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NATIONAL INSTITUTE FOR MATERIALS SCIENCE

NIMS NOW INTERNATIONAL

No. 3

Tackling social issues in a time of global transition

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In line with its slogan, "The true value of materials is in their use," NIMS carries out materials research with the goal of developing practical products that will benefit the public.
NIMS was founded 20 years ago as a result of a merger of its two predecessors: the National Research Institute for Metals and the National Institute for Research in Inorganic Materials.
It has since developed a succession of new materials to address ever changing social needs.

The world is currently going through a major transition.
What type of materials research is most needed to satisfy the demands of today's society?

Development of materials vital to social problem-solving in a time of global transformation

NIMS' problem-solving mission

NIMS and its two predecessors (the National Research Institute for Metals (NRIM, founded in 1956) and the National Institute for Research in Inorganic Materials (NIRIM, founded in 1966)) have been committed to meeting materials R&D requests from the Japanese government and industry. As a result, they have produced a number of socially beneficial materials over the years.

Japan's rapid economic growth from 1955 to 1973 was largely led by the manufacturing sector, particularly the steel industry. Around 1968, when the country's GDP became the second highest in the world, huge numbers of high-rise buildings, bridges and tunnels were constructed using steel and other structural materials. This nationwide development later led to the launch of the Structural Materials for the 21st century (STX-21) project in which NIMS, NIRIM and their collaborators developed tough, corrosion- and heat-resistant steel alloys.

In addition, NIRIM developed a potassium titanate fiber to replace asbestos after it was found to be carcinogenic. NIRIM also succeeded in synthesizing diamonds from the vapor phase. These extremely hard synthetic diamonds have traditionally been used in a wide variety of tools, such as cutting machines. More recently, they have been processed into jewelry diamonds and used in radiation sensors. They have also been used in wide bandgap semiconductor and spintronics research, producing promising results.

NIMS inherited NRIM and NIRIM's mission to create socially beneficial materials through basic research when it was formed in 2001. NIMS has since expanded its mission and laid out its research policy: solving global environmental, energy and natural resource-related issues through materials research. NIMS is fully committed to real world problem solving.

NIMS' problem-solving approaches

NIMS has two fundamental approaches to research.

First, NIMS works to pioneer new areas of research by conducting creative and innovative basic research. Second, NIMS aims to develop new materials by fully exploiting its resources: accumulated research expertise, state-of-the-art research equipment and outstanding human resources.

The development of sialon phosphors is a good example of NIMS' achievements in pioneering new areas of research.

SiAlON phosphor

Sialons were initially researched by private companies seeking to develop heat-resistant automobile engine materials. However, when sialons were found to be inadequate for this purpose, sialon research lost momentum. Subsequently, NIMS investigated the usefulness of physical properties of sialons other than their heat resistance and developed sialon phosphors. At the time, extensive efforts had been underway to develop a red phosphor to produce a white LED capable of generating more natural white light. This goal was finally achieved using the red sialon phosphor NIMS developed. Today, this phosphor is incorporated into most white LEDs.

The development of practical heat-resistant materials by NIMS is an example of its success in enhancing its research strengths. Because NIMS had many years of experience in superalloys and ultrahigh temperature materials research, it was able to develop nickel-based single crystal superalloys with among the world's highest heat resistance. These superalloys have been used in jet engine turbine blades and research is underway to use them in thermal power plant gas turbines. NIMS and its predecessors have developed numerous other new materials and put them into practical use in efforts to resolve various social issues.

Aircraft engine with internal components made of highly heat-resistant materials developed by NIMS

Aligning Japan's industrial structure with global trends

The world is going through a transition. It is facing an urgent need to meet the UN's sustainable development goals (SDGs), such as addressing climate change and diversity issues. As a result, many conventional activities and practices are being reviewed around the world.

Japan's industrial sector is also undergoing structural reform to better cope with these global issues. The automotive industry and IT companies are expected to play a particularly crucial role in solving climate issues through carbon neutrality initiatives.

Urgent need to achieve carbon neutrality

Achieving carbon neutrality is one of Japan's top priorities. The national government has announced the goal of reaching net zero greenhouse gas emissions by 2050. To ensure that we meet this long-term goal, Japan also pledged in April 2021 that it would reduce its greenhouse gas emissions by 46% from the FY2013 level by 2030. Both goals are very ambitious, requiring greater scientific and technological innovation than ever before.

Electric vehicle motor equipped with dysprosium-free magnets

NIMS has been developing green materials and technologies which can be used to reduce environmental impact. These materials/technologies include a hydrogen liquefaction technology to enable widespread use of clean hydrogen energy, next-generation batteries, permanent magnets for use in electric vehicle motors, next-generation solar cells, thermoelectric materials, catalysts and superconducting materials. NIMS is putting particularly great efforts into the development of hydrogen liquefaction technology and successors to lithium-ion batteries.

NIMS' contribution to medicine amid the COVID-19 pandemic

In 2020, the world was rocked by the spread of the new coronavirus and its impact still continues to be significant.

NIMS has developed organic materials for medical use, such as high-performance surgical adhesives and artificial bones. NIMS' other medical products include a new nanofiber sheet used to promote the regeneration of peripheral nerves. This sheet is currently undergoing clinical testing and is expected to be put into practical use in the near future. The fluorescent biosensor (see p. 6) NIMS developed for medical use may enable early detection of not only new coronavirus infection but also cancer. In addition, NIMS has developed sports materials (see p. 9)

Preparing for natural disasters

Ten years have passed since the Great East Japan Earthquake. As an earthquake-prone country, every building in Japan is required to take anti-earthquake measures. In addition, a significant portion of Japan's civil infrastructure, such as its roads and bridges, was built during a period of rapid economic growth which ended nearly 50 years ago. These aging structures urgently need to be reinforced. NIMS has developed anti-corrosion steel by leveraging its rich experience in basic research on metallic material corrosion. Moreover, NIMS has developed seismic dampers (see p. 12) with among the world's highest durability ratings which, when installed in high-rise buildings, are capable of absorbing vibrations generated by large earthquakes. These NIMS accomplishments were made possible by its strong tradition in metallic materials research, including its R&D activities in the STX-21 project.

Adoption of DX in materials development: facilitating both economic growth and problem solving

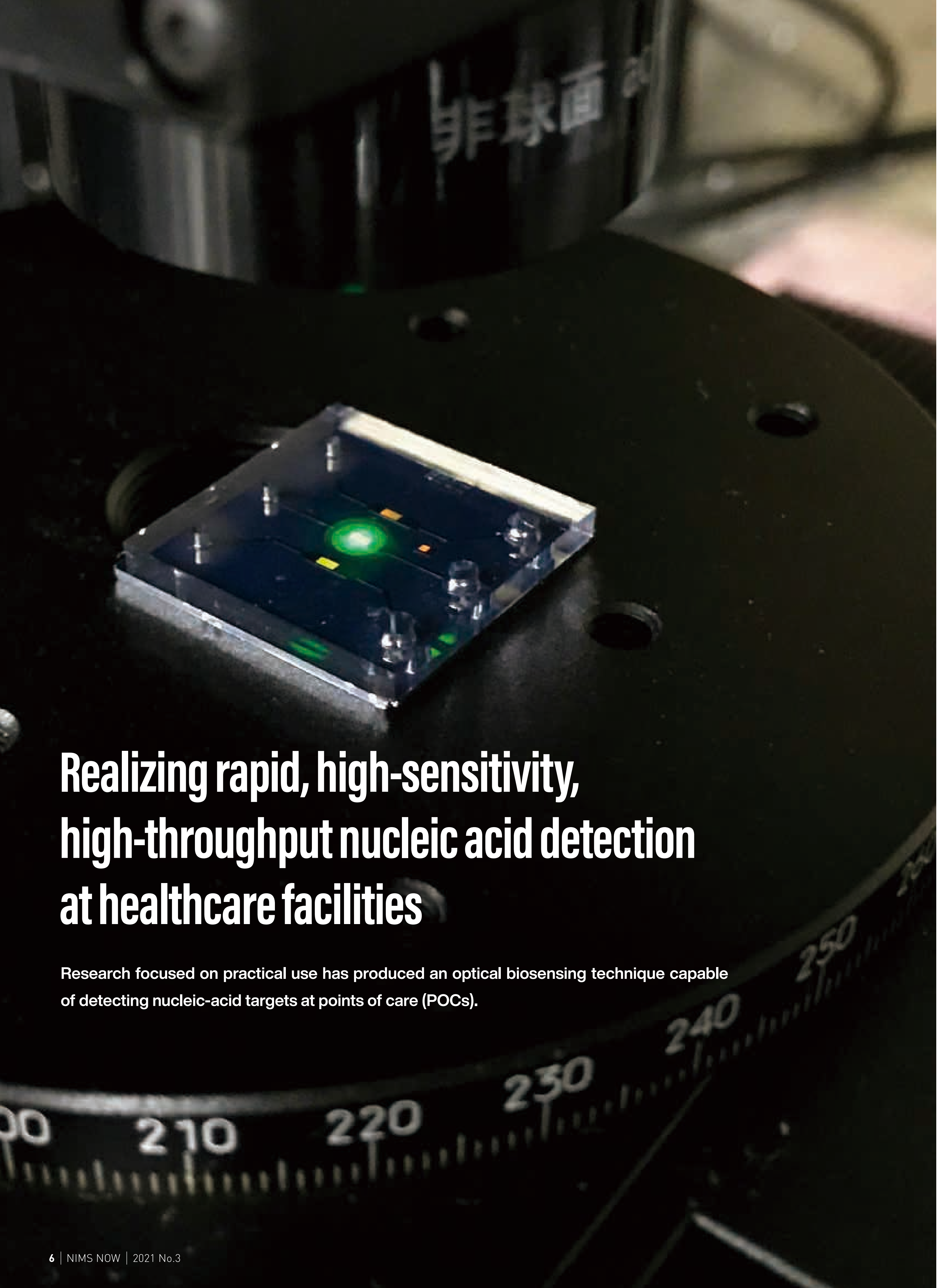
The importance of digital transformation (DX) in materials research is rapidly increasing. The Japanese government has drawn up strategies to promote innovation in materials research in order to further increase Japan's international competitiveness in materials R&D—a traditional strength. The purpose of this initiative is to make Japan the world leader in the development of a sustainable society capable of simultaneously achieving economic growth and solving social issues. The importance of DX is underscored in these strategies. NIMS and its predecessors have been able to conduct productive research by leveraging the abundant materials data they have generated over the years and NIMS has been actively using AI in recent years. NIMS is also developing a database system to collect, store and provide materials data from universities and public research institutes across Japan. (We will feature DX activities at NIMS in the next NIMS NOW issue.)

Attacking the underlying causes of social issues through strategic basic research

Social issues are becoming more severe and complex in this time of global transition and they need to be solved expeditiously. Some issues are of domestic importance while others, such as climate change and the COVID-19 pandemic, are of global significance.

Solving these social issues will require completely novel materials and transformational innovations. NIMS will boldly tackle significant challenges in this time of radical change.

(Text: Takeshi Komori)



Realizing rapid, high-sensitivity, high-throughput nucleic acid detection at healthcare facilities

Research focused on practical use has produced an optical biosensing technique capable of detecting nucleic-acid targets at points of care (POCs).

Public concern about health and medicine is now greater than ever before. Techniques to screen for unknown viruses such as the novel coronavirus must have high-throughput capacity in addition to being highly sensitive. The demand to develop these techniques has suddenly become an urgent social issue.

A NIMS researcher published research in 2021 on the development of an optical biosensor capable of detecting specific nucleic acids—a promising technology.

New concept for detecting nucleic acids

In novel coronavirus testing and genetic testing for early stage cancers, modern medical diagnostic techniques target nucleic acids, such as DNA and RNA. Many medical diagnoses can be made by analyzing the genetic information in the sequences of nucleic acids.

New types of cancer testing focus on the detection of specific nucleic acid sequences using next-generation sequencers. However, these tests are expensive and time-consuming. Therefore, low-cost, rapid methods and point-of-care testing (POCT) techniques are highly desirable. PCR tests for novel coronavirus infection are slow and labor-intensive because of the additional need to transport test samples from sampling locations to PCR testing laboratories.

Fluorescence biosensing is a POCT technique capable of detecting target nucleic acids in a bodily fluid sample by irradiating them with laser or LED light. Because a bodily fluid sample usually contains only a very small amount of nucleic acids, fluorescence intensity is usually enhanced to increase nucleic acid detection sensitivity. A current major trend in fluorescence biosensing research is to explore "hot spots."

A hot spot is a nanometer-scale location at which a very intense resonant electric field is induced, enhancing fluorescence intensity. However, hot spots are extremely small and identifying them requires highly specialized skills.

Would it be feasible to put fluorescence biosensing into practical use, including in POCT? Masanobu Iwanaga at NIMS developed a technology that has brought fluorescence biosensing one step closer to this goal.

Fluorescence detection of target nucleic acids at POCs

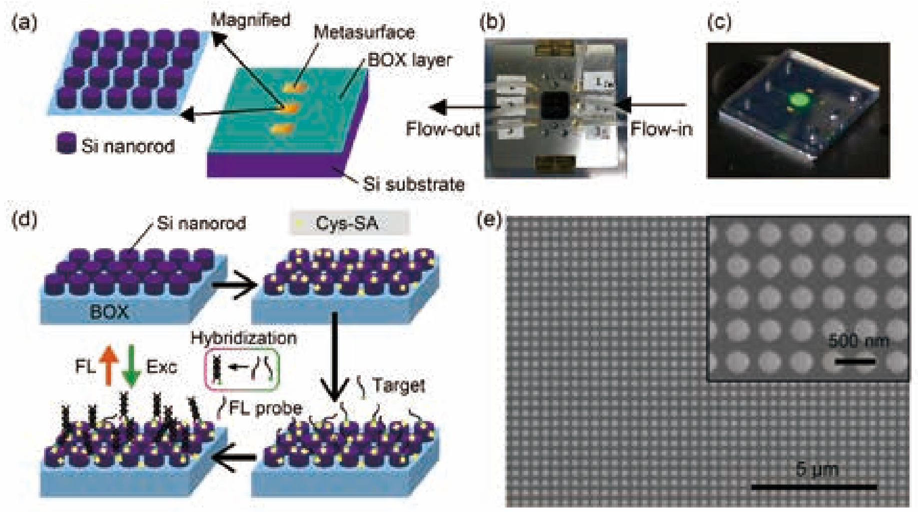
"I began my professional career as a physicist researching photoluminescence dynamics," Iwanaga said. "My research focus later shifted to the development of artificially designed nanostructures (i.e., metamaterials and metasurfaces) with novel functions. These previous research experiences led to the recent development of a fluorescence biosensing technique."

Iwanaga has developed metasurfaces composed of arrays of nanosized cubes and rods made of silicon (Figure 1(a)).

When a bodily fluid sample (e.g., a serum) flows over the metasurface substrate, target nucleic acids are captured and detected on the metasurface. For this metasurface to function properly as a biosensor, the nanorods first need to be coated with binding molecules targets. Second, these binding molecules have to capture the targets. Finally, fluorescence-labeled sequences complementary to the target flow over and hybridize with the targets. Thus, when the target nucleic acids are present in a sample, intense fluorescence is observed.

"The nanorods are precoated with chemically modified binding molecules," Iwanaga said. "This pretreatment allows only targeted nucleic acids to adhere to the nanorods. When the targets bind to the nanorods, the metasurface—independent of the positions at which the targets are bound—exhibits intense, uniform fluorescence. This is a fundamentally different mechanism from hot spot detection." Use of different types of binding molecules allows this technique to detect a wide-range of target biomolecules, including those of cancers and the novel coronavirus. Fluorescence intensities on nanorod surfaces can be more than 1,000 times greater than those on flat silicon surfaces.

Looking back on his recent fluorescence biosensing research, Iwanaga felt that the initial step—realizing metasurfaces that can greatly enhance fluorescence—was most challenging. "Many researchers have tried to conceive of a way of increasing fluorescence intensity on metasurfaces by thousands of times. However, finding the right metasurfaces to actually achieve this was very challenging. After overcoming this hurdle, I was able to expand the applicability of this technology by making slight modifications in a variety of ways. In retrospect, the chance of making the initial



Figu re 1. Metasurface sensor. (a) Schematic of the silicon metasurface structure (left) and appearance of metasurface substrate (right). (b) Metasurface sensor chip holder through which a sample fluid passes. (c) Metasurface sensor chip being illuminated by green LED light. (d) Procedure for capturing and detecting target nucleic acids on the metasurface. (e) Electron micrograph of the metasurface.
[Source: M. Iwanaga, Biosensors 11, 33 (2021)]

breakthrough was very slight and I was fortunate."

Research products must satisfy users' needs

It's important that this fluorescence biosensing technique be practical for use at clinical sites. "Testing for pathogens using serums and other bodily fluids is a common practice for medical diagnoses," Iwanaga said. "This biosensor can also be used to detect various pathogens through a simple procedure. You just need to prepare reagent kits tailored to the target pathogens in advance, coat the metasurface substrate with the reagent and introduce serum samples into the biosensor. Testing results can be obtained at POCs within a short period of time. My ultimate goal is to create a biosensor capable of delivering test results within 30 minutes."

This biosensor is able to quantify the amount of targets detected by evaluating different fluorescence intensities. Non-target molecules and microbes present in blood samples hardly affect test results. Moreover, Iwanaga succeeded in replacing gold, which he initially used to construct the nanostructures, with silicon to reduce production costs without compromising performance. These characteristics have increased the potential usability of the biosensor at POCs.

As described above, this technology is useful in detecting pathogenic viruses, including the novel coronavirus. Iwanaga believes that his research can meet social needs.

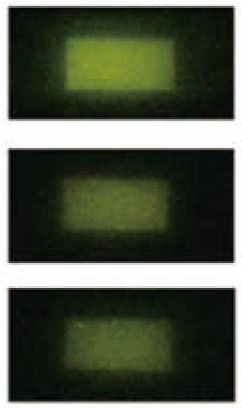
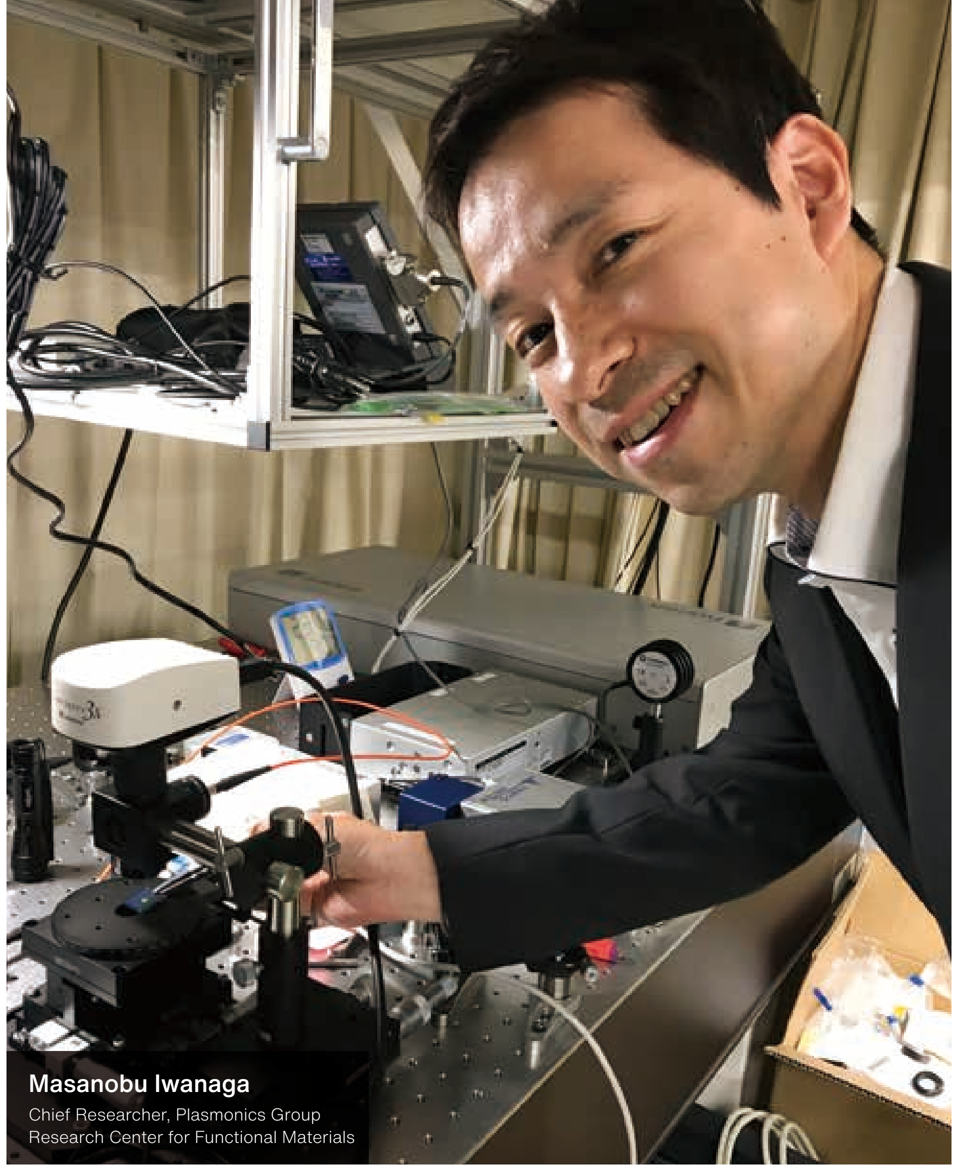

Target type: US CDC 1000 fmol/mL
50 fmol/mL
2.5 fmol/mL

Figure 2. Detection of novel coronavirus nucleic acids. The rectangular sensor is capable of detecting even very low concentrations of nucleic acids (2.5 fmol/mL). Detection of higher concentrations of nucleic acids is seen as brighter fluorescence.
[Source: M. Iwanaga, Biosensors 11, 33 (2021)]


Masanobu Iwanaga
Chief Researcher, Plasmonics Group
Research Center for Functional Materials

"Research projects are often designed to address specific needs," Iwanaga said. "However, your area of expertise does not always match these needs. For example, it would be difficult for researchers with expertise in organic synthesis to contribute to hydrogen production research even though it's a trendy research topic. This type of mismatch is common among researchers. What I was trying to achieve in my research was simple: my original interest was to increase fluorescence detection efficiency, finally resulting in improving the performance of biosensing. As I continued my research, the needs for viral detection suddenly arose. My research happened to suit social needs at the right time."

Iwanaga has already received a number of inquiries about his fluorescence biosensing research from medical researchers and others. "I want to put the technology into practical use as soon as possible in collaboration with private companies. However, it might take some time to do this because this testing method is quite different from conventional ones."

As mentioned above, hot spot detection has been the most popular idea for enhancing fluorescence intensity among biosensing researchers. However, hot spots are extremely small and identifying them is demanding—a major disadvantage for use at POCs. By contrast, the metasurface sensor is a more user-friendly and reproducible technique. Demand for this expeditious biosensor is likely to grow in the near future. "This novel technology can detect target nucleic acids substantially more quickly and easily than existing methods," Iwanaga said. "I'm confident that continued research and accumulation of promising results will eventually convince more healthcare providers regarding the usefulness of this technology."

(By Takeshi Komori)

Surface science contribution to give Olympic athletes a competitive edge

NIMS sometimes conducts unique problem-solving research for unusual clients. Some happen to be top athletes looking for ways to beat their rivals.


Ski waxes come in many colors.

Meeting athletes' needs using surface science

According to Kazuya Shimoda, a NIMS senior researcher, NIMS has been collaborating on research with world-class winter sports athletes for over a decade. "As our work with them deepened, I realized that my research results could really influence their chances of winning Olympic medals. This gave me a sense of great responsibility," Shimoda said with a smile.

Immediately after assuming a new position at NIMS in April 2013, Shimoda's then-superior Hideyuki Murakami invited him to conduct surface science research applicable to winter sports. Inspired by this, Shimoda became a surface science researcher.

NIMS launched this line of research when Murakami and Toshinobu Kawai (Associate Professor, University of Tsukuba) began jointly researching and developing speed skating skate blades. For this project, Shimoda and Murakami looked for ways of minimizing frictional resistance between the ice surface and skate blades. Their results led to the development of a technique capable of removing unwanted small particles from skate blade surfaces using plasma generated by a corona discharge. This technique was applied to the skates used by Japan's male athletes who competed in short-distance speed skating events during the 2014 Sochi Olympics.

After the Olympics, Shimoda received another request from the University of Tsukuba. This time, his mission was to investigate the friction generated between skis and snow surfaces during Nordic combined skiing. Nordic combined is a ski event in which athletes compete in both cross-country skiing and ski jumping. Skiers can improve their race times by using skis with superior gliding performance. Shimoda launched his research to find a means of improving the gliding properties of skis with his sights set on the 2018 Pyeongchang Winter Olympics.

Insights gained from ski wax composition analysis

Ski wax reduces frictional resistance between skis and snow surfaces. Because the wax gradually rubs off during long-distance cross-country skiing, several layers

Waxing skis for competitive athletes requires specialized skill and experience.

of wax need be applied. A base wax is first applied, followed by three to four layers of a glide wax and finally a top wax. These different wax layers have different roles. The top wax layer, which makes direct contact with the snow surface, is designed to enable skiers to make a strong dash at the start of a race. It scrapes off easily once skiers have gained speed and start gliding. This then exposes the subsequent wax layers, which are designed to facilitate gliding over long distances.

"The gliding performance of skis is influenced by various environmental factors, such as snow conditions, snow hardness, slope steepness and sun exposure levels (e.g., sunny and shady areas)," Shimoda said. "It is therefore important to select optimum wax compositions and durability for different sections of a race trail. There are several hundred different types of ski waxes. I need to compare all of them in order to determine the best wax to use for each layer."

Countries with traditional strength in cross-country skiing appoint as many as 10 wax experts. Their job is to narrow the vast list of available waxes to a fewer promising ones based on past experience and by actually trying waxed skis out on snow. By contrast, Japan's cross-country skiing team has only two or three wax experts and they are sometimes headhunted by other teams. To deal with this issue, the head coach of the Japanese Nordic combined team, Takanori Kono, made the following urgent requests to Shimoda: 1) develop an algorithm capable of simulating the way wax experts select optimum waxes; 2) scientifically assess the validity of the algorithm and 3) narrow the whole range of waxes available to a small number of promising waxes for use at the Pyeongchang Olympics.

Dedicated experiments under simulated race conditions

"Under warm conditions, snow softens and melts, producing water, which acts as a brake and slows down skiers," Shimoda said. "This problem can be reduced by adding fluorine to waxes, thereby increasing their water repellency. By contrast, ways of increasing skis' gliding efficiency when snow is hard and icy at lower temperatures are poorly understood. One published study has found that water molecules present on ice surfaces behave like a spinning gas, enabling objects in contact with an ice surface to slide more easily. However, this study concerns ice, not snow, which makes it necessary for me to find the answers myself. During actual races, harder waxes need to be used for colder snow. In addition, waxes need to be tough (i.e., resistant to abrasion) and impermeable to water molecules and ice crystals. I conducted wax R&D with these three requirements in mind. To create waxes that do not adsorb water molecules (H_2O), thereby preserving ice crystals spinning on the snow surface, I added chemical elements that do not bind with oxygen atoms (O)."

Shimoda accompanied the Japanese cross-country skiing team when it traveled to Pyeongchang to compete in the pre-Olympic skiing events. At the racing venue, he measured ambient temperatures and humidity and carefully inspected the temperature and conditions of the artificial snow distributed over the race trail. The race site was extremely cold, hitting temperatures below -10°C. He found that the snow temperature was about the same as the ambient temperature in shade and several degrees higher in areas exposed to the sun.

Shimoda inspecting snow conditions

Shimoda sampled artificial snow in Pyeongchang and brought it back to Japan. He then analyzed its composition and created very similar artificial snow. He conducted a series of indoor experiments under simulated race site conditions in which he allowed waxed skis to glide over the artificial snow at various snow temperatures and collected various data, including the friction coefficients between ski and snow surfaces, wax hardness and wax durability. Shimoda then analyzed the relationship between the parameters measured and wax composition. He therefore found that the friction coefficient and wax hardness vary depending on the fluorine content of the wax and the snow temperature. He also found that finding a hardness balance between artificial snow and wax is very important in improving wax durability.

When waxes are too hard, they scrape the snow, increasing frictional resistance and decreasing skis' ability to glide. Similarly, when waxes are too soft, they are scraped off by hard snow, decreasing skis' gliding efficiency. Shimoda therefore concluded that a perfect hardness balance between the snow and the waxes needs to be achieved by adjusting the fluorine content of waxes while taking snow temperature and hardness into account. Based on these analyses, Shimoda was able to narrow several hundred types of waxes, including ones he developed, down to about a dozen candidates from which optimum waxes could be selected on the days of the races.

Helping athletes win a medal through material optimization

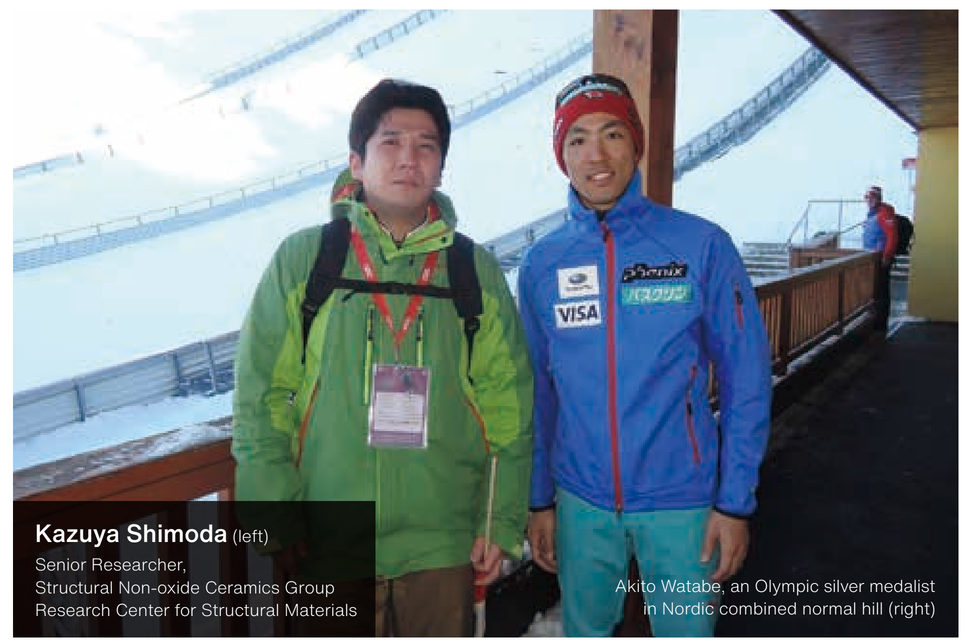
Before the Olympics, the Japanese cross-country skiing team competed in World Cup ski events. Shimoda accompanied the team to further increase his expertise in ski waxes. During the Pyeongchang Olympics held in February 2018, Akito Watabe won a silver medal in the Nordic combined normal hill event using ski waxes Shimoda had worked on.

"Winning an Olympic silver medal is a tremendous accomplishment. If my wax candidate selection made even a small contribution to his achievement, I'm very honored," Shimoda said humbly.

"Generally speaking, nearly all (99%) of a great victory can be attributed to the athlete's efforts," Shimoda said. "I hope that our efforts to optimize materials will provide them with the small (1%) competitive advantage they may need to win a medal by enabling them to ski a little faster and jump a little farther."

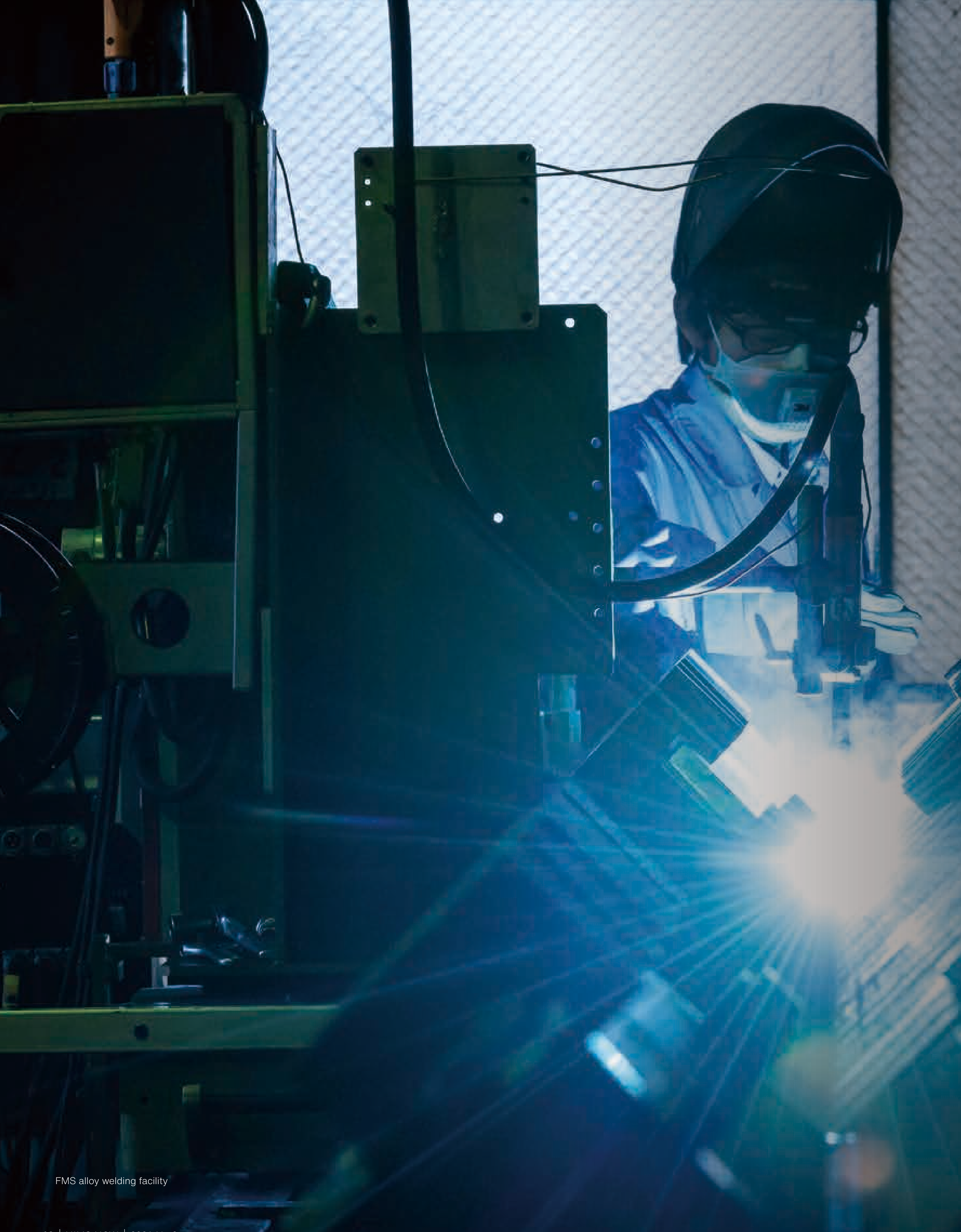
Advanced materials research will continue to meet the requests of top athletes.

(By Osamu Shimizu, Academic Groove Movement)



Kazuya Shimoda (left)
Senior Researcher,
Structural Non-oxide Ceramics Group
Research Center for Structural Materials

Akito Watabe, an Olympic silver medalist in Nordic combined normal hill (right)



FMS alloy welding facility

The second stage of FMS alloy seismic damper

Some technologies that are already in practical use need to be upgraded continuously. Seismic dampers are used to protect buildings from earthquakes. FMS alloys were developed by NIMS and in practical use as seismic dampers by its collaborators. Efforts to improve these alloys have been ongoing since their introduction.

Seismic dampers: anti-earthquake components in building infrastructure

Have you ever heard of seismic dampers? They are installed in buildings to absorb seismic wave energy during an earthquake. There are three approaches to protect buildings from earthquakes. First, sufficiently strong and ductile earthquake-resistant building design can be employed. Second, a building's superstructure can be substantially decoupled from the ground motion (i.e., seismic base isolation). The final approach is equipping a building to absorb seismic energy, thereby mitigating seismic motion. Since the 1995 Great Hanshin Earthquake, the number of buildings with base isolation structures and seismic energy absorption structures has increased. Concurrent with this trend, active efforts have been made across Japan to research and develop various anti-seismic structures, components and technologies. Seismic dampers are a type of seismic energy absorption structure.

Three types of materials are used in seismic energy absorption dampers: oils, viscoelastic materials and steels. Steel dampers have been most commonly used because they are comparatively low cost, require no maintenance and are very stiff. Researchers have therefore been seeking to develop higher performance steel dampers with longer fatigue lives.

The use of shape-memory alloys in seismic dampers is one potential means of achieving this goal. Some shape-memory alloys are known to be "superelastic": they are capable of returning to their original shapes without being heated when the external forces applied to them are removed. The idea of using these alloys as seismic damper materials was proposed more than 30 years ago, resulting in a number of research projects both in Japan and overseas to put them into practice. However, attempts to use superelastic nickel-titanium-based alloys as structural components were largely unsuccessful due to their high cost and poor workability.

New discovery inspired the development of FMS alloys

NIMS researcher Takahiro Sawaguchi and Takenaka Corporation had been jointly researching iron-based shape-memory alloys since 2003. Because these alloys are not superelastic, the research team initially considered them to be unsuitable for use in seismic dampers. However, the team later found that the fatigue properties of these alloys improve after they are subjected to repeated deformation.

"Contrary to popular belief, seismic dampers that lacksupersticity are more effective in absorbing seismic energy," said Atsumichi Kushibe, a former member of the joint research team (currently an associate director at Takenaka Corporation). "Our iron-based shape-memory alloys consistently exhibited long fatigue lives, which convinced us that they would make excellent seismic damper materials." The team has since focused its research on FMS alloys: shape-memory alloys composed primarily of iron (Fe), manganese (Mn) and silicon (Si).

Steel component production lines are usually designed to manufacture steel products containing approximately 1% Mn and 0.2–0.3% Si. By contrast, the iron-based alloys Sawaguchi's team developed normally contained 28% Mn, 6% Si and chromium (Cr). Because of the high Mn content of these FMS alloys, existing production lines were unable to manufacture them at a reasonable cost.

Awaji Materia and Nippon Koshuha Steel were the two companies responsible for the manufacturing of the FMS alloys Sawaguchi's team developed. They suggested to Sawaguchi that they would be able to produce the alloys if the Mn content could be reduced from 28% to 15%. To accommodate their request, Sawaguchi worked to modify the composition of the alloys. As a result, he succeeded in developing an FMS alloy with 15% Mn content (detailed composition: Fe-15Mn-10Cr-8Ni-4Si, where the numbers are the content in mass percentages). The addition of Cr and nickel (Ni) and optimization of the Si content improved the alloy's physical properties, including strength, workability, impact toughness and corrosion resistance, and enabled it to melt in an electric furnace.

"We faced many challenges before finally succeeding in reducing the FMS alloy's Mn content from 30% to 15%," Sawaguchi said. "We struggled to find the right alloy composition that exhibits desirable fatigue properties. This forced us to go back to the alloy with 30% Mn content and restudy its microstructure. FMS alloys do not have the ability to return to their original shapes by themselves. However, they can be restored to their original shapes when certain types of external forces are applied to them (e.g., back-and-forth earthquake shaking motion). FMS alloys are very resistant to fatigue caused by repeated deformation. I was able to reduce the alloy's Mn content without compromising its excellent fatigue properties. The key to this success was understanding how the crystalline structures of FMS alloys change in relation to changes in their compositions."

FMS alloy samples were successfully manufactured in 2012. They were approved for practical use as seismic damper materials by the Minister of Land, Infrastructure, Transport and Tourism in 2013 and were then installed in the JP Tower Nagoya completed in 2015.

Additional requirements for use in the Aichi Sky Expo building

After the successful installation of FMS alloy seismic dampers in the JP Tower Nagoya, they were approved for integration into the Aichi International Convention and Exhibition Center (a.k.a., Aichi Sky Expo). This project required the development of two new techniques: a welding technique to join FMS alloys with other metals to form desirable structures and a continuous casting technique for mass production of the alloys.

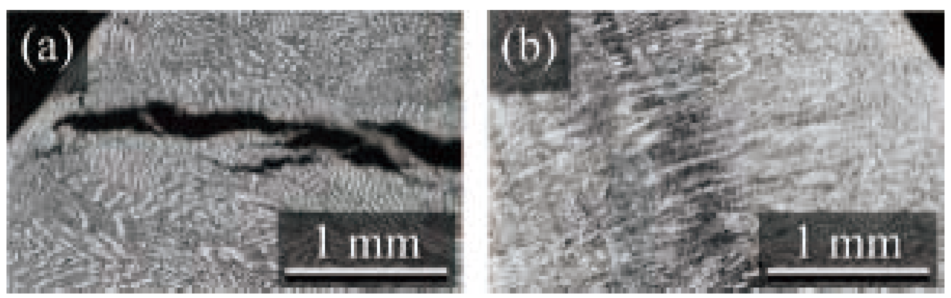
Proper welding techniques allow two different types of alloys to be joined together. The Aichi Sky Expo building was designed to employ many braces in its architecture, including brace-type dampers with FMS alloy core components. The dampers were welded into a cross-shaped beams with carbon steel plates and the joined structures were then bolted to the building framework (see the photo on p. 12).

"When we developed the first FMS alloy for use in the JP Tower Nagoya, we did not have time to make it adequately weldable to other metals due to the deadline for obtaining the approval of the MLIT Minister," Sawaguchi said. "Nevertheless, the alloy product met all requirements for the project. To achieve its widespread use, however, we had to address some issues, including improving its weldability to other metals."

In the JP Tower Nagoya project, FMS alloys were used as core components in large seismic dampers and were bolted to other damper components. However, bolting is often difficult in smaller dampers. FMS alloy weldability to other metals needed to be improved to make the alloys usable in a wider range of architectural designs. This was achieved by a research group led by Terumi Nakamura (leader of the NIMS Welding and Joining Technology Group) before the alloys were submitted for the approval of the MLIT Minister for use in the soon-to-be-constructed Aichi Sky Expo building.

The second technical challenge was continuous alloy casting. This was achieved by Awaji Materia and Nippon Koshuha Steel. NIMS contributed to their efforts by performing product quality assessments. The use of this casting technique increased the maximum size of a single batch of an FMS alloy from 10 tons to 60 tons.

The construction of Aichi Sky Expo—the fourth largest exhibition space (60,000 m^3) in Japan—was completed in 2019.



(a) First-generation FMS alloy. Cracks are caused by high temperature. (b) Second-generation FMS alloy. No crack has developed under the same high temperature conditions. [F. Yoshinaka, et al., Scripta Mater. 197 (2021) 113815]

Further improving FMS alloys by correcting uneven phosphorus distribution

After the success in welding FMS alloys to other metals during the Aichi Sky Expo project, the research team worked to weld two FMS alloy pieces together. Achieving this would enable the processing of the alloy into many different shapes, which would in turn provide greater architectural design flexibility. Making it possible to perform this type of welding without specialized skills was also desirable in order to reduce labor costs.

Some welding techniques used to join two FMS alloy pieces are known to cause uneven distribution of the phosphorus present in small quantities within the alloys. This makes the alloys prone to developing fatigue cracks, shortening their lives. While skilled welding engineers can prevent this problem, promoting widespread use of FMS alloys made a solution not reliant on specialized skill desirable.

During the casting of FMS alloys, phosphorus concentrations are minimized. However, welding causes phosphorus concentrations to localize, making phosphorus distribution across alloys uneven. Correcting this uneven distribution was vital in making FMS alloy seismic dampers useful for a wide range of applications.

Creating second-generation FMS alloys from scratch

To address the phosphorus issue, Sawaguchi and his colleagues first developed a method of predicting the fatigue lives of alloys based on atomic movement within them and used it to investigate the mechanisms behind the long fatigue lives of FMS alloys.

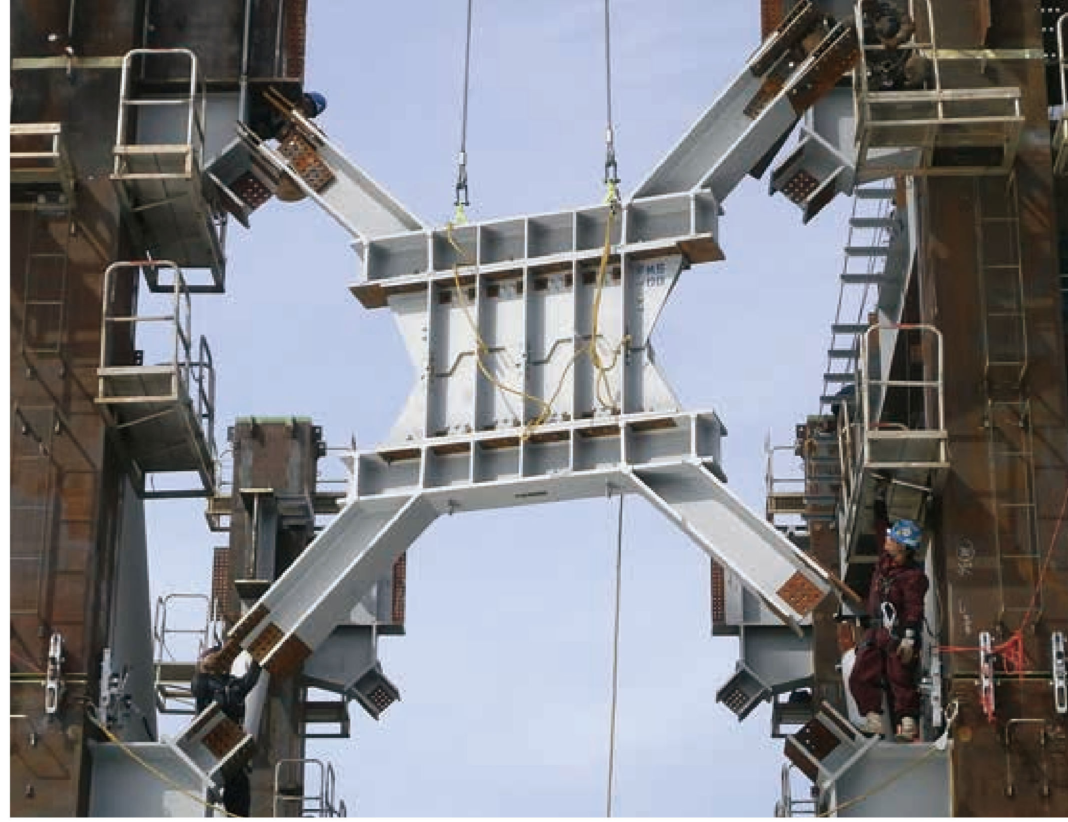
Sawaguchi's team then fundamentally reassessed the compositions of FMS alloys. Welding two pieces of the same type of regular steel together causes phosphorus present in them to distribute unevenly. The known remedy for this is to adjust the Cr/Ni ratio. The optimum Cr/Ni ratio can be determined using the Schaeffler diagram, a tool applicable to a variety of steel materials.

However, it eventually became clear that the Schaeffler diagram* is not directly applicable to FMS alloys due to their novel compositions. Since no other method of predicting optimum Cr/Ni ratios was available, Sawaguchi's team decided to find it experimentally. They prepared many alloy samples with different compositions from scratch, welded pieces from the same alloy samples together and collected data. The team worked with Nakamura's group to formulate and weld alloys and continued their joint research with Takenaka Corporation.

Sawaguchi and his colleagues finally succeeded in finding the optimum Cr/Ni ratio in March 2021. The team increased the Cr by 1% and reduced the Ni by 0.5% by weight, thereby creating a new FMS alloy which can be welded to another piece of the same alloy without developing hot cracking. In addition, fatigue durability was confirmed to be as excellent as previously developed FMS alloys. These results have been published in a scientific journal (see the figure on p. 14).

The newly developed alloy was called a second-generation FMS alloy to reflect the fact that its composition was completely and precisely readjusted. Changes were made not only to the concentrations of traditional alloy constituents (Fe, Mn and Si) but also to the more unconventional ones (Cr and Ni).

The published study garnered a huge response and the research team has received many inquiries from overseas, particularly from earthquake-prone Asian regions. In addition, second-generation FMS alloy research was accepted for funding in 2020 from the industry-academia collaborative R&D category of the A-STEP Program (Adaptable and Seamless Technology Transfer Program through Target-driven R&D) run by the Japan Science and Technology Agency (JST). This research is therefore attracting a great deal of interest and expectations for it are high.



FMS alloy seismic damper being integrated into the JP Tower Nagoya

Perfecting FMS alloys: basic research that meets social needs

Sawaguchi feels fortunate that his recent basic research led to the production of practical materials.

"My general research approach has been to ensure that my scientific pursuits contribute to society," Sawaguchi said. "Given that reinforcing Japan's civil infrastructure is an urgent social issue, I have always searched for structural materials research projects that match this demand. I was very fortunate to be involved in these FMS alloy projects. Our focus has been to design strong seismic dampers with long fatigue lives and high energy absorption capabilities—technologies vital to protecting lives and assets from large earthquakes."

Sawaguchi is also aware of the great importance of achieving widespread use of FMS alloys. "Development of the first-generation FMS alloy was very well received because it was actually put into practical use," Sawaguchi said. "However, large-scale commercialization of it is a whole different challenge. Commercialization of new materials is impossible unless they are profitable. It is therefore important for materials research to take into account material and production costs, economic feasibility and marketability. At the same time, we also need to fulfill our mission as basic scientists: advance understanding of fundamental mechanisms behind physical phenomena of interest." Sawaguchi's FMS alloy research is far from over as he wants to further improve the alloys' usability and durability. "There is still room for improvement," Sawaguchi said. "This research will be considered completed when the working mechanisms of FMS alloys are understood and their widespread use is achieved."

(By Takeshi Komori)

Takahiro Sawaguchi
Leader of the Vibration Control Materials Group
Research Center for Structural Materials

* The Schaeffler diagram is a tool for predicting the amount of ferrite within metallic welds. It is used to estimate the quantity of chemical elements in the weld based on the compositions of base materials and weld metals.

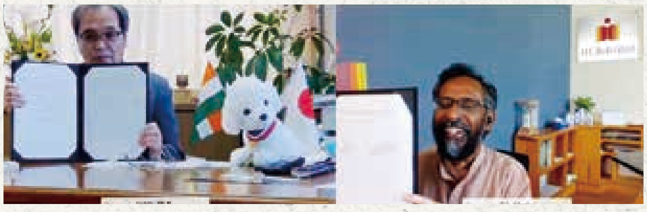
NIMS NEWS

NIMS and IITH launched Joint Research Center

The Indian Institute of Technology Hyderabad (IITH) and NIMS signed an agreement for opening "IITH-NIMS Joint Research Center" on 6th April 2021.

IITH is one of the world-renowned Indian Institutes of Technology (IITs) for science and engineering education. Hyderabad is a University with particularly close ties to Japan as it was established using technical and financial support from the Ministry of Foreign Affairs of Japan and Japan International Cooperation Agency (JICA).

The opening of this joint research center will further strengthen these ties and support the future leaders of both countries to achieve the best research results in the field of materials science.



The online signing ceremony for the joint research center installation contract. Prof. Hashimoto (President of NIMS, left) and Prof. Murty (Director of IITH, right).

NIMS Scientist Wins the 9th PSIPW

Dr. Sherif El-Safty (Independent Scientist of NIMS, left) and Prof. Hashimoto (President of NIMS, right).

Dr. Sherif El-Safty, Independent Scientist of NIMS, received 9th Prince Sultan Bin Abdulaziz International Prize for Water (PSIPW) in the category of Creativity Prize.

PSIPW is a scientific prize with a focus on innovation, inventors and research organizations around the world which contribute to the sustainable availability of potable water and the alleviation of the escalating global problem of water scarcity. Dr. El-Safty's team has developed novel nano-materials that quantitatively detects and selectively removes a wide range of water contaminants in a single step.

Hi, my name is Daniel and I am from the UK. I have been a researcher at NIMS since November 2017, originally as a JSPS fellow with Dr. Jonathan Hill, before joining ICYS in December 2019. My research focuses on the synthesis of new chromophores for the production of singlet oxygen and their subsequent incorporation into nanomaterials. Working at NIMS has allowed me to apply my training in organic chemistry towards applications in materials science by developing my skills in this field, leading to new and unexpected results in my research.

Coming to Japan has been a great experience, allowing me to encounter the culture and meet many researchers from Japan, as well as people from all over the world. I have been able to travel to many places in Japan, from the far north prefecture of Hokkaido, for the snow festival, to the farthest south prefecture of Okinawa, and many in between. Japan is a fantastic country to live in for those who are interest in conducting research in a place that also allows for some adventures!

Daniel Payne
(British)
ICYS Research Fellow

Visiting Chureito Pagoda in Kawaguichiko with my partner and parents. The left is me.

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To subscribe, contact:
Dr. Yasufumi Nakamichi, Publisher
Public Relations Office, NIMS
1-2-1 Sengen, Tsukuba, Ibaraki, 305-0047 JAPAN
Phone: +81-29-859-2026, Fax: +81-29-859-2017, Email: inquiry@nims.go.jp

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