regenerate Me\(_3\)Si\(^-\).

\[
\text{Scheme 20. The reaction of 54 with a catalytic amount of ArS(ArSSAr)\(^+\)B(C\(_6\)F\(_5\))\(^-\) followed by adding allyltrimethylsilane} (\text{Ar} = \text{p-MeOCH}_3\text{H}_2).
\]
It is noteworthy that the direct (in-cell) electrolysis\(^3\) of a diene in the presence of ArSSAr was also effective to initiate the reaction. Thus, a catalytic amount of electricity was passed through a solution of \(45\) (0.30 mmol) and ArSSAr (1.0 mmol) (0.20 F/mol based on \(45\)). After the electrolysis, the reaction mixture was stirred for 0.5 h to obtain the cyclized product \(46\) in 82% yield (d.r. = 1.1 : 1). This method can be applicable to other dienes such as \(52\), \(54\), and \(56\) to obtain the corresponding cyclized products (53, 55, and 57).

### 4.2 Cation chain reactions involving cyclization of olefinic thioacetals

In 3.2, we discussed the formation of alkoxycarbenium ions by the reaction of thioacetals with \(\text{ArS}^+\). The cationic chain reaction involving this process has also been developed.\(^{40}\) The general reaction scheme is shown in Scheme 21. The reaction of an alkoxycarbenium ion, which is generated by action of a thioacetal with \(\text{ArS}^+\), with an olefin leads to the formation of the second cation.\(^{31}\) The reaction of the second cation with ArSSAr gives sulfenylated product to regenerate \(\text{ArS}^+\). \(\text{ArS}^+\) would act as an activator of another molecule of the thioacetal. Therefore, the overall reaction should take place with a catalytic amount of \(\text{ArS}^+\).

![Scheme 21](image)

**Scheme 21.** The cation chain reactions involving the formation of alkoxycarbenium ion.

There are several points to be considered.\(^{31}\) The formation of the alkoxycarbenium ion takes place quantitatively as we discussed in 3.2. However, the reaction of the alkoxycarbenium ion with an olefin might be unfavorable because the second cation does not have a neighboring cation stabilizing group such as an oxygen atom, and this step might be a bottle-neck of the overall reaction.\(^{37}\) The last step to form a stable product from the unstable second cation, however, could be energetically favorable, making the overall reaction successful. Another important point to be considered is that the second step could be made entropically favorable by the intramolecularization of the reaction.

The concept works. For example, treatment of thioacetal \(59\) (R = C\(_7\)H\(_5\)), \(\text{Ar} = p\text{-FC}\(_6\)H\(_4\)) bearing a carbon-carbon double bond with 0.2 equiv of \(\text{ArS}(\text{ArSSAr})^+\text{B}(\text{C}_6\text{F}_3)_4^+\) (\(\text{Ar} = p\text{-FC}\(_6\)H\(_4\)) at \(-78^\circ\text{C}\) led to the formation of cyclized compound \(60\) (82%) (Scheme 22).\(^{48}\) In this case, ArSSAr (1.00 mmol) was electrolyzed with 0.04 F/mol of electricity in \(\text{Bu}_4\text{NB}(\text{C}_6\text{F}_3)_4\)\(\text{CH}_2\text{Cl}_2\) at \(-78^\circ\text{C}\), and the resulting solution containing \(\text{ArS}(\text{ArSSAr})^+\text{B}(\text{C}_6\text{F}_3)_4^+\) (0.04 mmol) and ArSSAr (0.94 mmol) was allowed to react with \(59\) (0.2 mmol).

![Scheme 22](image)

**Scheme 22.** The cyclization of olefinic thioacetal with a catalytic amount of \(\text{ArS}(\text{ArSSAr})^+\text{B}(\text{C}_6\text{F}_3)_4^+\).

In section 4.1, we discussed cationic chain reactions of dienes involving intramolecular carbon-carbon bond formation, which is net addition of ArSSAr to dienes. In contrast, this reaction is net isomerization. A cationic chain mechanism shown in Scheme 23 seems to be reasonable.

![Scheme 23](image)

**Scheme 23.** Mechanism of cationic chain reaction of olefinic thioacetal mediated by \(\text{ArS}^+\).

High stereoselectivity observed (exclusive formation of the cis isomer) indicates that the carbon-carbon bond formation and the subsequent reaction of the resulting cation with ArSSAr take place in somewhat concerted manner. The fact that use of an excess amount of ArSSAr accelerated the reaction is consistent with this mechanism. At higher concentrations of ArSSAr, this step becomes more favorable and hence the overall reaction is accelerated.

The reaction is generally applicable to various olefinic thioacetals bearing a carbon-carbon double bond (61, 63, 65, 67, 69, and 71) to give the corresponding cyclized products (62, 64, 66, 68, 70, and 72) as shown in Scheme 24. The present method is useful to construct a tetrahydropyran ring that serves as a popular structural unit in a variety of biologically interesting molecules.\(^{49}\) It is also noteworthy that the \(\text{ArS}\) group could be used for further transformations.
Scheme 24. Intramolecular carbon-carbon bond formation mediated by ArS(ArSSAr)\(^+\)B(C\(_6\)F\(_{14}\))\(_2\).

The \textit{in-cell} method is also effective. The electrolysis of a mixture of an olefinic thiaoaldehyde bearing a carbon-carbon double bond and ArSSAr gives the corresponding cyclized product.\(^7\) The reaction is usually conducted by passing a catalytic amount of electricity (0.20 F/mol based on thiaoaldehyde) through a solution of an olefinic thiaoaldehyde (0.2 mmol) and ArSSAr (1.0 mmol) in 0.1 M Bu\(_4\)NB(C\(_6\)F\(_{14}\))/CH\(_2\)Cl\(_2\) at \(-78\) °C under constant current conditions, and after the electrolysis the reaction mixture is stirred for 20 min to obtain the corresponding cyclized product.

5 Conclusion

Low-temperature electrochemical oxidation of ArSSAr generates ArS\(^{+}\), which has been characterized as ArS(ArSSAr)\(^+\) based on spectroscopic studies such as CSI-MS and \(^1\)H NMR analysis. The resulting ArS(ArSSAr)\(^+\) reacts with carbon-carbon multiple bonds to give diarylthio-substituted compounds and thiofluorinated compounds. ArS(ArSSAr)\(^+\) also serves as an effective reagent for rapid generation of alkoxy carbocation ion pools from thiaoacetals at \(-78\) °C. The resulting alkoxy carbocation ion pools react with carbon nucleophiles to give the corresponding carbon-carbon bond formation products (indirect cation pool method). The reactions of alkoxy carbocationium ions with stilbene derivatives give thiochroman derivatives. In addition to these stoichiometric reactions, ArS(ArSSAr)\(^+\) also promotes catalytic reactions such as cationic chain reactions. For example, the treatment of dienes with a catalytic amount of ArS(ArSSAr)\(^+\) in the presence of ArSSAr leads to net addition of ArSSAr involving intramolecular carbon-carbon bond formation, providing a new type of time and space integration of carbocatic reactions.\(^{30}\) The reaction of olefinic thiaoacetals also gives cyclized products. The \textit{in-situ} generation of a catalytic amount of ArS\(^+\) is also effective for the cationic chain reactions. These stoichiometric and catalytic reactions demonstrate that the electrochemically generated ArS\(^+\) opens a new aspect of chemistry of organic cations\(^31\) and synthetic transformations utilizing organic cations.

Acknowledgments

This work was financially supported in part by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science. We are deeply grateful to Nippon Shokubai Co. and Nippon Chemicals Co. for providing NaB(C\(_6\)F\(_{14}\)) as a precursor of Bu\(_4\)NB(C\(_6\)F\(_{14}\)). We also thank Prof. Hendrik Zipse of Ludwig-Maximilians-Universität in München for fruitful discussions. K.M. acknowledges JSPS for financial support.

References


d chain reactions have been 

S. Isoe, 

Gawara 

S. Isoe, 

K. Fujita and T. Mitsudo, 

Chem. Soc. Jpn., 


