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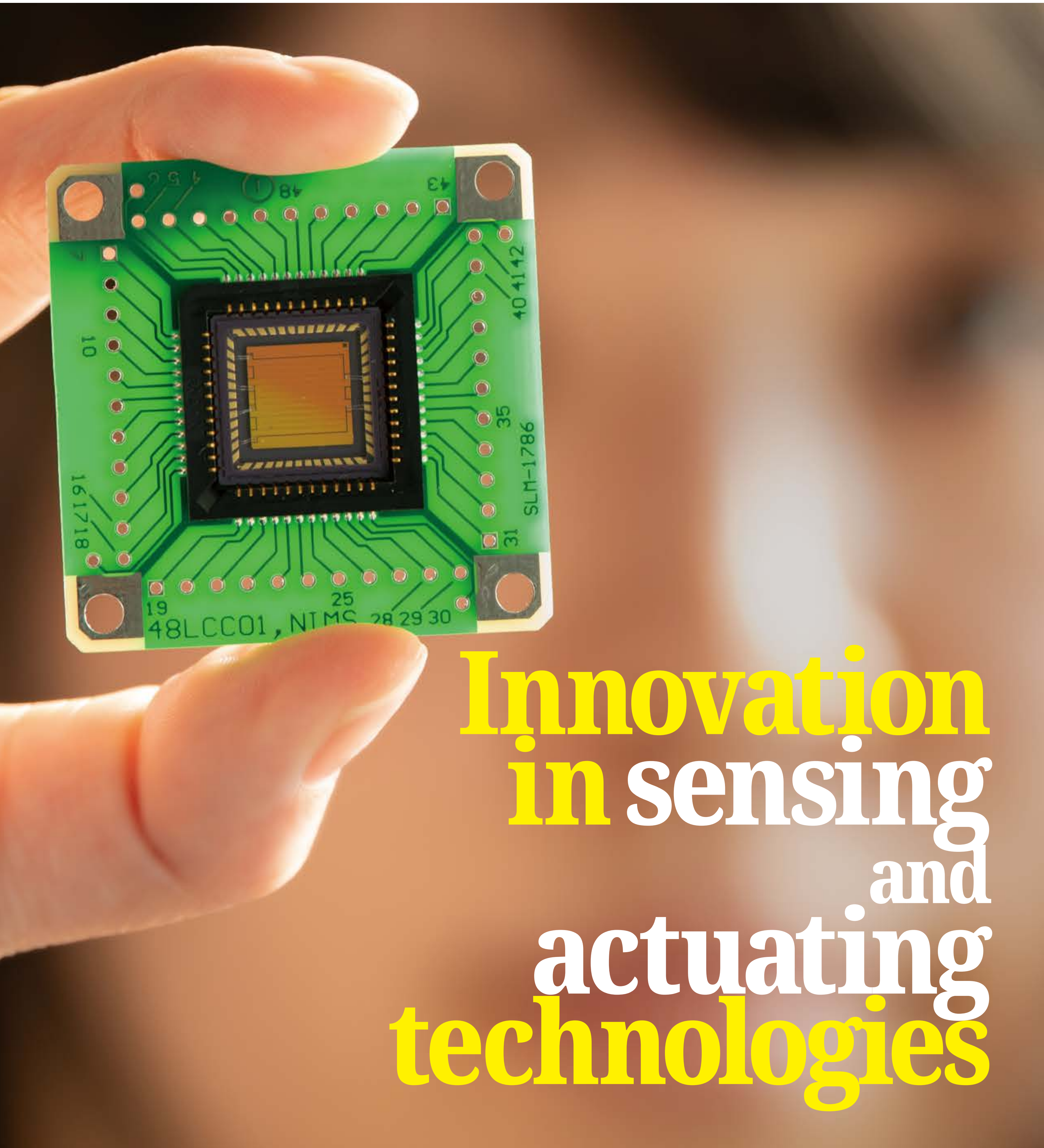
NIMS NOW INTERNATIONAL
NATIONAL INSTITUTE FOR MATERIALS SCIENCE
No. 1



Innovation in sensing and actuating technologies

Innovation in sensing and actuating technologies

Japan's Society 5.0 is an initiative to develop an advanced information society which will represent nothing less than a new phase in human social evolution, akin to the shift from hunting and gathering to agriculture and from that to an industrial society. The goal of this initiative is to solve social issues by collecting various data in physical space (the real world), analyzing it in cyber (virtual) space and taking appropriate actions in the real world in response. This process involves advanced technologies, such as AI, IoT, robotics and big data.

The system required to achieve this goal has two key components: sensors and actuators. Sensors collect real-world data, convert it into electrical signals, and transmit it through cyberspace. Actuators receive and interpret these electrical signals and solutions generated in cyberspace and translate them into physical actions to address issues in the real world.

What types of sensors and actuators need to be developed to bring the Society 5.0 concept into reality? NIMS researchers have been tackling this great challenge.

Research leaders answer questions

Sensors and actuators: linchpins of the Society 5.0 initiative

NIMS launched a project to develop sensors and actuators in 2018 with the aim of inventing innovative devices and systems vital to bringing Japan's Society 5.0 vision into reality. Jin Kawakita, a project leader, is directing the development of sensors, while Masayuki Takeuchi is coordinating the development of actuators. We asked these two leaders about their current progress and the future prospects of the project.

Ambition to create novel sensors and actuators

— What are the driving forces behind this project and what are its goals?

Kawakita: The objective of the Society 5.0 initiative is to establish systems capable of collecting large amounts of data from physical space (the real world) and analyzing it within cyberspace (using computers and servers) to identify and recommend solutions to real-world problems. For this purpose, diverse types of data need to be collected. However, existing sensors are inadequate or even unable to collect certain types of data. Our research therefore focuses on creating sensors capable of collecting these types of data and transmitting them through cyberspace.

In addition to the need for new sensors, actuators are needed that are capable of acting for other devices and people in the real world in response to data analysis performed in cyberspace. Actuators that will be in direct contact with people will need to be made of soft materials and move adaptively. Because practical actuators with these characteristics are not used very much around us today, our main goal is to develop them.

— These goals sound very challenging.

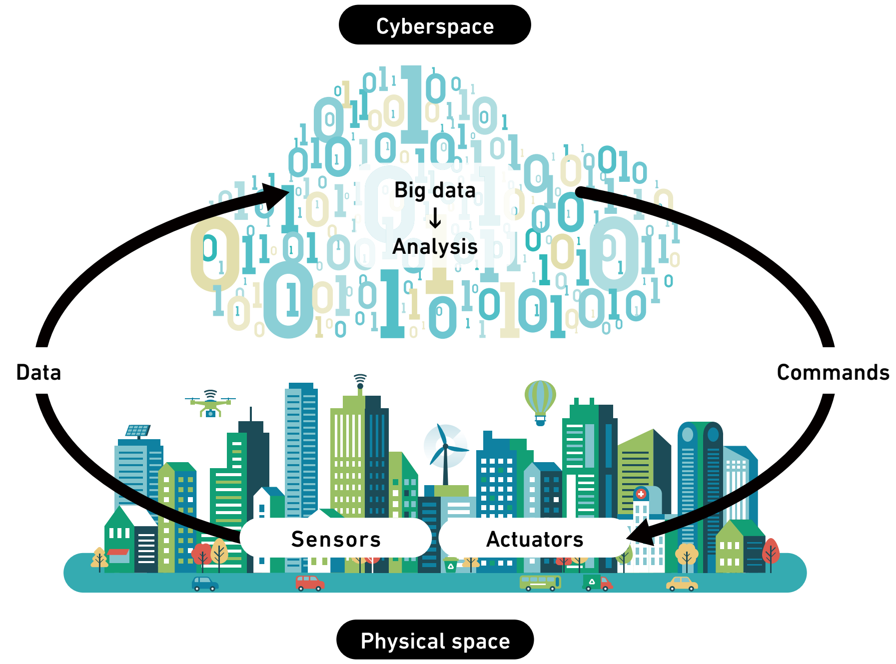
Takeuchi: Yes, indeed. The sensors we need to develop for the Society 5.0 initiative must be able to convert measurement data into electrical signals, a form compatible with transmission through cyberspace. This is very difficult to achieve. All previous attempts to convert gas flow data and data on the amount of fine water droplets detected in the air into electrical signals have been incomplete. The researchers working on this project are dedicated to finding ways of achieving data-signal conversion.

Kawakita: NIMS is undertaking these challenges because of its strengths in materials science and microfabrication techniques. For example, NIMS has succeeded in significantly improving the detection sensitivity of gas and biomolecular sensors using metamaterials: materials with micropatterns which have enabled them to exhibit new functions (see p. 10 for gas sensors).

Takeuchi: With regard to actuator development, NIMS has little experience with soft materials as its main research targets have generally been metals and other inorganic materials. However, we decided to work on soft actuators after carefully examining the research interests of individual project participants. Our research focus can be divided into two types of materials: ion-containing polymeric membranes that can bend in response to voltage application and shape-memory polymers (see p. 14).

Kawakita: Bendable polymer membranes may potentially be used to develop haptic technologies that can reproduce tactile sensation (see p. 12), such as remote palpation technology.

Takeuchi: Yes, that's a possibility. Soft actuators also have an issue to overcome, however: they lack the ability to apply force. Although this problem can be solved to some extent by stacking many membranes, this also makes the movement of the material sluggish. To resolve this issue, we are working to improve the materials we are researching and conducting basic research on actuators with new working principles.



Functions of sensors and actuators in Japan's Society 5.0 concept

Sensors installed in physical space collect various types of measurement data and transmit them through cyberspace. The aggregated data is then analyzed using AI and other technology. Analytical results are translated into commands, which are then sent to actuators via cyberspace.

Accelerating development through dynamic approaches

— Do you have any unique ways of advancing this project?

Kawakita: This project has been conducted in two ways: team research, in which team members work together to achieve common objectives, and independent research, in which individual NIMS researchers—whose proposals have been selected—conduct their own research. In addition, we annually invite renowned experts from various fields, including sensors, actuators, IoT and AI, to strictly evaluate each of our research subjects in terms of their progress and direction. Through this process, promising subjects are selected annually, making this entire project very dynamic.

Takeuchi: I'm participating in team research that explores actuators with new working principles. Some of our team members are also engaged in other subjects, such as researching cellulose nanofibers and developing organic material-based electrodes. I greatly value our team research format in which individuals with different expertise work together to achieve common, challenging goals. I also recognize the importance of individuals engaged in independent, challenging research as their contributions are making the entire project more robust.

— What are the future prospects of the project?

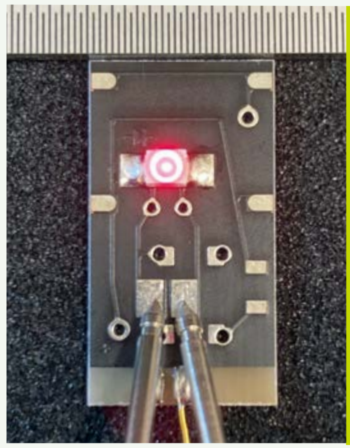
Takeuchi: The Society 5.0 initiative has united NIMS researchers specialized in organic materials and polymers in the effort to develop soft actuators. Although we virtually started from scratch, we were able not only to develop actuator materials but also to actually test the movement of actuators within a relatively short period of time, greatly boosting our confidence. While we still have many issues to overcome, we intend to work together until we are able to make recommendations about actual settings in which our actuators would be most useful.

Kawakita: Through this project, we've also gained know-how on the assembly of materials to create sensing and actuating devices/systems and developed collaborative partnerships. As a result, we've been able to expedite our development efforts. These are our major achievements so far. I believe that this experience will help us accelerate our future effort to develop a device using novel materials. While NIMS traditionally works in active collaboration with raw material manufacturers, in this project, we're also working with many companies that produce nearly complete products. With the help of these companies, I hope we can put the devices we've developed into practical use.

Sensor/actuator research

NIMS researchers have been developing sensing and actuating devices/systems with a wide range of applications, including healthcare, agriculture and the environment. The following is a list of NIMS' ongoing research subprojects.

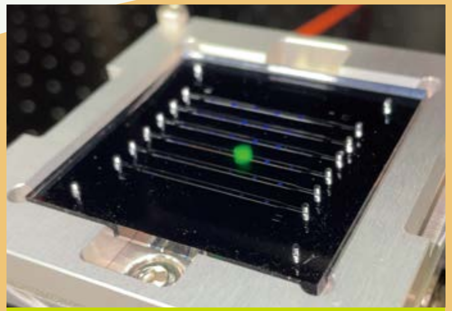
Healthcare



Light source for optical sensing

Principal investigator: Takayuki Nakanishi
Affiliation: Luminescent Materials Group
Areas of application: healthcare

We have developed a novel, small, high-output near-infrared emitter using phosphors developed by NIMS. A combination of this light source and existing optical sensors may be used to analyze a person's vital signs and to conduct agricultural and food analyses.



Biomolecular sensor

Principal investigator: Masanobu Iwanaga
Affiliation: Plasmonics Group
Areas of application: healthcare

This metasurface sensor detects various biomolecules, including DNAs and proteins, with high sensitivity. It can be used to diagnose diseases in their early stages.

Haptic actuator

Principal investigator: Masafumi Yoshio
Affiliation: Molecular Mechatronics Group
Areas of application: healthcare
See p. 12.

Periodontal bacteria sensor

Principal investigator: Akihiro Okamoto
Affiliation: Electrochemical Nanobiotechnology Group
Areas of application: healthcare

This sensor can quantify periodontal bacteria in saliva by measuring the small amounts of electricity that bacteria's metabolism produces. The sensor may serve as a handy tool for the easy detection of periodontal diseases at nursing homes and hospitals.

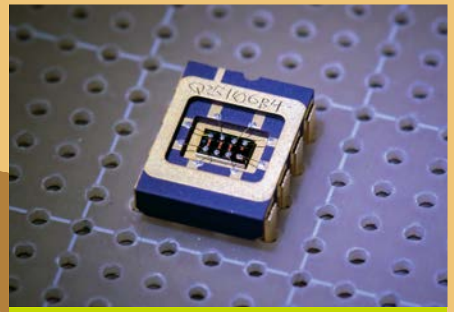
Shape-memory surgical suture

Principal investigator: Mitsuhiro Ebara
Affiliation: Smart Polymers Group
Areas of application: healthcare
See p. 14.

Olfactory sensor

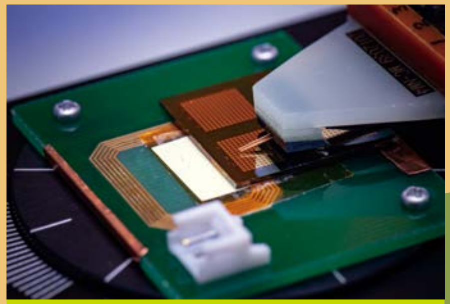
Principal investigator: Genki Yoshikawa
Affiliation: Olfactory Sensors Group
Areas of application: agriculture, healthcare

We measure complex odors using multiple sensors and analyze odor patterns using AI. We are investigating the applicability of this olfactory sensor system in a variety of sectors, including the agriculture and livestock industry, medicine and healthcare.



Imaging of environmentally harmful gases

Principal investigator: Hideki T. Miyazaki
Affiliation: Plasmonics Group
Areas of application: agriculture, environment, etc.
See p. 10.



Magnetic sensor

Principal investigator: Tomoya Nakatani
Affiliation: Magnetic Materials Group
Areas of application: healthcare, environment, etc.
See p. 8.

Paper actuator

Principal investigator: Junko Aimi
Affiliation: Molecular Mechatronics Group
Areas of application:environment, etc.

This "paper actuator" is made from cellulose nanofibers containing ions. When a voltage is applied, the paper bends due to the movement of ions.

Hydrogen sensor

Principal investigator: Taku Suzuki
Affiliation: Ceramics Surface and Interface Group
Areas of application: environment, etc.

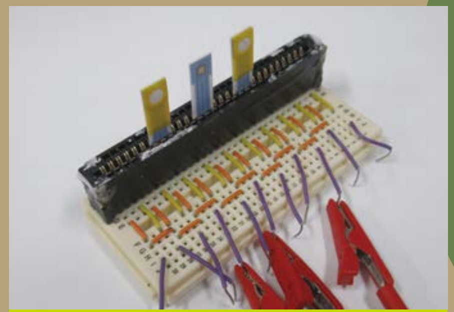
This sensor is capable of measuring hydrogen with a high degree of selectivity and sensitivity using a combination of chemical reactions that take place on its surface and at its electrode interface. The possible application includes monitoring hydrogen leaks at hydrogen fueling stations.

Agriculture

Moisture sensor

Principal investigator: Jin Kawakita
Affiliation: Electrochemical Sensors Group
Areas of application: agriculture, healthcare

This sensor is capable of detecting fine water droplets in the air with a high degree of precision. It can detect dew condensation—a cause of plant diseases—in the early stages. It also can be used to measure fingertip perspiration, an indicator of heatstroke risk.



Aldehyde sensor

Principal investigator: Shinsuke Ishihara
Affiliation: Frontier Molecules Group
Areas of application: agriculture, environment, etc.

This sensor uses a series of chemical reactions to measure formaldehyde, a cause of "sick building syndrome", and to detect ethylene, a plant hormone that causes fruit to ripen.

Micropump

Principal investigator: Taichi Ikeda
Affiliation: Electronic Functional Macromolecules Group
Areas of application: healthcare, environment, etc.

We have fabricated a prototype electrically driven polymeric actuator. Our goal is to develop a wearable device equipped with an insulin administration controlling actuator for use by diabetic patients.

Heat flux sensor

Principal investigator: Yuya Sakuraba
Affiliation: Magnetic Materials Group
Areas of application: environment, etc.

This sensor is capable of quickly measuring the flow of heat (heat flux) before it causes the change in temperature. The device may be useful to conserve energy within a system by speedily detecting thermal energy loss.

Environment and other fields

SENSOR RESEARCH 1

Research on magnetic sensors for biosensing and ultra-high-density magnetic recording

Some materials and devices show change in electrical resistance in response to an externally applied magnetic field. This phenomenon, called magnetoresistance, was discovered in 1856. Various types of magnetoresistance effects have since been identified, including giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR). These effects have been exploited in magnetic sensors and memory devices. Tomoya Nakatani has been researching and developing two types of next-generation magnetic sensors: an ultrasensitive magnetic sensor for use in biosensing and an ultra-high-resolution magnetic sensor to read the nano-scale magnetic bits in hard disks.

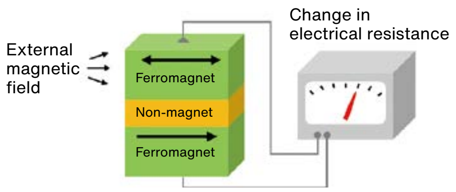
Research on ultrasensitive magnetic sensors for biosensing

The heart and brain are known to generate extremely faint magnetic fields in the picotesla (10^{-12} T) to femtotesla (10^{-15} T) range. Measuring these magnetic fields is useful in diagnosing cardiac, cerebral and neural diseases. Currently, only a superconducting quantum interference device (SQUID) is able to measure such subtle magnetic fields. However, because a SQUID is a large and expensive instrument in which superconductors operate at cryogenic temperatures, its use has been limited to major hospitals and research institutions. Nakatani has been working to develop a smaller and cheaper alternative to a SQUID capable of measuring cardiac and cerebral magnetic fields.

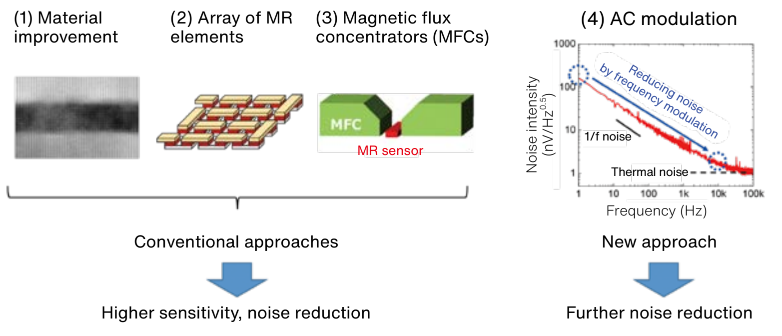
"There is particularly high demand for technologies capable of taking magnetocardiographic measurements from fetuses," Nakatani said. "Electrocardiography—a method of measuring electrical signals generated by the heart—is currently used to diagnose and treat cardiac diseases. However, this method is inapplicable to fetuses because their bodies are covered in vernix, a greasy substance that acts as an electrical insulator. Unlike electrical signals, magnetic fields can be measured through vernix. Magnetocardiographic measurements therefore could be used to detect cardiac diseases in unborn children. A brain–machine interface (BMI)—a direct communication pathway between the brain and an external device, such as a robotic arm—currently uses the brain's electrical signals. In addition to these electrical signals, measuring the brain's magnetic fields would allow more sensitive monitoring of cerebral activities, improving BMI precision. For these reasons, researchers have been trying to develop smaller, cheaper sensors capable of measuring cardiac and cerebral magnetic fields."

The global research community has been working to develop ultrasensitive magnetic sensors using a combination of three approaches: (1) enhancing sensor materials, (2) using an array of magnetoresistance elements and (3) using magnetic flux concentrators (MFCs). The second approach is intended to reduce magnetic noise by interconnecting multiple magnetoresistance elements. The third approach aims to increase the sensitivity of a magnetic sensor by concentrating the magnetic flux of interest. Nakatani is working to enhance the materials used in TMR sensors by sandwiching an insulation layer between two ferromagnetic layers. In addition, he is attempting to optimize the design and processing methods for magnetoresistance element arrays and MFCs.

Nakatani is also working to reduce magnetic noise using a new, fourth approach: frequency modulation by alternating current magnetic field (called AC modulation). The noise generated by magnetoresistance elements generally increases as frequency decreases (i.e., the 1/f noise phenomenon). The 1/f noise can be reduced by improving sensor materials, but only to a limited extent. Nakatani is therefore developing a technique to substantially reduce 1/f noise by increasing sensor operation frequency. Nakatani spoke of his ambitious goal. "Using a combination of the four approaches, including AC modulation, I hope to achieve picotesla sensitivity before this project ends at the end of FY2022."



Working principle of a magnetoresistance sensor
In principle, a magnetoresistance sensor has a triple-layered structure: a non-magnetic layer sandwiched between two ferromagnetic layers. When an external magnetic field is applied to the sensor, the magnetization direction in one of the ferromagnetic layers changes (the top layer in this diagram), causing the electrical resistance of the three-layered structure to change due to the magnetoresistance effect. The strength of the external magnetic field can be measured by gauging this change in electrical resistance. A giant magnetoresistance (GMR) sensor has a non-magnetic middle layer made of a metal while a tunnel magnetoresistance (TMR) sensor has a non-magnetic middle layer made of an insulator.



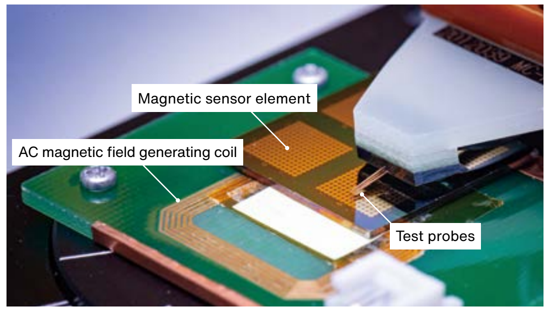
Four approaches to developing a highly sensitive magnetic sensor

Development of a next-generation magnetic sensor for ultra-high-density hard disk read heads

Nakatani is also researching and developing a magnetic sensor capable of reading data on ultra-high-density hard disks.

The recording density of hard disks has significantly increased amid rapid expansion in the amount of digitally stored information. The world's first practical hard disks released in 1956 had an areal density (the quantity of information that can be stored within a given surface area) of 2 kilobits/in^2. Today, this density has increased to 1 terabit (10^{12} bits)/in^2—more than 500 million times the original density. The highest possible hard disk areal density is said to be 5 terabits/in^2. The next-generation magnetic sensors (i.e., read heads) capable of reading these ultra-high-density hard disks will need to be very small and have a large signal-to-noise ratio.

The most prevalent type of read head until around 2005 was the GMR sensor, which is composed basically of a non-magnetic metal layer sandwiched between two ferromagnetic metal layers. These GMR sensors have since been replaced by TMR sensors. However, TMR sensor performance has already reached its theoretical limits. The middle layer in a TMR sensor is an MgO insulator, making it difficult to reduce the electrical resistance of the three-layered sensor film and increase its magnetoresistance ratio. As an alternative to TMR sensors, Nakatani has been researching CPP-GMR (current-perpendicular-to-the-plane giant magnetoresistance) sensors for many years. Unlike GMR sensors, in which the electric current flows parallel to the plane of the sensor film, in CPP-GMR sensors, electric current flows perpendicularly, enabling these sensors to produce larger magnetoresistances. In addition, the electrical resistance and noise of CPP-GMR sensors are smaller than those of TMR sensors because they are composed entirely of metallic films. However, existing CPP-GMR sensors equipped with ferromagnetic layers composed mainly of cobalt and iron have small magnetoresistance ratios, making them unsuitable for use as read heads in ultra-high-density hard disk drives.



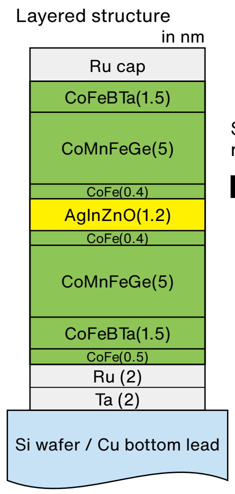
AC modulation experiment

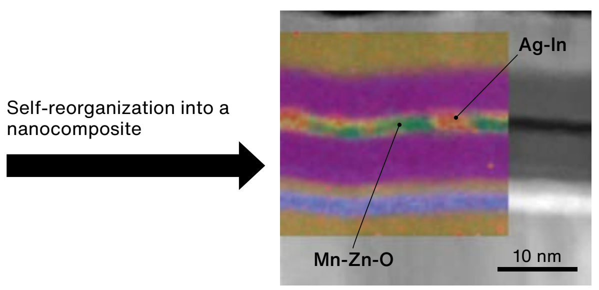
To overcome this problem, Nakatani developed a new CPP-GMR sensor in which a silver-indium-zinc-oxide layer—a metal–oxide hybrid material—is sandwiched between two ferromagnetic Heusler alloy layers (composed of cobalt-manganese-iron-germanium alloy). This sensor was confirmed to be able to show the capability to a hard disk with an areal density of 2 terabits/in^2 in 2019.

Although Nakatani succeeded in identifying the optimum material compositions through systematic experimentation, he was uncertain of the mechanism responsible for his CPP-GMR sensor's high performance. Nakatani therefore asked his NIMS colleague to conduct a structural analysis using a scanning transmission electron microscope shortly after his success. This analysis revealed the secret behind the material's performance. "Manganese in the Heusler alloy layers spontaneously diffused into the silver-indium-zinc-oxide layer, resulting in the self-organization of a nanocomposite layer composed of a mixture of manganese-zinc-oxide insulators and silver–indium alloys," Nakatani said. "Electric current flows only through silver–indium alloys, simultaneously reducing the electrical resistance of the sensor film and increasing its magnetoresistance ratio, which led to the high performance. NIMS has world-class structural analysis technologies, which enabled me to make rapid progress in my R&D."

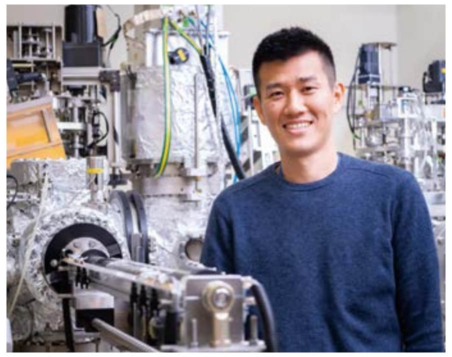
Inspired by Nakatani's success, some private companies resumed their temporarily suspended CPP-GMR R&D. "Although I still need to overcome some hurdles, I hope to put this CPP-GMR sensor into practical use as soon as possible by collaborating with private companies and other organizations," Nakatani said enthusiastically.

(by Kumi Yamada)





Structure of the CPP-GMR (current-perpendicular-to-the-plane giant magnetoresistance) sensor developed by Nakatani
Nakatani fabricated the layered structure shown on the left. This structure then self-transformed into a nanocomposite layer (right) composed of a mixture of manganese-zinc-oxide (Mn–Zn–O) insulators and silver–indium (Ag–In) alloys. This transformation resulted from the diffusion of manganese from the Heusler alloy (CoMnFeGe) layers into the silver-indium-zinc-oxide (AgInZnO) layer.



Tomoya Nakatani
Senior Researcher,
Magnetic Materials Group
Research Center for Magnetic and Spintronic Materials

Development of a sensor capable of quickly and sensitively detecting target gases in the air

Gaseous molecules, including nitrogen oxides (NO_x) and sulfur oxides (SO_x), have unique absorption spectra in the mid-infrared (IR) wavelength range. Existing high-sensitivity IR detectors, which exploit these absorption spectra to detect target gases, contain highly toxic mercury and cadmium. Hideki Miyazaki has been developing low-toxicity IR detectors using metamaterials. He is also exploring the employment of IR detectors for gas sensing in agricultural and environmental applications, aiming at future integration of his metamaterial IR detector into a camera to visualize the distribution of gases.

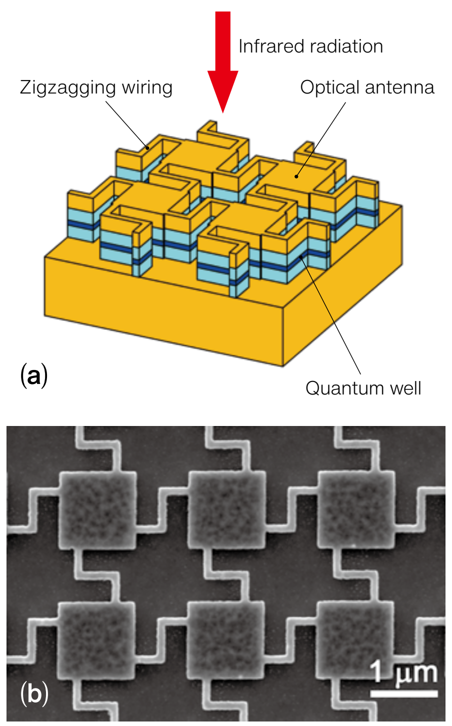
Sensitive IR detection through combined use of quantum wells and metamaterials

A quantum well is a synthetic material composed of alternating layers of two types of semiconductor crystals of atomic-level thickness. Miyazaki and his colleagues have developed a quantum well IR detector composed of a gallium arsenide quantum well layer with a thickness of only 4 nanometers (1nm=10^{-9} m) and aluminum gallium arsenide barrier layers.

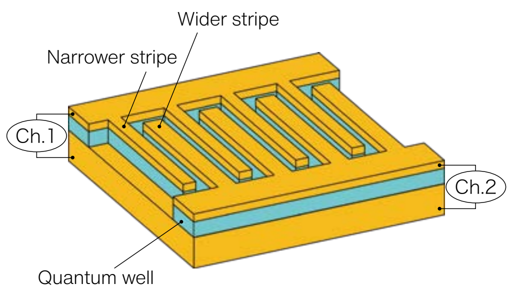
Although quantum well IR detectors were actively researched 20 to 30 years ago, efforts to put them into practical use have been unsuccessful because of their insufficient sensitivity. Recently, Miyazaki succeeded in developing IR sensors with a significantly higher degree of sensitivity by combining quantum wells and metamaterials.

A metamaterial is a material with micropatterns of geometric shapes on its surface which enable it to exhibit new functions. Using computer simulations, Miyazaki designed a metamaterial that is an assembly of numerous square-shaped optical antennae smaller than the wavelength of IR light arranged in a periodic pattern. He then fabricated it on the surface of a metallic substrate with a high degree of precision using nano-processing technology. Individual antennae were designed to simultaneously resonate with incident radiation, enabling them to efficiently collect it. Incident radiation is thereby amplified before reaching the quantum wells, greatly boosting the sensitivity of the IR detector. In February 2020, Miyazaki's metamaterial IR detector was confirmed to be 800 times more sensitive to IR with a wavelength of 6.7 μm than the same quantum well IR detector without metamaterials.

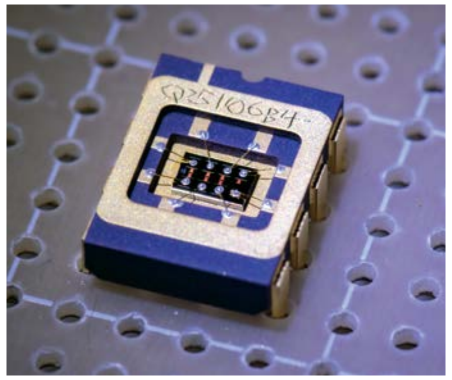
"The thin, zigzagging wires that connect the individual optical antennae also play a vital role," Miyazaki said. "Individual antennae resonate with incident radiation of a target wavelength. This resonance can be precisely synchronized by fine tuning the bend and length of the wires, thereby increasing the sensitivity of the IR detector. This allows the wavelengths targeted to be changed freely by modifying the shape and size of the optical antennae and wiring. This design flexibility is the great appeal of working with metamaterials."



Metamaterial infrared detector developed by Miyazaki
A schematic diagram (a) and a scanning electron micrograph (b) of the IR detector. An array of quantum well detectors is composed of a quantum well layer (dark blue) sandwiched between upper and lower barrier layers (light blue). This layered structure is further sandwiched between gold layers (yellow). Each square-shaped optical antenna is smaller than the wavelength of IR light. Numerous optical antennae are arranged in a periodic pattern and are interconnected by zigzagging wiring. This structure collects incoming IR and sends it to the quantum wells. The targeted wavelengths can be freely changed by modifying the shape and size of the optical antennae and wiring.



Infrared detector designed to measure NO_x consisting of two optical antennae with alternating stripes of different widths
Two optical antennae equipped with stripes of different widths were combined. The narrower stripes (Ch. 1) measure the intensity of radiation with a shorter wavelength while the wider stripes (Ch. 2) measure the intensity of radiation with a longer wavelength.



Prototype infrared detector equipped with striped optical antennae

High-speed gas concentration measurements

Miyazaki is also developing a metamaterial IR detector with different optical antennae shapes designed to measure gas concentrations. A concentration of a preselected gas can be determined by measuring two different wavelengths: a wavelength that is highly susceptible to absorption by the target gas and another wavelength that fully penetrates it. The concentration of the target gas can then be determined by comparing the detected intensities of these two wavelengths.

To measure two different wavelengths simultaneously, Miyazaki created an IR detector consisting of two optical antennae with a series of stripes. One antenna has narrower stripes than the other. These two types of antennal stripes are arranged in an alternating pattern. The narrower and wider antennal stripes are designed to resonate with shorter and longer wavelengths, respectively.

"I designed the antennae to measure the intensity of radiation with a wavelength of 6.25 μm, a wavelength highly susceptible to absorption by nitrogen dioxide (NO_2)," Miyazaki said. "I then actually measured NO_2 using an IR detector equipped with these antennae and succeeded in determining its concentration. These very responsive quantum well IR detectors may be useful in automobile development. For example, they could be used to monitor the concentration of NO_x emitted from a running engine every millisecond."

Experimental demonstration of CO_2 imaging using the world's highest performance camera
Image of a hose releasing CO_2 into a greenhouse taken using an ordinary camera (left). The same image taken using a CO_2 imaging camera (a snapshot from a video clip). The flow of CO_2 released from a hose into the greenhouse was visually recorded in real time.

Real-time imaging of gas movement using an IR detector

In addition to developing IR detectors, Miyazaki has also been conducting experiments aimed at monitoring gases of agricultural and environmental significance using IR radiation. Conventional gas sensors are only able to measure the concentration of a gas in a small area at one time. Measuring a gas concentration distribution across a large space therefore requires the use of many sensors positioned in various locations.

"Video imaging of a gas in the air across a space would reveal its behavior, such as its spatial distribution and flow," Mayazaki said. "These types of information have been available only through simulations for all gases except for carbon dioxide (CO_2). I knew that video imaging of CO_2 could be achieved using a combination of existing technologies. To bring this into reality, I asked a camera manufacturer to construct the world's highest performance camera capable of recording video of CO_2 movement with support from PRISM (the Public/Private R&D Investment Strategic Expansion Program), Japan's R&D promotion program."

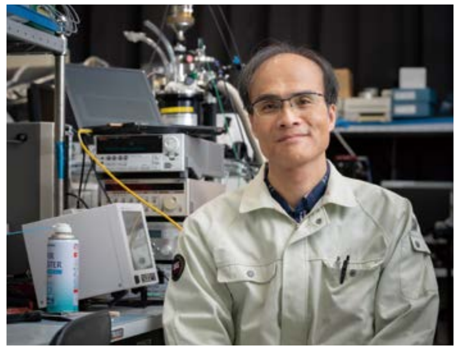
CO_2 can be detected using a commercially available IR camera equipped with indium antimonide (InSb) semiconductor devices. Miyazaki integrated a filter which allows only radiation with a wavelength of 4.26 μm to pass through it to the custom-made camera. He also cooled the filter to a cryogenic temperature of -195°C to prevent it from emitting IR radiation. Through these steps, he was able to create a camera with the ability to record video of CO_2 using high-contrast images. The video recording performance of this camera was verified in agricultural greenhouse experiments conducted in November 2021 (joint research with Ehime University, Toyohashi University of Technology and the Japan Agricultural Cooperative (JA) in Nishimikawa).

This particular greenhouse has adopted CO_2 enrichment, an agricultural technique that has attracted attention in recent years. The intended effect of this technique is to significantly increase crop yields by raising greenhouse CO_2 levels above atmospheric CO_2 levels, thereby promoting photosynthesis. No means of measuring the distribution and flow of CO_2 supplied from a CO_2 generator into a greenhouse was previously available. During the greenhouse experiment, Miyazaki and his collaborators succeeded in imaging the movement of CO_2 released from a hose and the way in which it spread through the surrounding area. Based on the captured images, the research team plans to make recommendations on efficient ways of supplementing CO_2.

Because this new camera is also able to image CO_2 exhaled by people, it could be used in coronavirus-related studies, such as studies on the effect of wearing a face mask and evaluation of indoor ventilation.

Miyazaki has greater goals in mind. "Existing IR cameras are incapable of imaging air pollution gases that absorb radiation with wavelengths of 5–8 μm, including NO_x and SO_x. The metamaterial IR detector I'm currently developing can measure radiation of any wavelength by modifying the metamaterials. I hope to integrate this IR detector into a camera, thereby enabling it to take visual images of these gases. After this is accomplished, I'd like to promote the use of this technology for environmental protection purposes." Miyazaki's success with the greenhouse experiment is the first step toward achieving these goals.

(by Kumi Yamada)



Hideki T. Miyazaki
Leader of the Plasmonics Group, Optical Materials Field, Research Center for Functional Materials

Quick-response, low-cost soft polymeric actuator: liquid crystalline columnar structure enables rapid ionic migration

Haptics is the sense of touch mediated by technology. Tactile sensations generated by forces and vibrations can be remotely reproduced using sensors and computers. Haptic technologies with a wide range of potential applications (e.g., remote medical examinations and virtual reality simulations) are vital to putting Japan's Society 5.0 concept into practice. Soft actuators capable of reproducing dynamic movements and a human's delicate sense of touch are a critical haptic technology component. In an effort to meet this demand, Masafumi Yoshio has developed a new type of soft polymeric actuator using liquid crystals.

Columnar structure serves as an "expressway" for ionic migration

Liquid crystals exhibit the physical properties of both liquids and solid crystals. Among the many types of liquid crystalline structures in existence, Yoshio has chosen to research mainly liquid crystals with columnar structures and has designed liquid crystalline molecules capable of self-assembling into these structures. He has also succeeded in steadying the columnar structures by polymerizing the molecules. Using this technique, Yoshio has developed unique polymeric materials, such as a membrane that filters sea water into fresh water and a film that can remove almost 100% of a virus.

In this sensor/actuator project, Yoshio decided to develop a new type of actuator made of ion conductive polymers using his experience in researching liquid crystals with columnar structures.

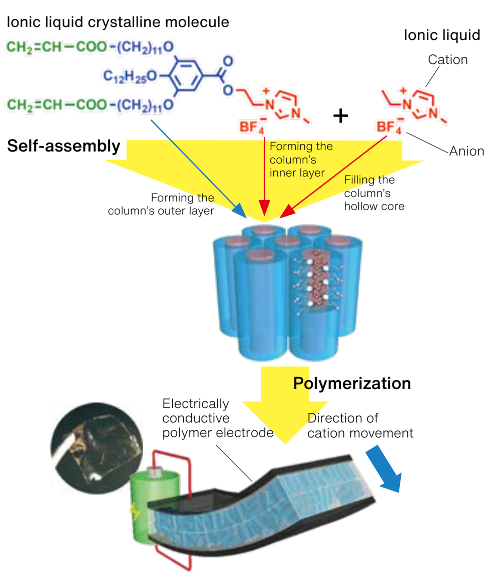
Ion conductive polymers allow the ions within them to be mobile. They contain cations and anions that differ in size. By sandwiching this polymeric material between two electrodes, the resulting composite can act as an actuator film that can flex back and forth. When voltage is applied to the film, the larger and smaller ions within it migrate in opposite directions. This causes the side of the film toward which the larger ions move to stretch, driving the film to flex.

Yoshio initially planned to create a polymeric material with a columnar structure through which ions can travel. A conventional ion conductive polymeric material is composed of tangled, winding polymers which prevent smooth, rapid ionic migration. Yoshio thought that an ion conductive polymeric material with a columnar structure would allow the ions within it to travel in a straight line. As a result, the material could act as an actuator film capable of flexing more quickly and with a greater degree of displacement.

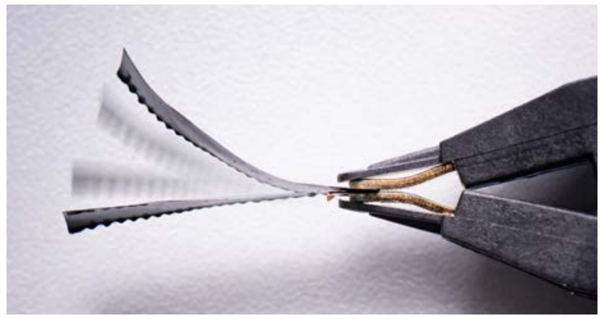
Yoshio quickly took action to verify his concept. He first mixed ionic liquid crystals, which have both positively and negatively charged components, with an ionic liquid composed of cations and anions. He then heated the mixture to approximately 50°C to liquify it. As the mixture cooled, the ionic liquid crystals spontaneously formed columnar structures. During this transformation, the charged components of the liquid crystalline molecules formed the inner layers of the columns while the remaining molecular components formed the outer layers and the ionic liquid filled the hollow cores. The columnar structure was then irradiated with ultraviolet light, which caused the loosely associated liquid crystalline molecules to polymerize, transforming the columnar structure into a columnar film. This film was then sandwiched between two layers of polythiophene-based electrically conductive polymers. When voltage was applied to this composite film, it flexed as Yoshio anticipated (see the upper right photo and p. 2 also).

However, Yoshio was unsure whether ions were really traveling through the columns. To verify this, he once again prepared the same mixture of liquid crystals and ionic liquid and liquified it at 50°C. He then irradiated the liquified mixture with ultraviolet light to polymerize the liquid crystalline molecules, thereby transforming the mixture into a film without the columnar structures. Yoshio anticipated that when voltage was applied to this film, the ions within it would move slowly because it lacked the columnar structure. As a consequence, he expected that the film would flex with a smaller degree of displacement.

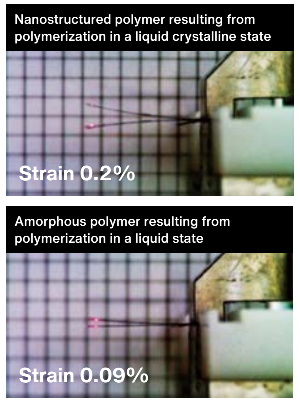
Yoshio conducted an experiment to compare the flex displacement of films formed from a liquid crystal phase and from a liquid phase and demonstrated that the latter film exhibited a smaller degree of displacement. "This experiment confirmed that I had indeed created a polymeric film with a columnar structure through which ions can travel efficiently," Yoshio said. "I hope to make the polymeric film flex with a larger degree of displacement and respond more quickly by arranging the columns so that they are perfectly perpendicular to the planes of the electrode layers."



Soft actuator film made of liquid crystalline polymers
The columnar structure is composed of ionic liquid crystals and ionic liquids. Each column is formed through self-assembly of the ionic liquid crystalline molecules in a specific manner: the red portion of the molecules (the positively and negatively charged molecular portion) makes up the column's inner surface, while the blue and green molecular portions make up its outer layer. The ionic liquid fills the column's hollow core. Application of ultraviolet light to the loosely associated columnar structure causes the acryl groups of the molecules (the green portion) to polymerize, transforming them into a columnar film. Yoshio sandwiched this film between two layers of electrically conductive polymer electrodes to form a soft actuator. Voltage application causes the actuator to flex. This occurs as larger cations in the ionic liquid migrate toward the negative side of the film while smaller anions move toward the positive side, causing the negative side of the film to stretch.



Voltage application causes the film to flex
The film is flexing up and down in this experiment in response to the application of AC voltage.



Comparison of displacement between films with and without the columnar structure
The film with the columnar structure (top) was polymerized in a liquid crystalline state, while the film without the columnar structure (bottom) was polymerized in a liquid state. In this experiment, AC voltage was applied to both films, causing them to flex up and down. Displacement of the film with the columnar structure was larger than that of the film without it.

Liquid crystalline molecules: materials with many advantages

This actuator film made of ion conductive polymers exploits the structural characteristics of liquid crystals—a novel actuator mechanism. It has proven to be sufficiently strong to lift 20 times its own weight and durable enough to withstand at least 2,000 repeated flexes.

Many of the conventional ion conductive polymers that have been researched are ion gels, a type of polymer that lacks an ordered structure. "Although ion gels have been a popular research subject, they are 80% ionic liquid by weight," Yoshio said. "By contrast, the polymeric material I have developed is only 8% ionic liquid. Its columnar structure allows ions to move through it efficiently." Ionic liquids are expensive and materials with higher ionic liquid content have a higher risk of it leaching out. For these reasons, high-performance ion conductive polymers with low ionic liquid contents are very advantageous and suitable for a wide range of applications.

In addition, Yoshio's liquid crystalline molecules are potentially capable of withstanding use in completely dry environments and at temperatures exceeding 100°C because its heat resistance is greater than that of conventional ion gel materials. "The molecule needs to be evaluated under extreme conditions, such as very low temperatures and in a vacuum. I'm still trying to prepare proper equipment to carry out these experiments," Yoshio said. "Stable materials can be used in a broad range of environments. My liquid crystal material could be used as a satellite coating, for example. This coating could vibrate when AC voltage is applied to it, removing dust from the satellite's surfaces. This is just one potential application."

Future applications for liquid crystalline molecule actuators

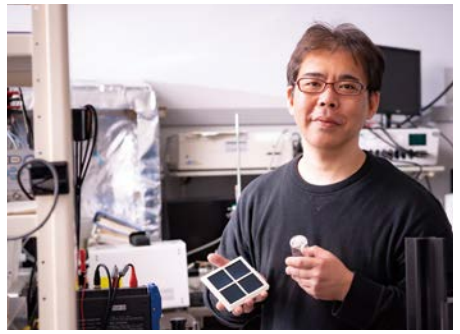
Yoshio dreams of creating gloves that allow their users to remotely feel tactile sensations of contact and movement. The performance of his current liquid crystalline polymer actuator is still insufficient to achieve this.

Human skin senses light touch by means of Meissner's corpuscles, which are located just beneath the epidermis, and Pacinian corpuscles located deeper in the skin layers. Meissner's corpuscles sense vibrations with frequencies below 50 hertz and amplitudes greater than 10 micrometers, while Pacinian corpuscles are most sensitive to vibrations with frequencies in the vicinity of 200 hertz and amplitudes of 1 μm. Displacing the skin surface by 10 μm is estimated to require 0.3 millinewtons of force. Currently available liquid crystalline actuators are able to vibrate at a frequency of a few hertz with an AC input voltage of 2 V and to generate 0.3–1.0 millinewtons of force under applying the DC voltage. Actuators capable of vibrating at higher frequencies need to be developed in order for them to generate force comparable to a light touch that human skin can sense.

"Making actuators that generate stronger forces at higher frequencies will require increasing the thickness of the polymeric film," Yoshio said. "However, this approach would decrease the proportion of columns oriented perpendicular to the film surface relative to the proportion of non-perpendicular columns. I'm currently trying out an alternative approach by perpendicularly orienting the columns using magnetic fields."

Yoshio's polymeric material has another advantage: its liquid crystalline structure can be modified in a variety of ways by altering the design of his liquid crystalline molecule. In fact, he is already working to develop different liquid crystalline structures, including a structure in which ions are guided to travel outside of columns and micelles (spherical structures), and a gyroid structure. "I think some of the materials I have developed are promising," Yoshio said. "In addition to improving actuator materials, I'm also studying other ways of enhancing their performance, such as attaching needle-like projections to their surfaces." Yoshio's creative research is making steady progress towards the goal of putting his products into practical use.

(by Kaori Oishi)



Masafumi Yoshio
Leader of the Molecular Mechatronics Group,
Polymers and Biomaterials Field,
Research Center for Functional Materials

Temperature-sensitive shape-memory polymer may enable safer fetal medical treatment

A sacrococcygeal teratoma is a tumor that develops on a fetus' tailbone. Although benign, it can grow very large and deprive the baby of blood, potentially impeding fetal growth, and in the worst case, causing death. An effective means of treating these tumors is therefore needed. Mitsuhiro Ebara has been researching a temperature-sensitive shape-memory polymer. This polymer may be used to gradually reduce blood flow to the tumor, slowly destroying it. This treatment is expected to be safer and gentler to fetuses and their mothers than surgical removal. In this sensor/actuator project, Ebara is developing a polymer that will be suitable for use in treating sacrococcygeal teratoma.

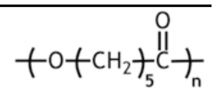
Smart polymers: stimulus-responsive materials

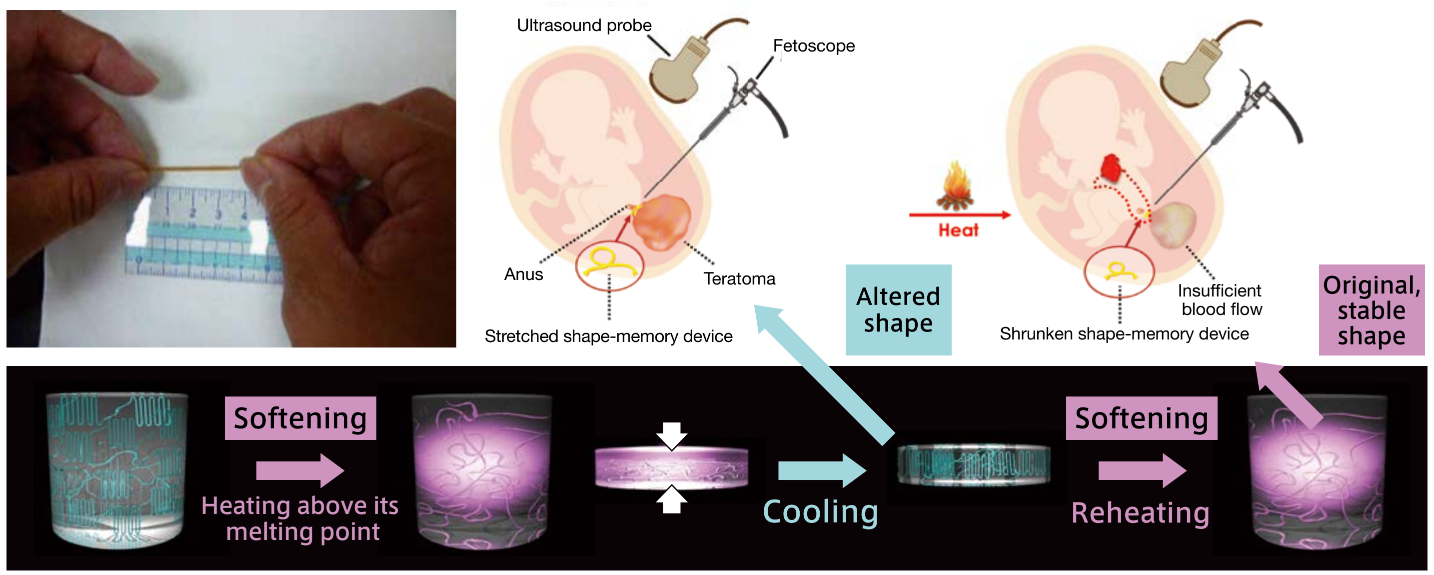
A polymer is a material consisting of very large molecules composed of many repeating subunits. Rubbers and plastics are common examples of polymers. Ebara has been researching smart polymers that change in response to external stimuli, such as heat and light. In this project, he mainly focused on a temperature-sensitive shape-memory polymer.

"Some may see sensors and actuators as mechanical devices," Ebara said. "However, smart polymers could also function as sensors and actuators as they have the ability to perform physical actions in response to stimuli." When a temperature-sensitive shape-memory polymer is stretched at room temperature, it retains the stretched form. However, heating it restores it to its original shape (i.e., it shrinks). This is different from stretching rubber, which returns to its original shape as soon as the force stretching it is released, and plastic, which remains stretched permanently.

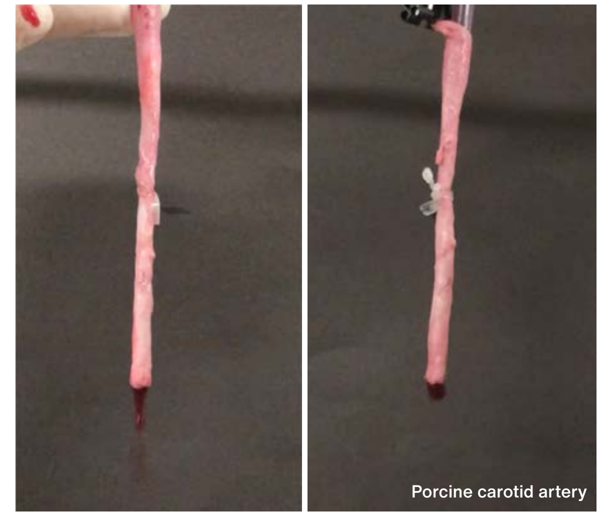
This unique physical property of the temperature-sensitive shape-memory polymer is produced by crosslinking the individual polymeric molecules that make up the material. Polymers without cross-linkages behave just like other types of common materials: when heated above their melting points, they liquify and their component molecules become freely mobile. However, when a polymer with cross-linkages is liquified, the movement of its component molecules is restricted to some extent because of the cross-linkages. This restricted movement enables the polymer to return to its most energetically stable original shape when it is heated to temperatures above its melting point. Thus, a temperature-sensitive shape-memory polymer can be manually reshaped at room temperature and its original shape can be restored by heating it.

Poly(ε -caprolactone)





(Top) Use of a shape-memory polymer to treat a sacrococcygeal teratoma.
(Bottom) Polymer's thermally induced shape memory mechanism.
This shape-memory polymer softens at temperatures above its melting point. The softened polymer can be deformed into any desirable shape. After cooling the deformed polymer, it retains that shape (the original shape). The polymer can then be reshaped at room temperature. When the reshaped polymer is heated again, it is restored to its original shape. This mechanism could be used to treat a sacrococcygeal teratoma. A string-like polymeric material in its original shape is first stretched at room temperature. The stretched polymer is then wrapped around the base of the tumor. When heat is applied to the wrapped string, it shrinks, gradually reducing blood flow into the tumor.



Blood flow control experiment using a porcine carotid artery as a model
The temperature-sensitive shape-memory polymer developed by Ebara was shaped into a loop (left). This loop was fit around a porcine carotid artery (right) and slowly heated, gradually—not rapidly—reducing blood flow. The use of this technique may offer safer medical treatments to fetuses and their mothers.

Treating babies with sacrococcygeal teratoma

Ebara has been working to achieve medical application of temperature-sensitive shape-memory polymers. These polymers have begun to be used in some medical devices, such as medical balloons and radiotherapy masks. Medical balloons, which can be inflated with air when they are softened at high temperatures, are used to create a hollow cavity within a collapsed bone resulting from osteoporosis and other causes so that an artificial bone can be inserted into the cavity to restore bone function. Radiotherapy masks are used to stabilize patients' heads while they undergo radiotherapy for brain tumors.

In this project, Ebara is developing a new technique to treat a sacrococcygeal teratoma, a tumor that develops on a fetus' tailbone. "The fetal tumor should be treated before birth to ensure the baby's early recovery," Ebara said. "However, surgical removal of the tumor requires high levels of skill as small errors could cause excessive bleeding from the tumor and damage the mother's placenta and fetal membranes. For this reason, most surgical removals are performed after birth."

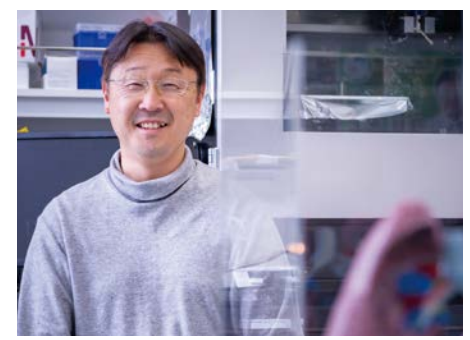
To reduce pediatric surgeons' workload and stress and to offer safer treatment options to babies and their mothers, Ebara is trying to develop a procedure to destroy the tumor by gradually reducing blood flow to it using a temperature-sensitive shape-memory polymer. First, a string-like polymer is stretched at room temperature and wrapped around the base of a sacrococcygeal teratoma. The wrapped string is then heated using a medical laser, causing it to shrink as it returns to its original shape, constricting blood vessels at the tumor's base.

In an effort to expedite the practical use of this treatment technique, Ebara has chosen to use Poly(ε-caprolactone)—a biocompatible polymer whose medical use has already been approved by the United States Food and Drug Administration (FDA)—as a starter material. He engineered this polymer so that its string form can be wrapped around an object and contracted in a controlled manner using heat. He achieved this by crosslinking the polymer's molecules and adjusting the extent of their cross-linkages, the molecular weight of the polymer and the number of branches in the polymer. Through these efforts, Ebara created a shape-memory polymer with optimum temperature sensitivity and sufficient hardness for medical use.

"My ultimate goal is to create a system capable of automatically adjusting the rate at which blood flow into a tumor is reduced while monitoring the health of the baby and its mother by means of measuring their cerebral magnetic fields," Ebara said. "This may be achieved by combining our shape-memory polymer and sensors capable of measuring cerebral magnetic fields which other NIMS groups are developing. I'm also studying a mechanism by which the shape-memory polymer, while wrapped around the base of a tumor, can be heated by applying external electrical stimuli through the mother's body."

Ebara has previously worked to develop medical materials at hospitals. This experience has made him keen to deliver technologies that are truly needed by healthcare providers. On the other hand, he is also aware that putting a new technology into practical use is a very laborious task. "It can easily take a decade to commercialize a newly developed technology," Ebara said. "This process involves joint development with private companies followed by clinical evaluation of the safety and effectiveness of the new technology." Ebara is entering a crucial period in his effort to deliver safer and more effective treatments for babies.

(by Akiko Ikeda)



Mitsuhiro Ebara
Leader of the Smart Polymers Group,
Polymers and Biomaterials Field,
Research Center for Functional Materials

NIMS NEWS

Six NIMS Researchers as "Highly Cited Researchers 2021"

Clarivate Analytics selected six NIMS researchers as its "Highly Cited Researchers 2021".

"Highly Cited Researchers" are authors of scientific papers that are in the top 1% in number of citations in a given research field based on Clarivate Analytics' Essential Science Indicators database.


Katsuhiko Ariga


Jonathan P. Hill


Takashi Taniguch


Kenji Watanabe


Yusuke Yamauchi


Jinhua Ye

*Listed in alphabetical order

NIMS researcher wins the Sir Martin Wood Prize

Atsushi Togo (Research and Services Division of Materials Data and Integrated System) was awarded the 23rd Sir Martin Wood Prize. This prize recognizes outstanding research conducted by young Japanese researchers and rewards them with financial incentives. The Prize is sponsored by Oxford Instruments plc, a British scientific instrument manufacturer, which funds the prize by collecting donations.

"I' m very honored by this recognition of my research, which was made possible by support from many people," Togo commented. "New scientific discoveries are made every day, and I' ll keep working and studying hard while taking care of myself mentally and physically."

Togo (right) and Julia Longbottom, British Ambassador to Japan, at the award ceremony

My name is Ngan T. K. Nguyen from Viet Nam. In 2018, I have finished a Ph.D. course from NIMS graduate program under the supervision of prof. Tetsuo Uchikoshi. I got a chance to continue working at NIMS as a postdoctoral researcher, then I passed the selection as an ICYS fellow researcher in 2021. My research field focuses to develop outstanding physicochemical properties of the metal atom cluster-based halides in nanocomposite for energy and environmental applications, one of the fields contributing to a sustainable society. NIMS supplies the finest approach with an international and friendly environment that motivates my goal to be a skillful scientist in the materials science field.

In addition, friendly people, culture, and excellent sightseeing are my main reasons to come to Japan. I have enjoyed the snowing land at Hokkaido, the ancient city at Kyoto or impressive mountains at Nagano, and many beautiful onsen places accompanying delicious foods. I was attracted by the festivals presenting traditional costumes or fireworks in every season. Japan is a promising country for living to me!


Visiting the ancient Kawagoe city in Saitama with my family.

NGUYEN Thi Kim Ngan
(Vietnamese)
ICYS Research Fellow

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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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