



GSCN was established in 2000 to promote research and development for the Environment and Human Health and Safety, through the innovation of Chemistry .

Green and Sustainable Chemistry a Quarter Century Ago

Kunio Nakajima

President, Japan Chemical Innovation Institute



A quarter of a century ago, problems such as producing starch by adding a catalyst to sunlight, water and carbon dioxide, and moving objects without using the power of a motor, as in the case of muscles, were studied. It was a plan to intensively research the regions of the body, from molecules to cells to tissues to organs to, finally, the individual; and as research domains, to study areas such as the brain and nervous system; cell genesis, growth, and differentiation; immunity; and substance and energy conversion.

It was basic research on the outstanding features of the body, including the human person. It sought to proceed internationally with a long-term vision of building a storehouse of seeds for future science and technology, while being a major resource for the development of science and technology that will be in future harmony with nature and people.

Today, the problems of global warming and energy and resources have since become more serious, and the need for solutions has become urgent.

Then-prime minister Nakasone planned to announce Japan's initiative on science and technology at the Tokyo Summit, but because preparations were not completed, it was proposed in Venice the following year. In the year after that, prime minister Takeshita provided concrete guidelines at the Toronto Summit.

When Nakasone announced that Japan would be a nation of basic research, the countries at the summit were surprised. The United States especially was initially suspicious, believing that "Japan would bring back the fruits of American basic research simply by offering some funds." However, as Japan participated in assemblies after assemblies, the skepticism lifted. It currently provides research funding to young researchers worldwide as part of the "Human Frontier Science Program." The program is being advanced not only with Japanese researchers, politicians, and administrators, but with also relevant members from major countries. Twenty-five years have gone by since the goal to be a basic research nation was first explained to the world at the two summits.

**Organic Electrosynthesis toward green sustainable chemistry
-Selective Electrochemical fluorination in ionic liquids-
(Tokyo Institute of Technology, Prof. Toshio Fuchigami, Assist Prof. Shinsuke Inagi)**

Recently, much attention has been paid to organic electrosynthesis as “Green Sustainable Chemistry”. Our recent work on volatile solvent-free electrochemical fluorination of organic compounds and conducting polymers in ionic liquids was briefly illustrated.

Organic Electrosynthesis as the Leader of Green Chemistry

Since environmental aspects are most important in the 21st century, environmentally friendly organic synthetic processes are highly desirable. Organic electrosynthesis is most promising as a clean process since it does not require any hazardous oxidizing and reducing reagents. Recently, demand of organic fluorine compounds is increasing rapidly, and fluorinated organic compounds are now key materials in the development of new types of pharmaceuticals and agrochemicals together with functional materials like battery and optoelectronics.

Selective Electrochemical Fluorination of Organic Compounds

Selective electrochemical fluorination is usually conducted in aprotic solvents containing HF salt ionic liquids such as Et₃N-nHF (n=3-5) and Et₄NF-nHF (n=3-5). The fluorination proceeds via a (radical) cation intermediate as shown in Scheme 1.



Scheme 1

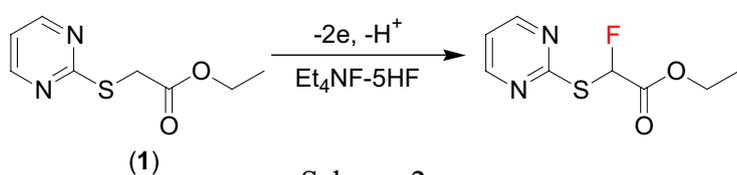
Since fluoride ions are quite difficult to be oxidized, organic substrates are generally oxidized prior to the discharge of fluoride ions. Therefore, fluorine gas is not generated.

Selective chemical fluorination is not straightforward, and it very often requires hazardous reagents. In contrast, selective electrochemical fluorination is a safe and clean process because it can be carried out under mild conditions without any hazardous and/or reagents. Furthermore, since hydrogen of organic compounds can be substituted with fluorine, the electrochemical method is superior to conventional chemical methods from an atom economical aspect. Although we have achieved selective electrochemical fluorination of various types of organic compounds in organic solvents to date, organic solvents are flammable and not always safe from health and environmental perspectives. With these facts in mind, we have developed volatile solvent-free electrochemical fluorination using ionic liquid HF salts as follows.

Solvent-Free Selective Electrochemical Fluorination in Ionic Liquids

In solvent-free system, the nucleophilicity of fluoride ions of ionic liquid HF salts is rather low, which results in decrease of fluorination yields. Previously, we found that ether compounds like dimethoxyethane (DME) greatly enhances the nucleophilicity of fluoride ions. Then, we successfully carried out the solvent-free electrochemical fluorination of α -(2-pyrimidylthio)acetate and *O*-ethyl benzothioate in the presence of ether-containing additives. As shown in Scheme 2 and Table 1, the addition of PEG additives (ca. 3%) into the reaction system highly improved the yield due to its anodic

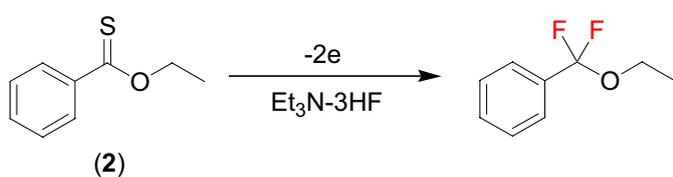
stability and coordination ability to counter cations of fluoride ions. Moreover, highly efficient difluorodesulfurization of *O*-ethyl benzothioate was achieved by using this unique effect as shown in Scheme 3 and Table 2.



Scheme 2

Table 1

Additive	Yield (%)
—	35
DME	58
Dioxane	5
PEG[$M_n \sim 200$]	60



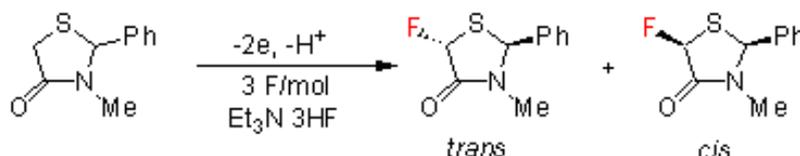
Schemes 3

Table 2

Additive	Yield (%)
—	22
DME	18
PEG[$M_n \sim 200$]	80

Electrochemical Fluorination in Ionic Liquids under Ultrasonication

The viscosity of ionic liquid fluoride salts is higher than that of ordinary organic solvents, therefore, the mass transfer of a substrate to the anode surface from the bulk of the fluoride salts is slower than that in organic solvents. However, highly efficient electrochemical fluorination of a 4-thiazolidinone derivative was achieved under ultrasonication since ultrasonication greatly enhances mass transport of the substrate. As shown in Scheme 4, ultrasonication also changed the stereoselectivity of the products.



Scheme 4

Under mechanical stirring: 24% yield (*cis/trans* = 50/50)
Ultrasonication: 77% yield (*cis/trans* = 38/62)

Electrochemical Fluorination of Polymer in Ionic Liquids

Although electrochemical substitution reaction to polymer main chain or side chain has been difficult, we recently accomplished a successive electrochemical fluorination of conducting polymer film fixed on electrode. As shown in Figure 1, the electrochemical difluorodesulfurization of a polyfluorene derivative was successfully carried out in ionic liquid, $\text{Et}_4\text{NF}\cdot 5\text{HF}$, to produce a novel conducting polymer having difluorofluorene unit. The use of ionic liquid as an electrolytic solution effectively prevented the detachment of the polymer film from the electrode.

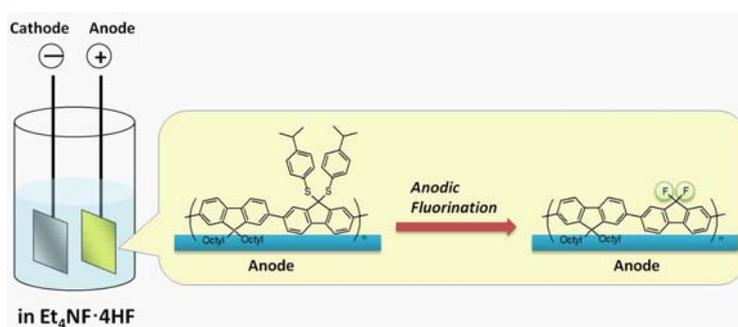


Figure 1

One-pot Reactions Catalyzed by Supported Gold Nanoparticles

Tamao Ishida and Masatake Haruta

*Department of Applied Chemistry, Graduate School of Urban Environmental Sciences,
Tokyo Metropolitan University*

Abstract:

Majority of fine chemicals are produced by multi-step reaction processes and a large amount of wastes is co-produced at each step. If more than two reactions can be carried out sequentially in the same reactor, the amount of solvents and energies consumed and wastes emitted can be significantly reduced. One of the characteristic features of gold catalysts is higher reactant and product selectivity than Pd and Pt catalysts, providing a great advantage to gold catalysts for one-pot reactions. Herein we report the recent progress in one-pot reactions catalyzed by supported Au catalysts.

Bulk gold is chemically inert and is regarded as a poorly active catalyst. However, Au turns out to be active for many reactions such as CO oxidation in gas phase to form CO₂ when it is deposited as small nanoparticles (NPs) with diameters below 10 nm on selected base metal oxides. Supported Au NPs catalyze not only gas phase reactions but also liquid phase reactions such as aerobic oxidation of alcohols. Palladium catalysts have been widely used for many oxidation and hydrogenation reactions, however, they often cause over-oxidations and over-hydrogenations. In contrast, Au catalysts generally exhibit lower catalytic activity but higher reactant selectivity and product selectivity to the desired compounds. Recently, one-pot reactions have been becoming one of the hot topics in green and sustainable chemistry. In one-pot reactions, more than two processes are carried out in the same reactor without separations and purifications of intermediates, resulting in high product yields. Accordingly, highly selective catalysts should be chosen or designed for one-pot syntheses to achieve high reactant and product selectivity at each step. In this consequence, Au catalysts are suitable for one-pot reactions in terms of high reactant and product selectivity.

Scheme 1 shows the examples of the one-pot reactions catalyzed by supported Au NPs. Nippon Shokubai Co. Ltd. announced in 2004 that Au/SiO₂-Al₂O₃ could catalyze the aerobic oxidation of ethylene glycol in methanol to obtain methyl glycolate in one-pot with high selectivity (Scheme 1a). Gold catalysts oxidize only one hydroxyl group of ethylene glycol to form aldehyde. Once monoaldehyde is formed, aldehyde readily reacted with methanol and is converted into hemiacetal and then oxidized to form methyl ester. In this reaction, the second oxidation of ethylene glycol, the methanol oxidation to form methyl formate, and other side reactions can be avoided by using gold catalysts.

On the other hand, we found that Au/NiO catalyzed *N*-formylation of amine to give formamide with high product selectivity in methanol (Scheme 1b). This reaction involves (i) the aerobic oxidation of methanol to form methyl formate, (ii) the reaction of methyl formate with amine to form formamide. Gold NPs on NiO showed high reactant selectivity to alcohol and did not catalyze the amine oxidation to form imine, oxime, and other by-products. From these examples, the catalytic performance of Au NPs for one-pot syntheses of fine chemicals can be tuned by the selection of suitable supports and the reaction conditions.

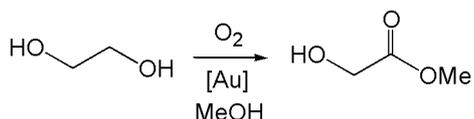
Recently, Au-catalyzed one-pot reactions involving two steps, oxidation and hydrogenation, has been

extensively studied. Corma and his co-workers demonstrated that Au/TiO₂ catalyzed one-pot synthesis of azobenzenes from nitrobenzene (Scheme 1c). In this case, nitrobenzene is hydrogenated to aniline at the first step and then oxidized to azobenzene with O₂ at the second step in the same reactor. Gold NPs on TiO₂ have high product selectivity to azobenzene and aniline was not re-oxidized to nitrobenzene. Gold catalysts have also higher reactant selectivity to nitro groups than alkene and formyl groups for hydrogenation, enabling the use of substituted nitrobenzenes as starting materials.

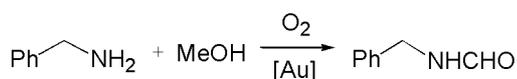
We used one-pot, three steps reactions for the synthesis of secondary amines from primary amines with alcohol via the formation of imine as an intermediate in the presence of alcohol-selective Au catalysts (Scheme 1d). In this reaction process, (i) only alcohol is oxidized to aldehyde, (ii) aldehyde reacts with amine to form imine, and then (iii) imine is hydrogenated to form secondary amine. When inert porous coordination polymers were used as supports for gold, we found that only Au clusters with diameters smaller than 2 nm could effectively catalyze the hydrogenation in the third step.

Furthermore, Au clusters supported on porous coordination polymers can catalyze the synthesis of secondary amine from aniline with alcohol under N₂ atmosphere without either of O₂ or H₂ in the presence of base. It has been found that the catalytic properties of Au dramatically change when it becomes clusters smaller than 2 nm. The one-pot synthesis of secondary amine under N₂ is an environmentally benign process since neither O₂ nor H₂ is required and water is the only by-product. The examples shown above suggest that Au clusters have a great potential for the development of new green sustainable one-pot process.

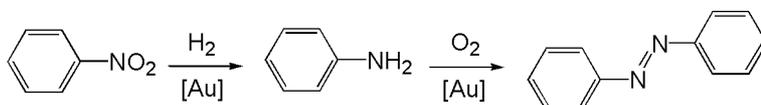
(a) Oxidation of ethyleneglycol to methyl glycolate



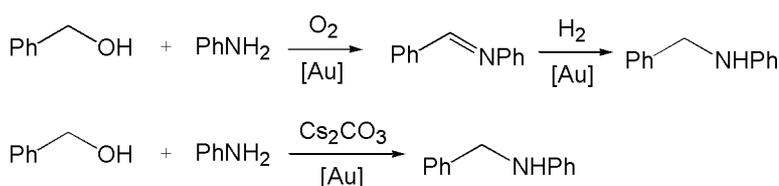
(b) *N*-Formylation of amine with methanol



(c) One-pot synthesis of azobenzene from nitrobenzene



(d) One-pot synthesis of secondary amines from primary amines



Scheme 1 Representative examples of one-pot reactions catalyzed by supported Au NPs.

Remarks by 9th GSC Symposium Poster Award Recipients

1. Taichi Koide PCR Project Team , Sumitomo Bakelite Co. Ltd.

I am deeply honored to be chosen for the poster prize out of the many fascinating posters presented. Sumitomo Bakelite developed new techniques for chemical recycling process of phenolic resins using supercritical fluid technology and is working toward their commercialization. Chemical recycling is a recycling method by which, theoretically, materials can be recycled over and over without degradation of their properties. We carried out experiments to confirm this. The results showed that using our company's chemical recycling technologies, we were able to substantiate this principle.

In the future, we wish to continue to develop processes that are friendly to a recycle-based society, and contribute to the continuation of a rich global environment.

2. Tatsuya Oka Graduate School of Engineering, Osaka University

I feel very honored to be awarded this wonderful prize. Participating in the GSC Symposium was a good opportunity for me to consider how I could best engage my research with the environmental problem. My research is on the development and application of porous polymers. For creation of porous materials, I attempted to simplify and save energy based on methods using phase separation. Furthermore, by introducing chelating agents as an application of the created porous substances, I developed a separating and removal agent that can improve water quality and recover resources. I am seeking to contribute this agent to the resource and environmental problem. I would like to share what I learned at this conference with members of my lab, and contribute to the development of chemical technologies that make possible energy and resource conservation and the creation of a recycle-based society.

3. Ryoichi Otomo Chemical Resources Laboratory, Tokyo Institute of Technology

My research sought to synthesize useful chemicals on solid catalysts using xylose, a biomass, as resource. For my presentation at this conference, I sought to synthesize furfural. The reaction, which previously took place in sulfuric acid, was able to proceed on a solid sulfo-containing meso-porous catalyst. By making possible the green synthesis of furfural using a solid catalyst, I hope to convert biomass resources into useful chemical substances via furfural. Currently, there is room for improvement for the catalytic activity and selectivity rate. I wish to keep working on the above problems for my research.

4. Ryosuke Kusumi Graduate School of Agriculture, Kyoto University

Our major specialization is the chemical conversion of renewable natural resources such as cellulose and its relatives into useful materials possessing adequate conformity with the environment and/or specific functions in some advanced applications, based on the systematic characterization at molecular and supramolecular structure levels. At this conference, we presented "Synthesis and Enzymatic Hydrolysis of Cellulose-based Graft copolymers", which is an excellent example of such advanced utility conversion. We gained valuable experience from active discussions with the conference participants, and seek energetically to pursue research that achieves more "modern" uses of the biomass materials.

5. Hiroshi Kaga Graduate School of Science, Tokyo University of Science

Production of solar hydrogen using photocatalysts is driven under mild conditions. Because it does not depend on fossil fuels, it can be said to be an ideal method of producing hydrogen. We were successful in developing a new layered metallic sulfide photocatalyst that displays extremely high activity to the production reaction of solar hydrogen. We are honored not only at the opportunity to present our research at the 9th GSC Symposium, but also to be chosen for the poster prize. We will not rest on our current achievements, but will seek to bring higher performance to the successfully developed photocatalyst, seek new photocatalysts, and develop high-performance materials for commercialization.

6. Aya Watabe Graduate School of Advanced Science and Engineering, Waseda University

I am truly thankful to be selected for the 9th GSC Symposium Poster Prize. I was awarded for the significance of using perovskite oxide as a catalyst and applying it to dehydrogenated ethyl benzene. Previously, this oxide was used only in the presence of oxygen. I experimented and verified that it could be used in an atmosphere free of oxygen components, and succeeded in broadening its scope of application. This oxide can be deployed in the construction of various metallic species, and is an extremely material because reaction activity and selectivity can be controlled. I wish to contribute to further clarifying the properties of this oxide catalyst, broadening its scope of application, and reducing its energy cost.

Member of Green·Sustainable Chemistry Network (GSCN)

Member of editorial board