Impact Objectives

- Undertake research on the synthesis of core-shell particles that combine functional materials
- Optimise various structurally controlled catalyst particles on the electrodes of metal-air secondary batteries and water electrolysis cells

Power and more

***Professor Tomoya Ohno** and **Associate Professor Shigeto Hirai** discuss their novel approach to materials science and how to combine the field with chemistry to overcome technological barriers*

Professor Tomoya Ohno

Associate Professor Shigeto Hirai

Can you talk a little about your research background in inorganic materials engineering?

TO: I belonged to the research group of Professor Hisao Suzuki of Shizuoka University, Japan, and Professor Marija Kosec, Professor Barbara Malič of Jožef Stefan Institute, Slovenia, and we conducted research on the chemical solution deposition of piezoelectric thin films. By combining the molecular design technology in the chemical solution process and powder engineering that I have cultivated so far, I developed research on the synthesis of core-shell particles that combine functional materials.

SH: I researched my PhD in Professor Paul Attfield's group at the University of Edinburgh, UK. Since 2015 at the Kitami Institute of Technology, I have been conducting research on electrochemical catalysts centred on the Oxygen Evolution Reaction (OER). Meanwhile, I was fascinated by the great potential of structural control of nanocoating and catalyst particles. Therefore, I started joint research with Professor Tomoya Ohno. As a result of investigating the effect of chemical molecular design on oxygen evolution catalytic ability, we succeeded in enhancing both OER activity and stability in $Ca_{1-x}Sr_xRuO_3$. Currently, we are mounting and optimising various structurally controlled catalyst particles on the electrodes of rechargeable metal-air batteries and water electrolysis cells.

Your latest research is developing core-shell nanomaterials for energy storage devices using chemical solution methods. Briefly, can you explain in layperson terms what this involves?

TO: These core-shell nanomaterials are essential for the catalysis of certain key reactions in next generation batteries. However, the active sites of the catalyst material may elute into the electrolyte solution during repeated charging and discharging. If prevented, it will be possible to create a battery that can be used for a long time. We are aiming to create this protection by coating the catalyst particle surface in a thin film. However, when a coating is applied, the catalytic activity may become lower even if dissolution can be prevented. To anticipate these effects, it is necessary to design the precursor of the coating material at the molecular level and develop core-shell particles with appropriate structure.

What is the ultimate impact of your studies?

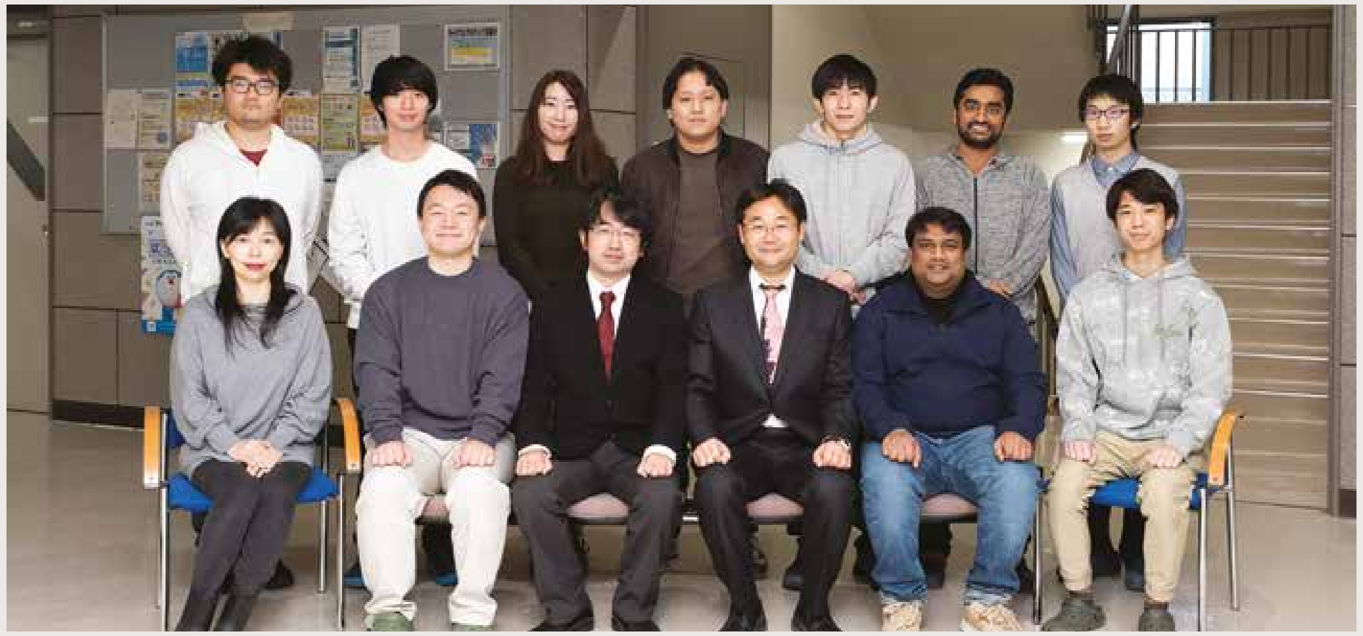
TO: Many of the currently reported technologies for coating particles are designed for coating basic materials such as silica and core particles are often targeted at micrometre order materials. However, the chemical reaction-based coating I developed is able to coat nanoparticles with functional materials containing composite metal oxides at the nano level. Therefore, we are currently using this technology for the creation of battery materials, but in the future, we believe that it can be applied to the development of a wide range of functional materials, such as magnetic materials and optical materials.

In what ways can you progress your findings to be applied to industrial applications?

TO: Currently, there are many hurdles in applying the synthesis of core-shell nanoparticles from the laboratory level to mass production processes. At present, my research group is talking with a Japanese machine maker about the development of equipment that can apply the process that I have proposed for mass production. If such a device will be realised, we believe that the material proposed this time may be implemented in industrial applications. We hope that the development of all solid-state rechargeable lithium-ion batteries, which we are currently researching, will lead to the creation of large batteries that are expected to be installed in automobiles, etc., in the future.

SH: We are also continuously searching for, and implementing, electrode catalysts with high durability and low-cost synthesis methods and starting materials with the aim of next generation metal-air battery for cell phones that require less frequent charging. ▶

Group members of the Inorganic Materials Chemistry Laboratory



Overcoming technological blocks

Material scientists at the ***Kitami Institute of Technology*** *have developed novel processes by which metal-air batteries may become the energy storage cornerstone of the 21st century*

The material sciences constitute one of the cornerstones of modern technology. This broad field concerns the preparation, modification and application of complex materials and compounds. The knowledge required covers physics, chemistry and engineering which work in concert to create the key components, surfaces and devices. These include everything from the key surfaces inside of batteries to the physical architecture of electronics, and even the special coatings employed on touchscreens.

The breadth of the field also accounts for the wide range of specialisms within the discipline. This is necessary due to the complexity and unpredictability of many of the novel materials and techniques being deployed. It requires significant knowledge and experience to understand how an additional element might interact in a catalyst or how a particular compound will behave when coating another material.

COLLABORATION FOSTERS RESULTS

Professor Tomoya Ohno and Associate Professor Shigeto Hirai are examples of the broad range of expertise required for successful materials science. Whilst they are based at the Kitami Institute of Technology, Kitami, Japan, Ohno specialises in surface coatings and powder technology whilst Hirai is an expert in electro- and solid-state chemistry. Together they started collaborating on research concerning the composition and coating of catalysts used in rechargeable metal-air batteries. All batteries rely heavily on both their electrochemistry and the material composition of their catalysts, so such work is a natural fit for Ohno and Hirai's specialisms. 'We are developing long-life, high-performance bi-functional catalyst particles that can be mounted on rechargeable metal-air batteries, as well as proposing positive particles coated with a solid electrolyte which are intended for use in all-solid state lithium-ion batteries,' outlines Ohno.

Metal-air batteries, unlike traditional battery designs, have an anode made of a pure metal and a cathode that is, functionally, the air. Whilst, chemically, the cathode is the air itself, there is typically a cathode material that catalyses the oxygen evolution reaction that is a core part of the process,' explains Ohno. 'The major advantage of the metal-air battery is the extremely high energy density associated with its design.' This means that the battery design has the potential to store a lot more energy than most conventional batteries. Consequently, metal-air batteries have the potential for widespread use in electric cars, national grid energy storage and, of course, in all devices that require regular charging. In the former, such an increased battery life would be transformative for the industry.

NEXT GENERATION ENERGY STORAGE

Whilst metal-air batteries have a potential energy capacity which is up to 30 times that of conventional lithium-ion batteries, its technology is still in progress. 'The main concern of metal air batteries is the reliability of the cathode, particularly the rate of the oxygen reduction and oxygen evolution reaction,' explains Ohno. 'This means that battery discharge is not reliable enough for power-heavy uses. At the same time, it also makes the recharging process inefficient,' he says. Another issue with metal-air batteries has been the harsh effects of charging at high cathodic potentials, potentially causing irreversible damage to it. Whilst there are other issues, the greatest issues preventing the broad application of metal-air batteries lie in its cathode.

Ohno and Hirai are using their combined expertise to overcome the issues of catalysis and stability of the cathode. Ohno has extensive experience in the coating of functional complex metal oxide materials. 'I came to realise that the coating of the catalyst at the metal-air battery cathode might hold the key to stabilising its function,' highlights Ohno. Hirai brings the knowledge of the electrochemistry underlying the rechargeable metal-air battery. This means he is best placed to suggest candidate coating compounds that will act as effective catalysts. It's this interaction between traditional materials science and chemistry that's driving the success of Ohno and Hirai's work. 'We are using the power of chemistry to develop various high-performance materials,' confirms Ohno. 'In chemistry, it is very common that the reaction will not proceed ideally, but occasionally we are able to realise what we originally envisioned and have reaffirmed the power of chemistry in materials science.'

> *We are now well positioned to upscale the testing and seek out industrial partners capable of scaling up manufacture and further testing*

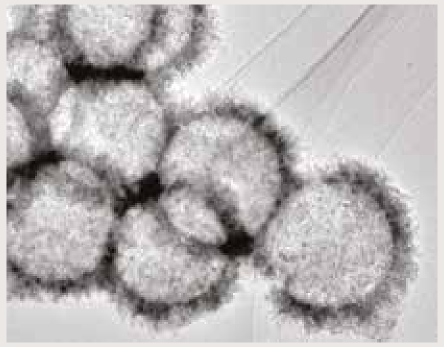
THE IMPORTANCE OF NANO

Broadly speaking, Ohno and Hirai are using chemical reaction and powder engineering techniques to add thin films of protective materials for the potential catalysts that could help stabilise the cathode. This is a liquid phase technique that uses the principles of deposition to evenly coat extremely fine layers of a compound onto a target structure. The thickness and structural regularity of the coating is essential and so the underlying nanostructure of the coated material is also important. 'To examine these structures, we make use of electron microscopy and nitrogen adsorption experiments,' confirms Ohno. After extensive research and old-fashioned trial and error, Hirai and Ohno were able to identify a calcium-strontium-ruthenium-oxide with a protected layer that had the potential to be the catalyst they needed.

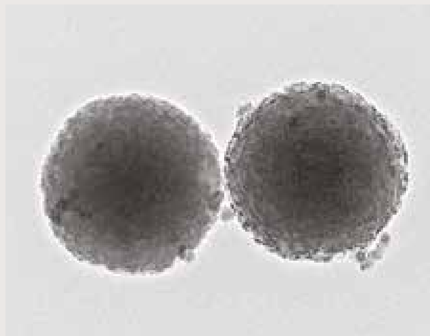
Once the compound was identified, formulated and coated onto the material that will catalyse the reaction at the cathode, it was, of course, necessary to test its potential in an actual metal-air battery. The results have been extremely encouraging. The new material was able to improve both the charge and discharge capacity of the battery. 'The coating of the protective layer on the bi-functional catalyst particles that were mounted on the metal-air secondary battery did not impede the catalytic activity, instead it significantly improved the stability, as we had designed,' enthuses Ohno. 'We have also confirmed that the effect differs depending on the structure of the coating layer,' he says. The immediate next step will be to apply the same principles to anode. However, the results already represent an important breakthrough in the potential application of rechargeable metal-air batteries.

MACRO FUTURE

Ohno and Hirai's work doesn't just represent a breakthrough in metal-air battery technology. Their methods, particularly that of coating important compounds at a nano scale. Ohno believes that this principle and their processes have a huge range of potential applications. 'The source of this technology lies in the design of precursor molecules for inorganic materials. It is a technology that can be applied to material systems other than the materials that we have proposed so far,' enthuses Ohno. 'We expect our work will be expanded into various fields such as magnetic materials, optical materials and electronic materials by selecting the combination of materials relevant to each case,' he confirms. Ohno calls on other academics as well as industry to make use of the principles they have outlined. It is clear that this team has opened a new path in materials science that may help break many of the technological barriers. ●



TEM image of TiO_2 nano-coated particle



TEM image of $BaTiO_3$ nano-coated particle

Project Insights

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Professor Tomoya Ohno studied Materials Science at Shizuoka University. He has worked at the Kitami Institute of Technology since 2005, and in 2017 he became Full Professor. His research area is materials science and particle technology. He is the Councillor of the Society of Powder Technology, Japan, and the editorial board member of *Advanced Powder Technology*.

Associate Professor Shigeto Hirai is based at the Kitami Institute of Technology and is an executive officer of the Materials Science Society of Japan. Hirai's current research is centred on electrochemistry and solid-state chemistry of energy-related materials.