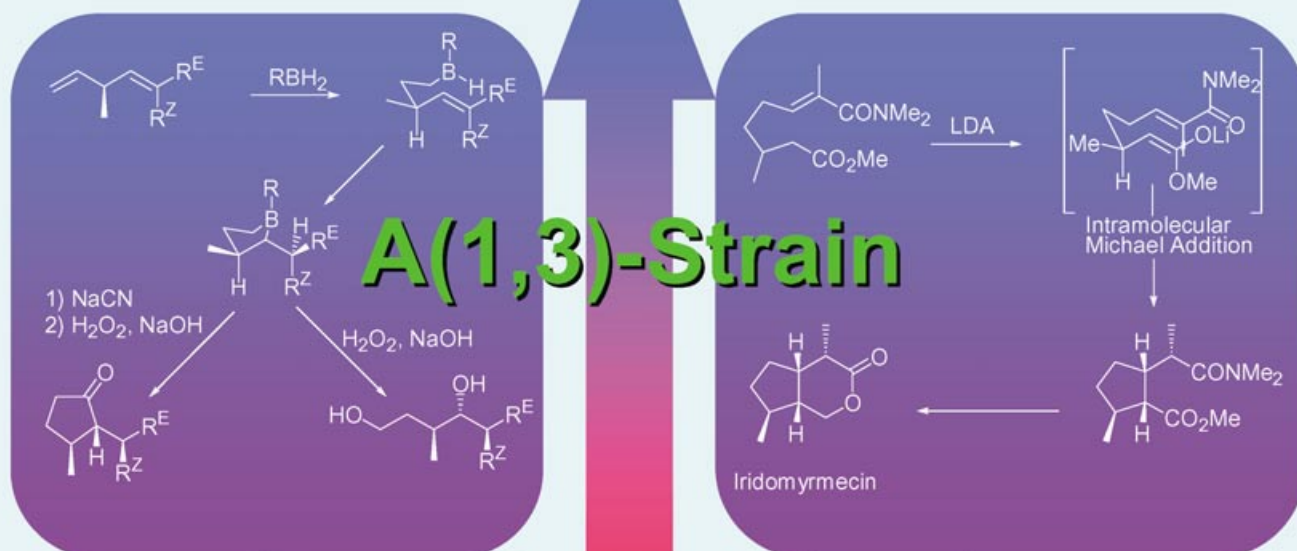


Photoresponsive Materials



Organic Synthesis



Seasoning Materials Chemistry by Using a Well-Matured Organic Concept

Yasushi Yokoyama*^[a]

Dedicated to Professor Amos B. Smith, III and Professor Yukio Kurita

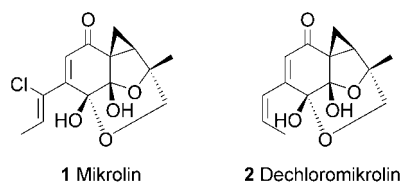
Abstract: The concept “introduction of allylic 1,3-strain (A(1,3)-strain) to photochromism” originated from the experience of total synthesis of natural products about 18 years ago, when the author was a post doc. It was first applied to synthetic organic reactions, then it was successfully employed in the diastereoselective photochromic reactions of diarylethenes. A diastereomeric excess of the photoreaction was 88% for the first example, and it was improved to 94% by the recent operation of rational molecular tailoring.

Keywords: allylic compounds • allylic strain • diastereoselectivity • photochromism

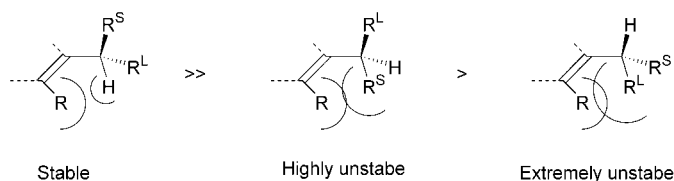
Introduction

Knowledge and experience of chemistry carried out a long time ago may give a chemist a new idea in a considerably different category.

During the period of August 1985 through September 1986, the author was a post doc working with Professor Amos B. Smith, III at University of Pennsylvania, Philadelphia (USA), in the field of total synthesis of architecturally novel, biologically important natural products; mikrolin **1** and dechloromikrolin **2**, for which Dr. Donna M. Huryn started the total synthesis. Early in January 1986, I was struggling with the stereocontrolled construction of vicinal asymmetric carbon



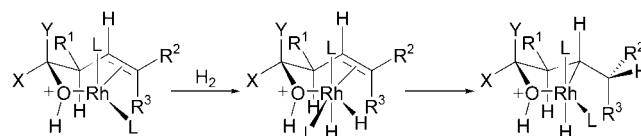
atoms in an intermediate compound needed for the synthesis of **1** and **2**. One day Professor Smith gave me



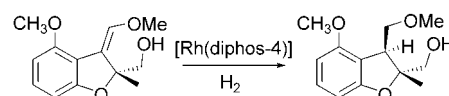
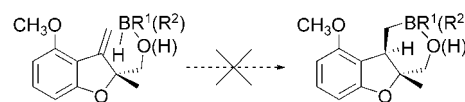
Scheme 1.

papers by Brown et al. and Evans et al. dealing with the hydroxyl-directed hydrogenation of olefins using the [Rh(diphos-4)]⁺ catalyst.^[1] From one of these papers,^[1a] I learned about allylic 1,3-strain (A(1,3)-strain).^[2,3] A(1,3)-strain works around a double bond as shown in Scheme 1. The strain between R and the substituent on the allylic carbon atom on the other side of the double bond is so severe that the smallest substituent (hydrogen in many cases) should face the substituent R. The reaction pathway of the stereoselective hydrogenation governed by A(1,3)-strain reported by Evans is shown in Scheme 2.

Until then, I was trying to introduce a hydroxyl group by an intramolecular hydroxyl-directed hydroboration (Scheme 3). However, all the attempts were unsuccessful, probably because of the reduced Lewis acidity of boron atom by the bonding (or coordinating) oxygen atom and the



Scheme 2.



Scheme 3.

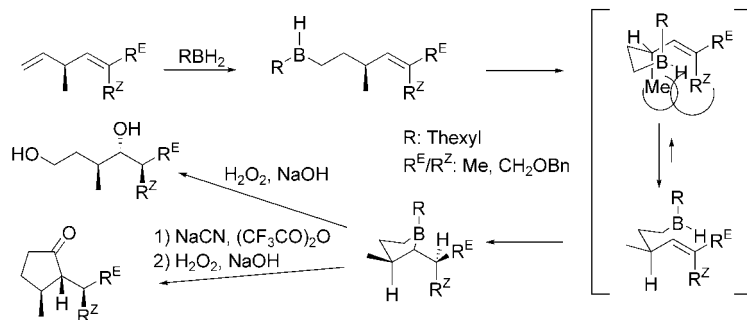
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strained bicyclo[3.1.1] transition state. I employed the Rh-catalyzed hydroxyl-directed hydrogenation on the methoxy-methylene derivative, the key step of the total synthesis, and it afforded the compound with desired stereochemistry almost exclusively (Scheme 3). The completion of the syntheses of mikrolin and dechloromikrolin were done by Dr. Norma K. Dunlap after I went back to Japan in September 1986.^[4]

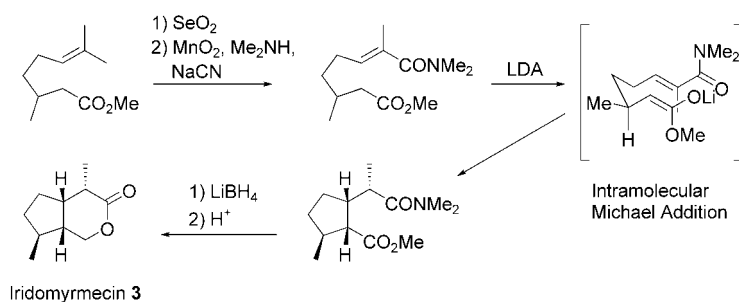
A(1,3)-Strain-Related Organic Synthesis

In the meantime, I was thinking about the intramolecular hydroboration governed by A(1,3)-strain after I went back to Japan. It was the integration of my unsuccessful experiment and a successful concept. There were several precedents reported from the laboratories of Still^[5] and Morgans.^[6] However, most of the reports were dealing with 1,5-dienes. I decided to carry out the A(1,3)-strain-controlled intramolecular hydroboration (cyclic hydroboration) for 1,4-dienes, to produce 1,4-diols as well as cyclopentanones^[7] in a diastereoselective manner (Scheme 4). During the next sev-



Scheme 4.

eral years, our group was concentrating on this kind of chemistry.^[8] The A(1,3)-strain-controlled reaction was not limited to hydroboration. We reported the intramolecular Michael addition, with which we completed a synthesis of a monoterpene lactone iridomyrmecin **3**, possessing four contiguous asymmetric carbon atoms, in as little as five steps from the commercially available methyl citronellate which has only one asymmetric center (Scheme 5).^[9]



Scheme 5.

Photochromism of Fulgides^[10]

Photochromism is defined as “reversible transformation of a single chemical species being induced in one or both directions by electromagnetic radiation between two states having different distinguishable absorption spectra” (Figure 1).^[11] There are two kinds of photochromic com-

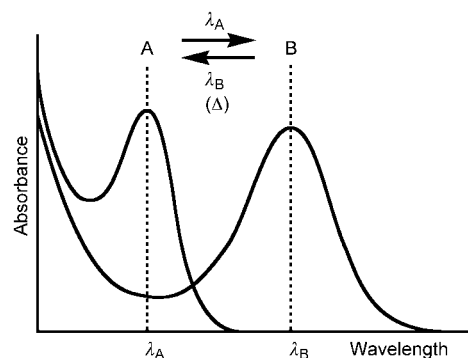


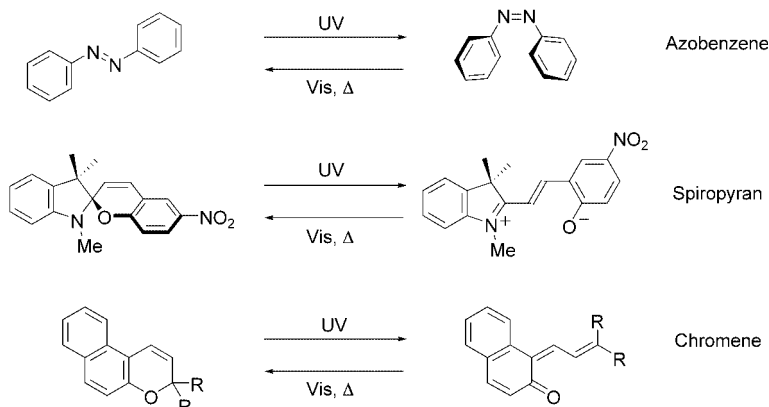
Figure 1. Schematic diagram of photochromism.

pounds. One is thermally reversible, the other thermally irreversible. The former is exemplified by azobenzenes, spiropyrans, and chromenes, and some of them have been commercially used for automatic light-regulating ophthalmic lenses. The latter, exemplified by fulgides,^[10] diarylethenes,^[12] and arylbutadienes,^[13] are candidates to be applied to photon-mode rewritable high-density optical memory media (Scheme 6).

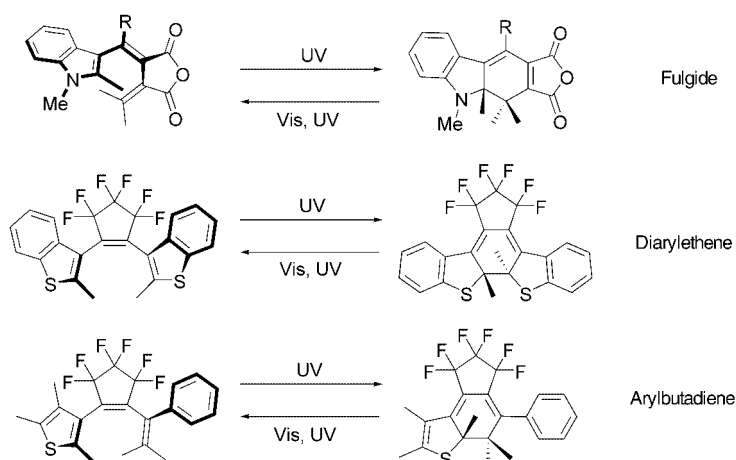
Before I went to Pennsylvania I had been collaborating with Professor Yukio Kurita of our university on the subject of photochromism, mostly on the thermally irreversible photochromic fulgides. Photochromism of fulgides is depicted in Scheme 6.

We have achieved the improvement of photochromic properties of fulgides; establishment of the relationship between the structure and quantum yields,^[14] lengthening of absorption maximum wavelength by introducing electronically influencing substituents,^[15] and control of the ability of photochromism of a dimethylamino-group-containing fulgide by the protonation–deprotonation equilibrium.^[16] The last phenomenon was the earliest example of non-destructive readout of memory when the thermally irreversible photochromic compounds are used for rewritable optical

Thermally Reversible Photochromic Compounds



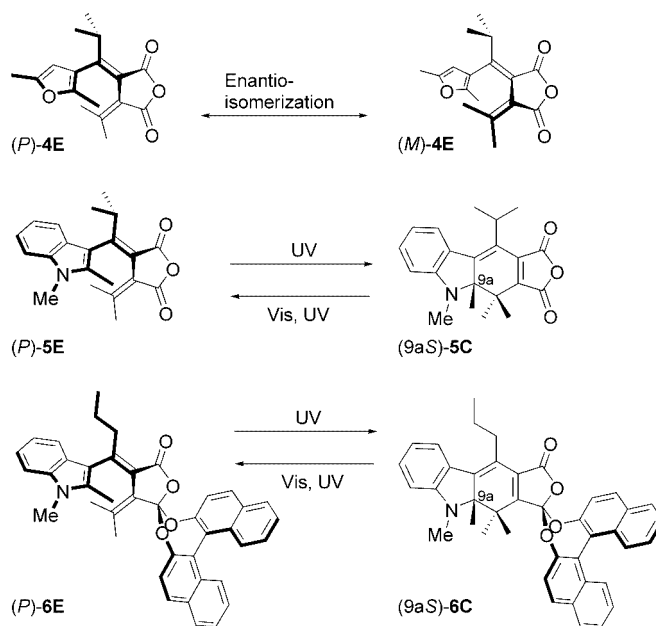
Thermally Irreversible Photochromic Compounds



Scheme 6.

memory media. Readout of memory by light without inducing photochromism (if induced, it is nothing less than the destruction of memory) is still a challenging problem.

Gradually, our interest moved towards the chiral photochromism, because the detection of change in optical rotation at the wavelength out of the absorption bands can be another method of nondestructive readout. We have clarified the racemization (enantioisomerization for a molecule) pathway of the helical structure of the sterically congested hexatriene moiety of furylfulgide **4** between the right-handed screw (*P*: plus) and the left-handed screw (*M*: minus),^[17] done the optical resolution of an indolylfulgide **5** into (*P*) and (*M*) enantiomers,^[18] and constructed a diastereoselective photochromic system with (*R*)-binaphthol-condensed indolylfulgide **6**, which showed the photochemical diastereoselective ring closure (i.e., **6E** with the right-handed (*P*)-helicity gave (9*aS*)-**6C** as the major diastereomer; Scheme 7).^[19] Then, we extended our interest to another series of thermally irreversible photochromic diarylethenes developed by Irie and co-workers.^[12]

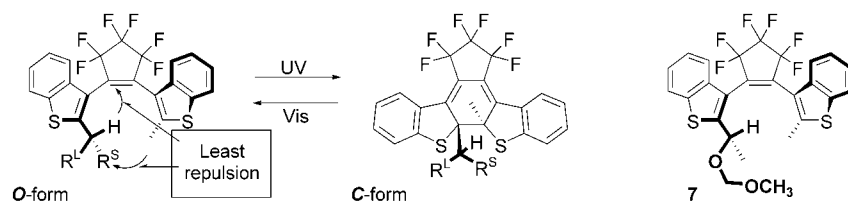


Scheme 7.

Diastereoselective Photochromism of Diarylethenes

Photochromism of diarylethenes, exemplified by bisbenzothienyl-hexafluorocyclopentene in Scheme 6, is also based on the 6π -electrocyclization of 1,3,5-hexatrienes. In order to establish the thermal irreversibility, the ring-closing carbon atoms of the open form (O-form) at the end of hexatriene moiety are fully substituted. Therefore the triene moiety is highly congested so that it is forced to take the helical structure. It is the origin of the chirality of these molecules. After photoirradiation, the helical chirality is translated to the two newly generated stereogenic carbon atoms.

As shown in Scheme 8, if the helical chirality of O-form would be fixed as one of the two helicities (*P* or *M*), then the chirality of the newly formed stereogenic centers of the closed form (C-form) would be determined unambiguously. We decided to employ the good old A(1,3)-strain around the 2,3-double bond of one of the benzothio-phenylene moieties in the O-form to control the helicity of the hexa-



Scheme 8.

triene moiety (Scheme 8). Because of the A(1,3)-strain, the hydrogen atom should face the hexafluorocyclopentene ring. As a result, other substituents would extend into the open space. The question is where would the second benzothiophene ring possessing a methyl group on C-2 be? Of course, we expected that it should take its position close to the smaller R^S substituent rather than close to the larger R^L substituent. If R^L exerts an electronic repulsion to the sulfur atom of the second benzothiophene, the position close to R^L becomes more uncomfortable for it. We chose a methoxy-methoxyl group as R^L and a methyl group as R^S on the target molecule **7**.

Compound **7** was subjected to 313 nm light irradiation in three solvents (Table 1). The changes in absorption spectra of **7**, by 313 and 519 nm light irradiation to **7** and to its UV-

Table 1. Diastereomeric excess of diarylethene **7** by 313 nm light irradiation.^[a]

Solvent	Conversion [%]	Diastereomeric excess [%]
hexane	80.4	86.7
toluene	84.7	88.1
ethyl acetate	84.8	87.5

[a] Concentration: 1.40×10^{-4} mol dm⁻³. Irradiation of 313 nm light: 60 min.

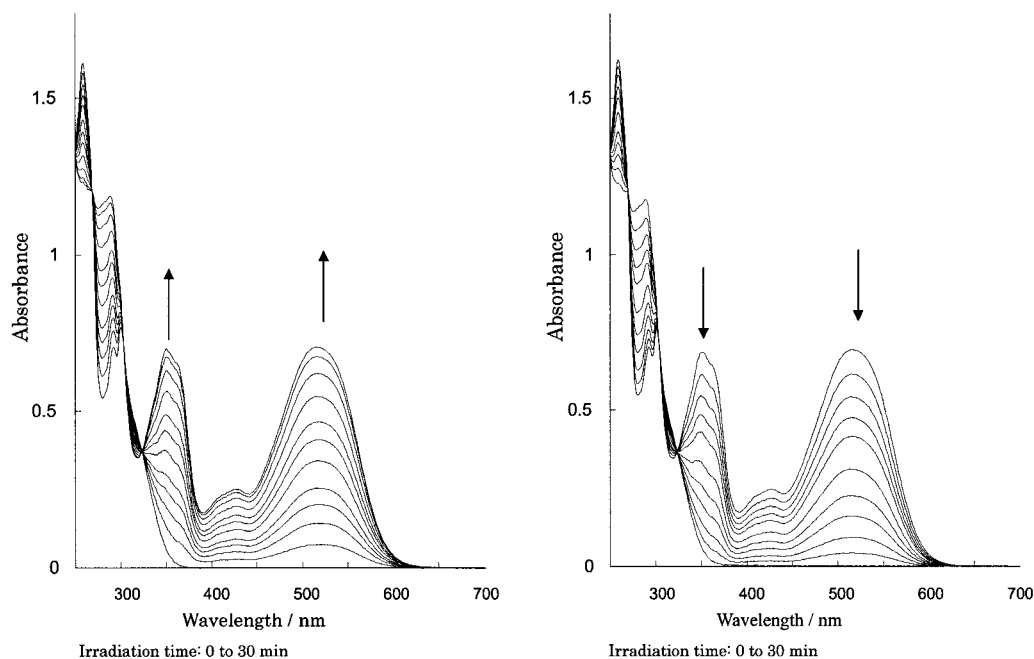


Figure 2. Change in absorption spectra by 313 nm light irradiation to **7** (left) and 519 nm light irradiation to the resulting photostationary state solution (right), in hexane.

photostationary state, respectively, are shown in Figure 2. The conversion to the C-form was always more than 80%, and the diastereomer excess was around 88%.^[20] It was more than we had expected, that a single stereogenic center governed the diastereoselectivity of the photocyclization so predominantly. This system was much simpler and much more effective than the previously reported diastereoselective photochromic reactions of diarylethenes^[21]: 88% diastereomer excess with more than 80% conversion, governed by only one stereogenic carbon atom, working at room temperature, in many solvents, and with no additives. The ORTEP drawing of the X-ray crystallographic analysis is shown in Figure 3, in which 1) the hydrogen atom faces the hexafluorocyclopentene, and 2) the second benzothiophene ring is located close to the methyl site, not on the methoxy-methoxyl site.

In order to obtain an optically active compound, an enantioselective preparation of (*R*)-2-(1-hydroxyethyl)benzothiophene was done by reducing 2-acetylbenzothiophene with (*S*)-2-methyl-CBS-oxazaborolidineborane complex developed by Corey et al.^[22]

Improved System

We then sought a better substituent to control A(1,3)-strain. We chose the acyl group, because the array of the oxygen atoms (O–C–O) is similar to the methoxymethoxyl group, yet it is easy to attach functional groups that may control

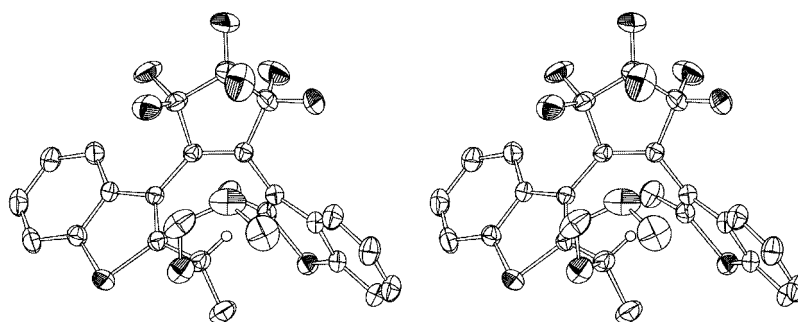
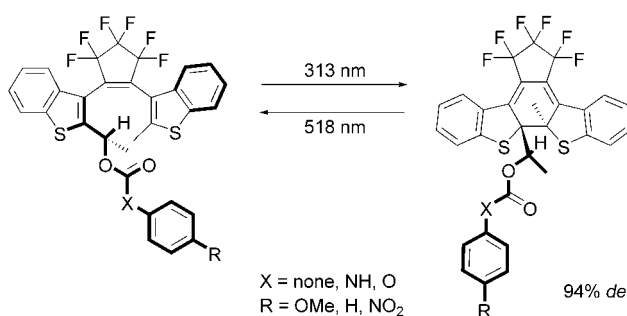


Figure 3. ORTEP drawing (stereo-image for parallel viewing) of X-ray crystallographic analysis of **7** (30% probability).

the electron density of the oxygen atoms. We synthesized benzoates, *N*-phenylurethanes, and phenylcarbonates with a hydrogen atom, a methoxyl, or a nitro group at the *para* position of the terminal phenyl group. One of the compounds synthesized exhibited 94% diastereomeric excess (Scheme 9). Details will be reported elsewhere.^[23]



Scheme 9.

Closing Remarks

The concept “introduction of A(1,3)-strain to photochromism” originated from the experience of total synthesis of natural products 18 years ago, and it was successfully employed in the research in photoresponsive materials. “Chiral photochromism” is interesting and important because it is quite useful 1) to be applied to the nondestructive readout method when these kinds of compounds are used for photon-mode rewritable high-density optical memory media,^[10,19,24] and 2) to control the properties and/or orientation of the environmental media of photochromic compounds such as liquid crystals^[25] or biological materials^[26] by light. Therefore we will continue research in this field.

The story is yet “to be continued.” I hope we will be able to show the readers what is happening right now in our laboratory through the journals in the near future.

Acknowledgement

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