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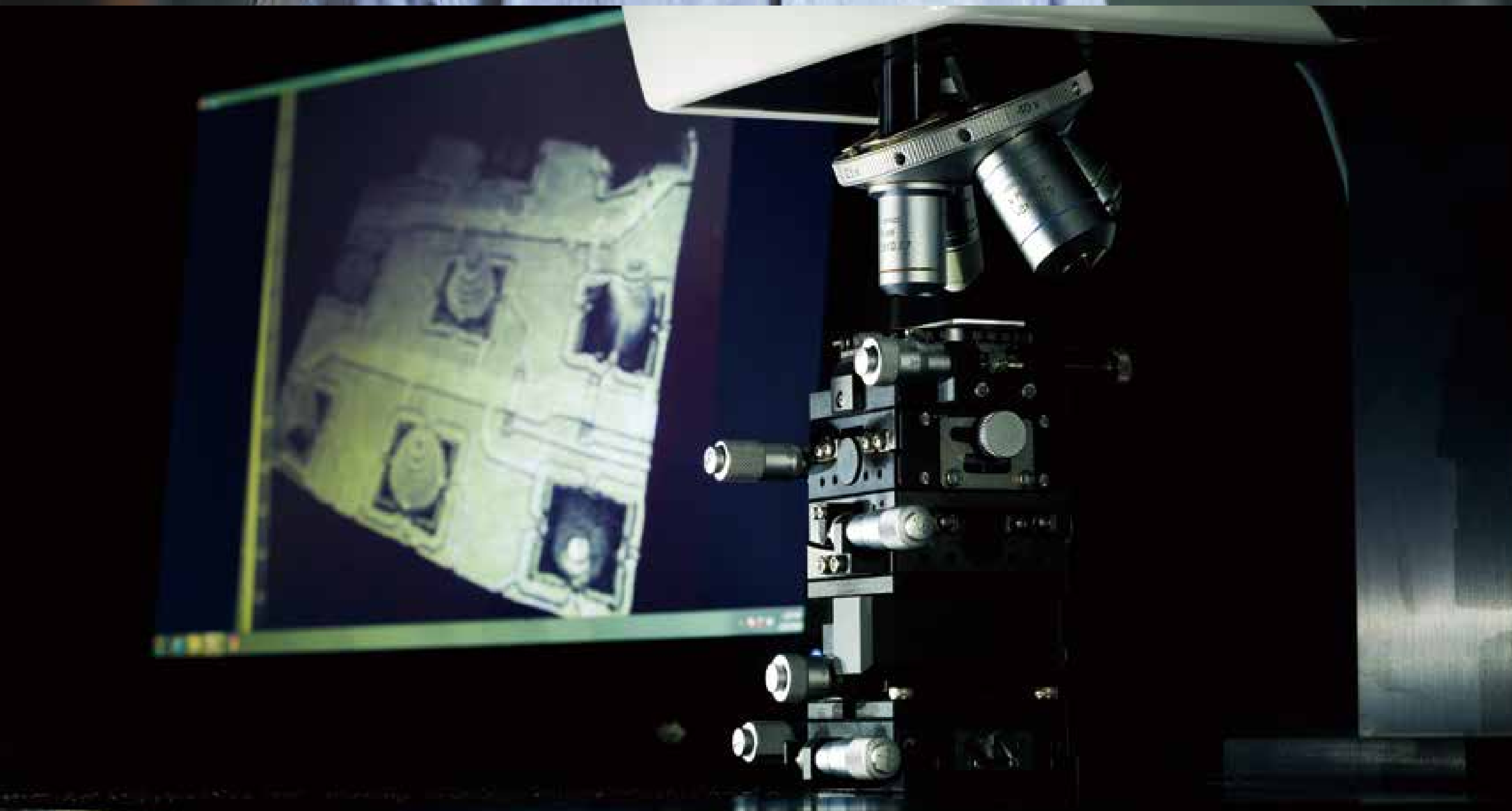
Intriguing future with leading-edge sensor technology



Intriguing future with leading-edge sensor technology

Sensor technology enables small devices to mimic our five senses.
You may not be aware of how much we benefit from this technology in our everyday life.

Virtually all of us rely on sensors through medical services, natural disaster forecasting, infrastructure management and environmental monitoring, among many other services. Application of sensor technology is likely to expand even more in association with the emerging Internet of Things (IoT).

NIMS researchers are also developing a series of fascinating sensors.
In particular, improvement of chemical sensors, such as odor sensor, is remarkable.
The key to such improvement is a creative mind.

Innovative ideas accelerate the search for new materials and development of revolutionary systems, and sensors of the future are expected to be smaller, more sensitive, more accurate, and provide us with vast amounts of information, more quickly and easily.

We shed light on NIMS's sensor development accomplished thus far and groundbreaking ideas.

Human senses and
some representative sensors

Kiyoshi Toko

President, Research and Development Center for Taste and Odor Sensing, Kyushu University

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Executive Vice President / Director of Research Network and Facility Services Division,
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Yasuo Koide

Advancement of AI boosts R&D of sensors

In anticipation of the arrival of an IoT (Internet of Things) society, sensors are drawing much attention. In particular, chemical sensors, including taste and odor sensors (electronic tongues and noses), are subject to intensive R&D driven by the advancement of AI (artificial intelligence). In light of this movement, Kyushu University Professor Kiyoshi Toko, who put taste sensors into practical use for the first time in the world, and NIMS Executive Vice President Yasuo Koide discussed the current status and the future of sensor R&D, with emphasis on chemical sensors.

Difference between physical and chemical sensors

Koide Professor Toko, you are well known as the world's first person to achieve practical application of taste sensors early in 1990. We will come back to that shortly, but first, let's review what sensors are. They are small devices that work in place of the five human senses, correct?

Toko That is right. Among the five senses, vision, hearing and touch are fulfilled by physical sensors while taste and smell are recognized by chemical sensors. Another way of defining physical and chemical sensors is that they respectively convert physical and chemical quantities into electrical signals. In this regard, taste sensors are classified into chemical sensors.

Koide Today, food and drug manufacturers around the world are using taste sensors for product development and marketing. But this is a rare example of chemical sensor application. In contrast, various physical sensors were put into practical use since their development began about 40 years ago. Why is practical application of chemical sensors making slow progress other than in some specific areas such as gas sensing?

Toko The slow progress is directly linked to the difference in mechanism between physical and chemical sensors. As you know, both sensors consist of two parts: a receptor and a transducer. A receptor recognizes certain substances or quantities, and a transducer converts physical or chemical quantity of the substance recognized into electrical signals, for example, voltage. A combination of a receptor and a transducer determines the sensitivity and substance selectivity of the sensor.

Koide Among physical sensors, visual sensors use light, audio sensors use sound waves, and touch sensors use pressure to measure the physical quantity of substances recognized by receptors.

Toko Yes. As physical sensors only need to measure one physical quantity, their structures are relatively simple. By comparison, taste and odor sensors need to measure taste and odor substances, which contains thousands of millions of substances, to quantify taste and smell sensations. It is very difficult for the sensor to identify multiple substances, measure their concentrations, make comprehensive decisions according to these measurements, and output electrical signals.

Koide My area of expertise is electronic materials/semiconductor engineering, and I have developed a visual sensor capable of detecting a deep ultraviolet light at the wavelength lower than 280 nm, using diamond. The receptor of this physical sensor recognized only one substance, like you said. In that sense, there are great differences between physical and chemical sensors.

Intensifying chemical sensor R&D

Koide At NIMS, research is underway to create sensors that meet recent needs and to achieve their practical application. For example, Genki Yoshikawa and Jin Kawakita are respectively developing odor sensors (see P.8) and moisture sensors (see P.12).

In addition to the chemical sensors you developed, what other chemical sensors have been commercialized by now?

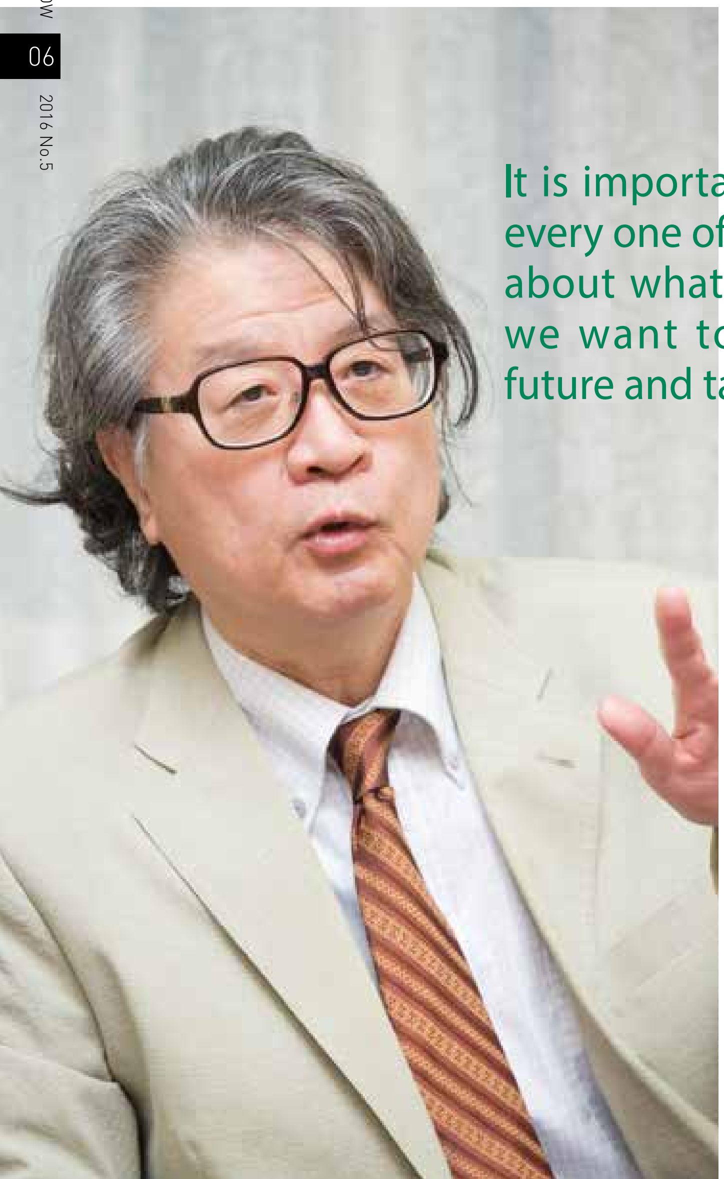
Toko First, a household gas leak detector is one of the commercialized chemical sensors. Its receptor contains an oxide semiconductor. Oxide semiconductors are a very reliable material and are also used, for example, in breathalyzers, which are employed in cracking down on drunk driving. The material also has a disadvantage, however. Its sensitivity and selectivity to chemical substances are low, so it is applicable only to certain kinds of gases. To address this issue, new odor sensors are being developed using organic materials.

Second, a blood glucose sensor is used to detect diabetes. This device detects blood glucose by directly measuring electrons generated at the electrode due to enzyme reactions. The industrial value of the blood glucose sensor has already grown to a trillion yen. Those are the types of chemical sensors I can think of that have been extensively commercialized.

Koide In recent years, information technology, including AI, is rapidly evolving, making it possible to handle big data. In light of the situation, R&D of chemical sensors is intensifying. It is now feasible to quickly process an enormous amount of information on several kinds of chemical substances recognized by a receptor, using AI and statistics.

Also, social needs for chemical sensors are increasing, for example, in measurement of pollutants and detection of particular chemical substances produced by cancer cells. These demands appear to be backing R&D of chemical sensors. Moreover, advancement of AI seems to be adding a further boost. I expect that chemical sensors will play a key role in building a safe and secure society.

Toko I totally agree with you. Furthermore, replacement of inorganic materials with organic materials will increase the kinds of chemical substances detectable by receptors of chemical sensors, thereby increasing the substance selectivity of the sensors. Recently, new methods to synthesize many organic materials were developed, so it has become easier to acquire organic materials with desirable functions. That is another factor promoting R&D of chemical sensors.



It is important for each and every one of us to think hard about what kind of society we want to create in the future and take actions.

There are no “basic odors”

Koide By the way, when I learned about the taste sensor you developed, I was shocked by the novel idea and wondered how in the world a physical device can distinguish tastes. You are currently serving as the president of the Research and Development Center for Taste and Odor Sensing at Kyushu University. Could you tell us what differences there are between taste and odor sensors?

Toko It is far more difficult to develop odor sensors than to develop taste sensors. There are five “basic tastes” representing the sense of taste: sweetness, saltiness, bitterness, sourness and umami (pleasant savory taste). So, there is a clear approach to sensing tastes, which is to classify measured chemical substances into these basic tastes. However, there are no “basic odors” representing the sense of smell.

Moreover, humans use only the tongue, on which taste receptors are located, to distinguish five basic tastes, but we use the brain, not the nose in which smell receptors are located, to recognize smells and process incoming odor information. Because the brain is involved in odor sensing, one’s experience and learning affect how one senses smells. That is why it is difficult to quantify odor sensation. This is the biggest issue preventing practical application of odor sensors.

Koide I heard that at the R&D Center for Taste and Odor Sensing, the faculty is appointed not only from departments of engineering and science but also from medical, dentistry and agricultural departments. Do you think that this sort of interdisciplinary approach involving medical and other faculty is essential in order to put chemical sensors into practical use?

Toko Absolutely. From the beginning, the R&D center was not specialized only for the development of sensors, but we also have been conducting other types of studies. For example, medical and agricultural faculty members are jointly searching for cancer biomarkers. If such biomarkers are found, the next step will be the development of sensors by engineers. We are taking both scientific and technological approaches to R&D of sensors. I think collaboration among diverse disciplines will become increasingly important in the development of chemical sensors.

Sensors that support IoT society

Koide In anticipation of the advent of IoT society and automated driving, demand for sensors is steadily increasing. Professor Toko, what kind of society do you expect to see in light of evolving sensor technologies?

Toko First, if chemical sensors become readily available more to the public, I think that would be good news for people with a disabled sense of taste or smell. Also, if sensors are installed in every physical device, big data is collected from these sensors, and AI becomes capable of optimally processing the big data, I think a very convenient society can be created like we see in science fiction films. For example, a future automobile might be able to pick you up wherever you are by calling it, and take you to wherever you want to go.

Koide On the other hand, with regard to IoT society, some people are concerned about security issues including invasion of privacy.

Toko In that regard, let me use an example of “watching sensor” for elderly people living alone. The use of visual sensors to assure the safety of elderly people has a high risk of invading their privacy, so, some people suggests to use odor sensors instead to reduce that risk. Also, assuming that sensors will be installed in every physical device and at every place near future, I think that a strategy is necessary under sound ethics to automatically delete the data using AI.

Koide Innovative ideas and inventions always come up suddenly, so, what society will be like in 20 or 30 years is unimaginable.

Toko That is true, but we are the ones who need to build a foundation for future society. It is important for each and every one of us to think hard about what kind of society we want to create in the future and take actions.

Koide You have a point there. It was nice talking with you today.

(by Kumi Yamada)

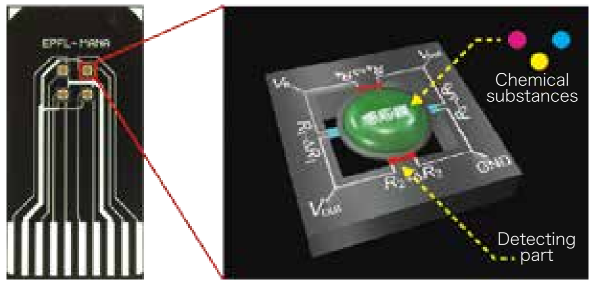
I expect that chemical sensors will play a key role in building safe and secure society.

RESEARCHER INTERVIEW

Developing MSS; world's first ultra-small, super-sensitive and versatile odor sensor

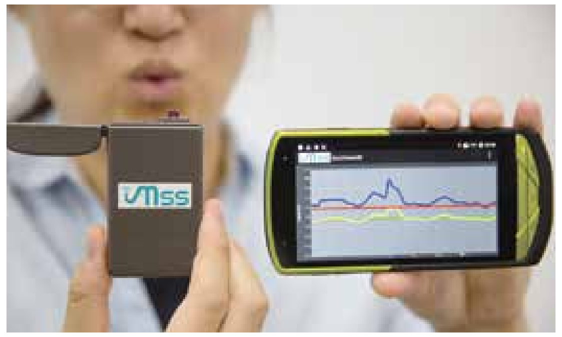
Genki Yoshikawa

Group Leader, Nanomechanical Sensors Group,
International Center for Materials Nanoarchitectonics (MANA), NIMS



■ MSS chip and its structure

An MSS chip (left) and a magnified inset showing an MSS element (right). The distance between each MSS element is about 1 mm. When molecules adsorb to a receptor layer coated on the circular center membrane, surface stress is induced, causing electrical signals through the electric resistance changes of the piezoresistors embedded in the four supporting bridges.



An image of mobile sensor system based on the MSS technology to detect breath components and to monitor health conditions

Sensors work in place of the five human senses. Physical sensors already have been put into practical use to fulfill three of the five human senses: the eyes (vision), ears (hearing) and skin (touch). In contrast, chemical sensors capable of fulfilling the roles of the tongue (taste) and nose (smell) have rarely been commercialized. To address this issue, Genki Yoshikawa, the leader of the Nanomechanical Sensors Group, MANA, developed a versatile and small chemical sensor capable of detecting a wide range of substances from gaseous molecules to other biomolecules, at high sensitivity.

Ultra-small, super-sensitive and versatile sensor developed

Commercialization of chemical sensors that recognize tastes and odors is making much slower progress compared to physical sensors. The biggest reason is that there are millions of different chemical substances that need to be detected by chemical sensors. As a result, commercialized odor sensors, for example, are limited to products specialized to certain chemical species as in the case of gas leak sensors. Amid this situation, Genki Yoshikawa, the late Dr. Heinrich Rohrer, and the Swiss Federal Institute of Technology in Lausanne (EPFL) jointly developed a Membrane-type Surface stress Sensor (MSS), which is attracting global attention.

"An MSS is versatile as it can detect a wide range of substances including gaseous odor molecules and biomolecules such as DNA and proteins. In addition, it is a very small and sensitive sensor," says Yoshikawa. Moreover, an MSS is capable of detecting substances not only in the air but also in opaque fluids like blood. Because of these capabilities, the sensor is expected to be useful in various areas such as management of food products and cosmetics, medical service, crime prevention and environmental protection.

An MSS is approximately 1 mm square in size and is made of silicon. Yoshikawa explained how this tiny device can detect odor substances at high sensitivity: "The circular membrane at the center of an MSS is coated with a material called a receptor layer, and is connected to the surrounding part via four bridges. The piezoresistor is embedded in each bridge. The piezoresistor is a material which changes its electric resistance when mechanical stress is applied to it. When gaseous molecules adsorb to the receptor layer, stress is generated in the layer, causing mechanical deformation of the central circular membrane. This deformation induces amplified stress to the surrounding bridges. Consequently, a great electric resistance change occurs in the piezoresistors that are embedded in the bridges. As a result, the MSS can electrically detect adsorbed substances at high sensitivity."

Identifying odor using electrical signal pattern

A receptor layer can be fabricated using various materials including organic materials (e.g., polymers), inorganic materials, and biomaterials. The types of receptor materials determine the substances that can be detected.

MSS can be manufactured using conventional semiconductor microfabrication technology, so, miniaturization and mass production can be performed easily. In addition, it is feasible to integrate several MSS elements on a silicon substrate to make it a multichannel system. By using different receptor materials among MSS elements, a system can detect various types of substances at the same time.

"Each receptor material coated on each MSS is not absorbing one specific substance but absorbing various types of substances depending on the types of receptor materials. Supposing that you want to identify complex odors produced by a mixture of several hundred kinds of gases from food or drink, it would be unrealistic to take the approach of detecting one odor component at a time. However, it may be relatively easy to identify complex odors by sensing gases using several types of receptor layers and recognizing different signal patterns associated with different gases. It has been assumed that both humans and dogs recognize smells in a similar way as the MSS," explains Yoshikawa.

So, it is important to ascertain the unique response pattern generated by each odor substance while taking into account the type of receptor layer material used. To address this issue, Yoshikawa is conducting a joint study with NIMS researchers, Kota Shiba and Gaku Imamura, to develop various types of receptor materials capable of adsorbing wide range of odor components at high sensitivity. He is also constructing a signal library in the industry-academia-government collaboration framework. Through these efforts, he hopes to increase the accuracy of odor identification, and expand the range of MSS application.

Achieved 100 times keener sensitivity than conventional sensors

Yoshikawa became interested in R&D of nanomechanical sensors about nine years ago. Before that, he was an assistant professor at the Institute for Materials Research, Tohoku University. Then, he worked at the University of Basel in Switzerland from 2007 to 2009 as a visiting researcher.

"I worked in a laboratory famous for nanomechanical sensor research. My objective there was to create sensors from scratch using a piezoresistive sensor chip. My advisor probably thought this was a good project for a newcomer from Japan. I was totally unfamiliar with such a project, but I began soldering resistors one by one, thinking that this was a great opportunity to learn new things."

At that time, a cantilever array sensor already had been developed as a chemical sensor capable of detecting diverse substances. The sensor is equipped with an array of minute cantilevers (projecting beams clamped at one end), which are micrometers in size. The basic working mechanism is same with MSS: The surface of a cantilever is coated with a receptor, and when a substance adsorbs to the receptor, the cantilever deflects. By measuring the amount of deflection, the substance can be detected.

There were two major deflection measurement methods: a method that uses laser light to read the deflection, and a method in which a piezoresistor is embedded into a cantilever and the change in resistance is read electrically.

"The former method allows highly sensitive detection, but the system tends to become bulky. On the other hand, the latter method can be implemented using a small and simple system, but the sensitivity is low. So, I tried hard to come up with a method to incorporate the advantageous characteristics of both methods. That is when I had an opportunity to work with the late Dr. Heinrich Rohrer."

Yoshikawa and Dr. Rohrer carried out hand-writing calculations and discussions almost every day. Later, Dr. Peter Vettiger, who was a colleague of Dr. Rohrer at IBM, introduced the EPFL team, including Dr. Terunobu Akiyama, a leading expert on microfabrication, to Yoshikawa and Rohrer. The team joined discussions since then. The intense discussions gradually optimize the sensor design, but were not enough to come up with a reasonable and beautiful design. So, Yoshikawa kept looking for an answer. Then one day, "When I was sleeping to recover from a cold, the idea of MSS suddenly came to me. I jumped out of bed and ran simulations on my PC. I was able to confirm that the sensitivity of the MSS would be much higher than any other systems."

The unique structure of the MSS preserved the strength of a piezoresistive cantilever sensor and increased the sensitivity by more than 100 times. In addition, mechanical/electrical stability increased dramatically, so the practical use of the MSS became much more realistic.

"To achieve practical application of the MSS, we launched the MSS Alliance in September 2015 as an industry-academia-government collaboration framework. NIMS by itself cannot handle the development of hardware or the analysis of big data containing an enormous amount of odor signals. As such, we are currently carrying out R&D in full collaboration with companies and professors with cutting-edge knowledge and technologies and knowledge," says Yoshikawa.

While aiming to commercialize the world's first odor sensor that can be used anytime, anywhere and by anyone, as soon as possible, he and his colleagues are also trying to establish a de facto standard for an odor sensor.

(by Kumi Yamada)

Tripartite talk on the MSS Alliance

NIMS, Kyocera and NEC

Aiming to set a de facto standard for odor sensors through collaboration among industry, academia and government

Junko Watanabe
Senior specialist,
Data Science Research Laboratories,
NEC Corporation

Masahiko Tajima
Deputy Manager, Development Department 1,
Life Systems R&D Division, Corporate R&D Group,
Kyocera Corporation

Genki Yoshikawa
Group Leader,
Nanomechanical Sensors Group,
MANA, NIMS

The MSS Alliance was launched on September 25, 2015, in order to achieve early commercialization of the odor sensor called the MSS (Membrane-type Surface stress Sensor), which was developed by a research group led by a NIMS researcher, Genki Yoshikawa. The alliance is a research collaboration framework among industry, academia and government, and consists of six organizations: **NIMS, Kyocera, Osaka University, NEC, Sumitomo Seika Chemicals and NanoWorld**. On this occasion, Masahiko Tajima (Kyocera), Junko Watanabe (NEC) and Yoshikawa (NIMS) got together and discussed the aim and appeal of the MSS Alliance, the significance of NIMS's collaboration and future prospects.

Unity of 3 sectors that possess leading-edge technologies

Yoshikawa The MSS Alliance has established collaboration among industry, academia and government, including the organizations represented by the two of you. Under this framework, NIMS is aiming at early commercialization of the MSS.

Tajima I heard that this is the first time for NIMS to make an alliance with companies and universities.

Yoshikawa Right. Development of odor sensors requires an interdisciplinary approach. Moreover, we need to have access to leading-edge technologies from various fields in order to achieve early commercialization. Fortunately, many Japanese companies possess cutting-edge technologies. I am very reassured by the fact that some of those top companies joined the alliance.

Watanabe We are delighted to be a member of the MSS Alliance as it has been providing us with new, rewarding challenges.

Yoshikawa NEC is analyzing odor data and developing algorithms.

Watanabe Yes. To enable MSS to discriminate complex odors, we need to use several MSS elements equipped with different kinds of receptor layers to adsorb odors. Then, we need to analyze the pattern of electrical signals generated by the adsorption. In the past, we had analyzed a lot of data, e.g. image data, collected by physical sensors, so the skills we developed through that experience are useful for this project. However, we have not analyzed odor data before, so we are learning new things through continuous trial and error every day.

Yoshikawa Kyocera is in charge of developing any and all types of hardware necessary for this project, including sensor control boards and gas flow channels.

Tajima The first challenge we encountered was to make a measurement module smaller. This is necessary because of the assumption that MSS will be used to measure various odors in different types of environments including outdoor open spaces. We finally came up with the current portable model after constructing many prototypes. We immediately started collecting data using this model.

An MSS can be considered as a self-learning sensor device as its accuracy increases in proportion to the amount of data collected. We were very impressed by this versatile, next-generation odor sensor. We think the sensor is potentially marketable in many areas.

Yoshikawa I agree. An MSS can be combined with many different types of receptor layer materials, so the range of substances it can detect will widen over time. Also, as we collect and analyze more data, we should be able to develop odor sensors more flexibly according to the objectives and conditions of their use. That is an exciting aspect of the MSS project and collaboration under the alliance. I am very glad that you felt potential in the heart of this collaborative work.

Watanabe I view the MSS not as a mere odor sensor, but also as a device that can create new markets. I really have high expectations for its marketability.

Tajima That is an interesting perspective.

Watanabe Smells are closely linked to human sensations such as comfort and discomfort. At present, there is no means to quantify smells, and skilled olfactory measurement operators determine odor pleasantness of products containing aroma chemicals. If MSS can be installed in smartphones in the future, it will become feasible to quantify users' emotional response to smells in real time. Using this data, products that better suit people's smell preferences may be developed without conducting questionnaire surveys.

Tajima I think so, too. The current MSS module is still a little sizable due to ongoing verification tests, but Kyocera has expertise to further miniaturize MSS and integrate them into another system. You can count on us for this.

Aiming at R&D that takes commercialization into consideration

Yoshikawa Those activities are a major step toward commercialization of the MSS. Because of the efforts by Kyocera and NEC as well as other members of the alliance, NIMS can focus on its specialties, which are R&D of receptor layer materials and basic research on the analysis of electrical signal patterns, while feeding back the verification test results into these research activities. I think the solid collaboration among the alliance members is really contributing to smooth progress of the project as the accuracy of the MSS is rapidly increasing and its optimization is advancing on schedule. NIMS alone could not make these accomplishments.

Tajima At the beginning, we had some concerns as we were totally unfamiliar with the mechanism of the sensor and the collaboration system. However, as the alliance members frankly expressed their opinions at the round-table meetings and progress was made in a step-by-step manner, we have built a relationship of mutual trust. I feel that the trust among us is the major driving force that is moving the alliance activities forward.

Watanabe We very much feel the same way in that regard. Usually, inter-company collaboration is very difficult to implement due to differences in the types of businesses and objectives. But in this collaboration, NIMS is playing a central role, is mediating interactions among member companies, and has clarified the role of each company. I think that is why this project is proceeding smoothly under a favorable relationship among the member organizations.

Yoshikawa NIMS intends full involvement in the collaborative R&D until commercialization is achieved, instead of leaving the commercialization step as a task to be undertaken entirely by companies. The MSS Alliance is truly the embodiment of this concept, and I hope that this project will become the first case of success in a collaborative project of this sort.

Tajima We hope that the MSS will be commercialized as the world's first device of this kind in a few years.

Watanabe I hope so, too. It will be great if the MSS contributes to the establishment of a safe and secure society by strengthening the management of food products and cosmetics, medical service, crime prevention and environmental protection.

Yoshikawa I am very encouraged by the words from you two.

The MSS Alliance secretariat fully supports the operation of the alliance for researchers like myself. I hope this project will also serve as a model case for inter-company collaboration as viewed from an administrative perspective.

We plan to eventually shift the current closed system to an open system, with NIMS playing the role of a platform. Under this framework, we hope that participating companies will freely expand their businesses by making proper license agreement. And also, I hope that we can work together to set a de facto standard for odor sensors.

(by Kumi Yamada)

RESEARCHER INTERVIEW

Moisture sensor capable of determining even the “quality” of moisture

Jin Kawakita
Chief researcher
Semiconductor Device Materials Group
International Center for Materials Nanoarchitectonics (MANA), NIMS

A new sensor which enables not only measuring the quantity but also determining the quality of moisture has been developed in NIMS. This “moisture sensor” has already received numerous inquiries from various businesses including beauty care, materials, infrastructure and housing industries. What is the quality of moisture? How does the device determine that? And what is the intended use of the device? We asked these questions to Jin Kawakita, Chief Researcher of Semiconductor Device Materials Group, MANA.

Hygrometer merely measures moisture content in the air

When the water or moisture content in the air is high, the condition may lead to fogging of mirrors and windows, mold growth and metal corrosion. On the other hand, when the moisture content is low, the condition may cause dry skin, influenza outbreak, and so on. Therefore, moisture has a variety of impacts on our everyday life.

The ideal room humidity is generally about 50 to 60%, depending on the temperature. Hygrometers have two types: instruments that measure the length of an animal hair or a nylon thread under tension, which changes as the material absorbs moisture; and instruments that measure electric current that changes as a polymer membrane absorbs moisture. Kawakita notes, “These instruments measure the amounts of moisture absorbed by a hair or polymer membrane. Moisture in the air takes the form of water droplets, and hygrometers cannot measure the size of the droplets.” The size of water droplets has various influences on humans, even at the same humidity. For example, when you use a mist sauna room, smaller water droplets infiltrate your skin more readily. Also, the smaller the water droplets released from a humidifier are, the farther they tend to spread. Accordingly, both the “quantity” and “quality” of moisture are important, and its quality is directly influenced by the size of water droplets.

The size of water droplets can be measured using a laser, but that requires a sizable instrument too large for everyday use. To address this issue, Kawakita developed a groundbreaking sensor—the moisture sensor—that is small and capable of determining the size of water droplets.

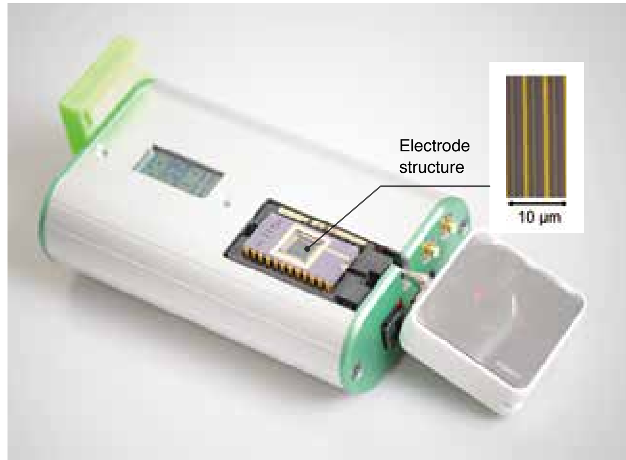
Able to identify 0.5 μm water droplets, quick response with zero power consumption

The moisture sensor has a simple structure. A total of 100 electrodes, 50 each of gold and copper electrodes, are arrayed alternately in parallel on a 5 mm-square silicon chip. When a water droplet bridges the gap between two adjacent electrodes, an electric potential difference is generated between the gold and copper electrodes, causing electric current to run. The current is measured to quantify the water droplets. The greater the amount of bridging water droplets, the greater the amount of electric current produced.

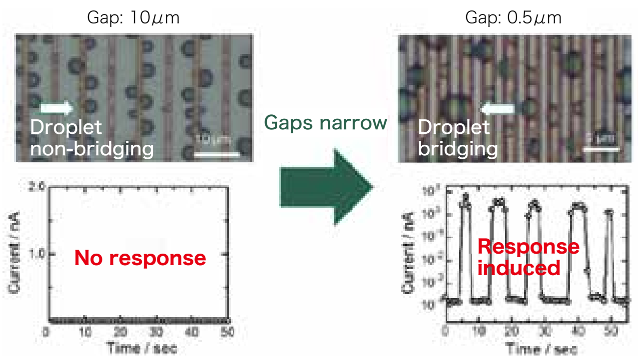
“If no electric current is produced by a chip with 10 μm electrode gaps, but current is produced by a chip with 1 μm electrode gaps, then, we can figure that the size of water droplets detected is larger than 1 μm and smaller than 10 μm. The use of one chip with a known electrode gap width only allows us to find whether droplets detected are larger or smaller than the gap width. However, if we use another chip with different electrode gap width, we can determine the size of water droplets more precisely,” explains Kawakita.

A dew condensation detector basically has the same mechanism as the moisture sensor, but major difference between the two devices is the electrode gap width. Dew condensation detectors on the market have an electrode gap width of at least about 100 μm, while the moisture sensor has a gap width of at least 0.5 μm (500 nm). The formation of extremely narrow electrode gap widths was made possible by semiconductor microfabrication technology. “The smallest water droplet recognizable by the naked eye is 10 μm. The moisture sensor is capable of identifying droplets that are invisible to the naked eye.”

■ Moisture sensor



■ Determining water droplet size



Schematics showing that when water droplets bridge gaps between two adjacent electrodes arranged in parallel, electric current is produced. By using another chip with different electrode gap widths and checking the chips’ electrical responses to droplets, the size of water droplets can be determined.

The moisture sensor has other notable features. First, its size is very small. Hygrometers and dew condensation detectors are several centimeters in size. In comparison, the electrode part of the moisture sensor is several hundreds of micrometers, and the silicon chip on which the electrode part is integrated is only 5 mm. Second, a hygrometer needs several to 10 seconds to respond because its measurement part gradually absorbs moisture. In contrast, the moisture sensor responds very quickly in 0.02 seconds. Lastly, almost no power is consumed by the sensing part of the moisture sensor. This is because electric current is generated and detected when a water droplet bridges the gap between two adjacent electrodes, virtually without any power input.

From beauty care to infrastructures

Kawakita says that potential areas of application are diverse for this moisture sensor. “First, the beauty care industry came up to my mind. For example, you can estimate the condition of your skin based on the size of water droplets released from the skin.” He also says, “The moisture sensor is useful in dealing with dew condensation.” The moisture sensor can detect small, invisible droplets before they condensate, making it possible to take dew condensation prevention measures such as turning a heater on beforehand.

Kawakita also developed a measurement instrument which extracts current signals, converts them to digital signals, and transmits them to a computer. In addition, he developed software that enables the display of measurement results. After putting these components together, he presented the moisture sensor at the International Nanotechnology Exhibition and Conference in January 2016. “People from surprisingly diverse industries showed interest in my sensor. Some of them already have made a license agreement or launched joint research with me. Some proposals are still under consideration. Some of the ideas about potential applications suggested by visitors were very creative, so I was very pleased to talk with them.”

Kawakita thinks the moisture sensor has a great potential in agriculture. “Moisture is a very critical factor for crops both during cultivation and transport. If sound moisture management is exercised using the moisture sensor, I presume that the quality of crops will be improved and labor shortage will be eased through automation.”

Measuring moisture and freshness

“Actually, I did not aim to develop a sensor capable of determining the size of water droplets at the beginning,” says Kawakita. Long before he started this project, NIMS was developing sensors to be used for constant monitoring of moisture on the surface of infrastructure, in order to understand the effect of the atmospheric environment on the corrosion of bridges and other infrastructure. The sensor was initially 5 cm square in size, but Kawakita worked on its miniaturization from 2014. “First, I narrowed the widths of the electrodes. Through this modification, I realized that the sensor can measure tiny water droplets, and the use of several sensors enables determination of droplet sizes. This realization led to the development of the moisture sensor in its current form.” Because existing semiconductor microfabrication technology is compatible with and available for their purposes, small sensors can be produced at low cost. Furthermore, the sensors are energy-saving, so they are suitable for constant monitoring of moisture on the surface of infrastructure at many measurement points.

Kawakita came up with the name “moisture sensor.” “‘Moisture’ is a synonym for ‘dampness’ in English, but it also means ‘fresh and youthful’ when Japanese people use the word in connection with cosmetics. Because I want to use the sensor for many purposes, I named it this way. Since people from many businesses are showing interest in it, I think the naming was a success.”

(by Shino Suzuki, PhotonCreate)

Research Highlight

For safe and secure society

Making smartphones toxic gas sensors

Shinsuke Ishihara
Senior researcher, Frontier Molecules Group,
International Center for Materials Nanoarchitectonics (MANA), NIMS

A revolutionary sensor, which enabled detection of toxic gases using a smartphone, was developed by Shinsuke Ishihara, Senior research of Frontier Molecules Group, MANA. We asked him about the mechanism of the sensor and future plans.

All of us have the possibility of being exposed to toxic gases through potential leak accidents around volcanic vents or industrial plants or acts of terrorism, among other risks. Even if you are exposed to toxic gases, the damage can be minimized by detecting poisonous gases at earlier point, which leads to quick escape to a safe place or quick administration of an antidote. However, current commercial toxic gas sensors are large, heavy and expensive, so it is not practical to install them in many places or use them as portable personal sensors.

High sensitivity by combining CNTs and supramolecular polymers

To fulfill these needs, Ishihara and a research group at the Massachusetts Institute of Technology (MIT), USA, jointly developed a small and inexpensive sensor capable of detecting toxic gases sensitively and easily. Ishihara explains, "The sensor has a simple structure—we just wrapped supramolecular polymers around carbon nanotubes (CNTs) and spread the CNTs between two electrodes. However, the supramolecular polymers are elaborately designed; when they are exposed to electrophilic toxic gases, weak bonds in the polymers break, causing them to detach from the CNTs," says Ishihara.

CNTs are highly conductive electrically. However, when they are covered with supramolecular polymers, they become poor conductors.

"When the sensor we developed comes in contact with toxic gases, the supramolecular polymers separate from the CNTs, which restores the high electrical conductivity of the CNTs. By measuring the change in conductivity, the sensor can detect toxic gases."

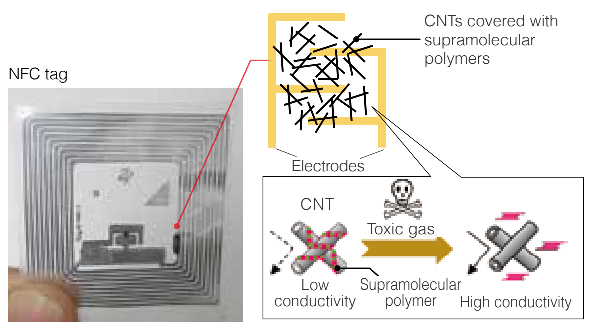
The use of CNTs allows miniaturization of toxic gas sensors, and many studies have reported on the development of toxic gas sensors using CNTs. However, because the amount of change in conductivity in these sensors was only 1% to 10% of the original conductivity state, the sensors often detected toxic gases falsely. "We developed a method that dramatically increased the amount of change in conductivity, by up to 3,000%, so that the sensor can always detect toxic gases accurately," says Ishihara proudly. "At first, I could not believe we achieved a 3,000% increase. So, I measured again and again until I was finally convinced that the measurements are accurate and reported the results."

Pairing NFC tag with toxic gas sensor

As soon as a fellow researcher at MIT received Ishihara's report, he made a suggestion to Ishihara. "His idea was to integrate the new sensor into an NFC tag circuit. I was intrigued by the idea and immediately took action." An NFC tag refers to a chip that enables "near-field communication," and it can communicate with NFC-compatible smartphones by holding the phone over the tag. Ishihara and his co-researchers designed the circuit in such a way so that when the NFC tag with the sensor is in a toxic-gas-free environment, the tag is unreadable, but when the tag with the sensor is exposed to toxic gases, and the sensor's conductivity increases by approximately 100%, it is readable by a smartphone. Ishihara and his co-researchers conducted experiments using thionyl chloride, an electrophilic chemical substance, and confirmed that only five seconds of exposure to a low concentration gas (10 ppm) rendered the NFC tag readable. "The new sensor can detect the presence/absence of toxic gases, and the use of the NFC tag enables transmission of the information from the sensor to a smartphone when the phone is simply held over the tag. It is also theoretically feasible to create a system to trigger an alarm and automatically notify a fire department," says Ishihara.

The sensor is disposable, and 1 g of chemical sensing material, consisting of CNTs covered with supramolecular polymers, makes 4 million sensors. So, it is feasible to mass-produce the sensor at low cost. Moreover, the NFC tags cost only several tens of yen per tag. "The sensor can be installed on walls of factories where toxic gases are used, train stations, and other crowded facilities. Also, people can carry the sensor with them when they visit volcanic areas or exercise caution against potential terrorism. I hope these applications will make society safer."

(by Shino Suzuki, PhotonCreate)



■ Toxic gas sensor embedded in an NFC circuit

Research Highlight

World's highest sensitivity accomplished!

Innovative alcohol sensor with hexagonal-pyramid-shaped zinc oxide nanoparticles

Noriko Saito
Senior researcher, Ceramics Surface and Interface Group,
Research Center for Functional Materials (RCFM), NIMS

Hexagonal-pyramid-shaped zinc oxide nanoparticles are a new material with high expectations as they may contribute to the realization of more sensitive alcohol detectors at lower cost. The material was synthesized by senior researcher Noriko Saito at the Ceramics Surface and Interface Group, RCFM, NIMS.

At present, there are two major types of alcohol sensors: semiconductor and electrochemical. In semiconductor sensors, which have superb sensitivity to low concentration gases, electrodes are wired on a substrate, and a gas-sensitive oxide semiconductor material is spread on top of that. When a gas sensitive material is exposed to gaseous alcohol, a reduction reaction occurs on its surface, resulting in decreased electrical resistance. The sensor detects alcohol by measuring this resistance change.

"Tin oxide (SnO_2) is mainly used as a gas sensing material in semiconductor sensors. Zinc oxide (ZnO) also had been suggested as a suitable gas sensing material, but its lower sensitivity and gas selectivity had been issues. I had been studying the synthesis of zinc oxide for use as a light emitting material, and because of this background, I got involved in alcohol sensor research," explains Saito.

World's highest sensitivity accomplished

To date, zinc oxide powder has been synthesized using mainly gas phase methods or solution methods. After examining these methods, Saito decided to use a solvothermal method, which uses several kinds of solvents. "In this method, zinc oxide particles can be shaped in a variety of ways by changing the kind of solvents used," says Saito.

For example, when zinc oxide was synthesized in water, the resulting product took the form of hexagonal cylindrical particles. On the other hand, when the synthesis was performed in a mixture of 90% ethylene glycol and 10% water, the resulting product took the form of spherical particles consisting of hexagonal-pyramid-shaped nanoparticles that underwent oriented aggregation. The shapes of particles also change greatly as a reaction progresses. Spherical particles cracked as the reaction advanced and eventually broke into wedge-shaped particles.

"I thought the sensitivity of ethanol sensors might increase as the particles disintegrate. So, I tried to stir the solution during zinc oxide synthesis, which resulted in the formation of dispersed hexagonal-pyramid-shaped nanoparticles. They appeared to be fragments of the spherical particles," says Saito. "I measured the sensitivity of these nanoparticles to ethanol, and found that the sensitivity was so high that we needed to extend measurement range. The resistance of the sample in air containing 50 ppm of ethanol was one-ten thousandths of the resistance of sample in air containing no ethanol. This material was 20 times more sensitive to ethanol than any zinc oxide-based sensors reported previously. Moreover, this material was as sensitive as platinum-added tin oxide, which is the most sensitive material to alcohol to date."

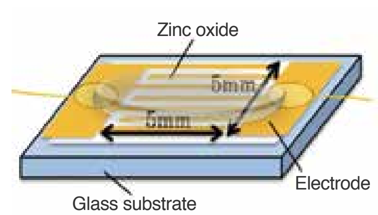
Research team found that the synthesized particles had the shape of hexagonal pyramids. Such particles had not been reported before, and they thought that these crystal planes are the cause of the high sensitivity. They submitted a patent application to register the particles as a new alcohol sensing material. "The synthesis of hexagonal-pyramid-shaped zinc oxide nanoparticles does not require precious metals such as platinum, so they can be mass-produced at low cost. I really hope that the development of this material will go all the way to commercialization."

Next goal is to develop gas sensor for health checkup

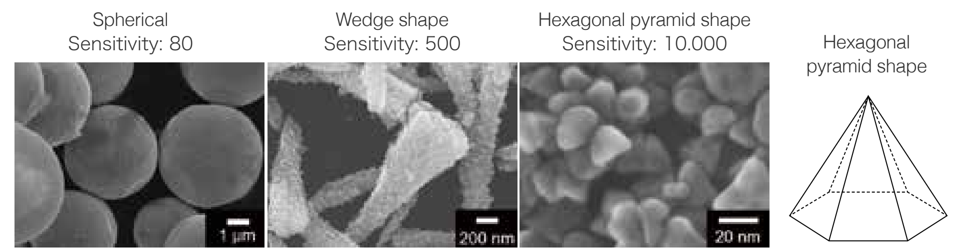
Saito also envisions the development of the gas sensor for health checkup. For example, it is known that the breath of diabetic and cancer patients contains many kinds of specific gases. If a sensor capable of detecting these gases is available, it will be useful in early detection of these diseases and comprehension of patients' conditions.

"The zinc oxide nanoparticles we synthesized using a solvothermal method are potentially applicable to the development of many other types of sensors," says Saito.

(by Shino Suzuki, PhotonCreate)

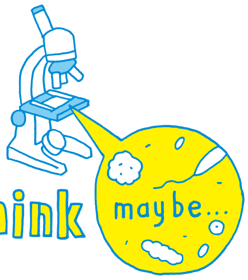


■ Structure of an alcohol sensor

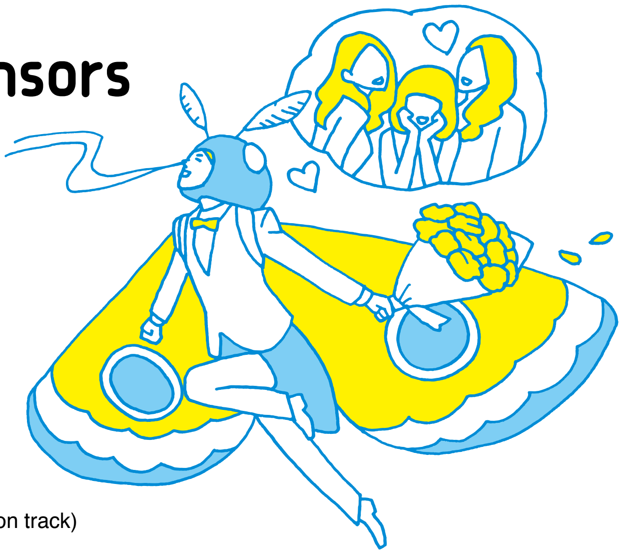


■ Various forms of zinc oxide nanoparticles and their sensitivity to alcohol

Science is even more amazing than you think



Era of a trillion sensors



Written by Akio Etori

Illustration by Joe Okada (vision track)

We humans sustain our lives by perceiving the surrounding environment through the senses of vision, hearing, smell, taste and touch, and adapting to it. So, the eyes, ears, nose, tongue and skin serve as vital sensors. However, our human sensors are not exactly superior to the sensors of other animals.

Dogs' sense of smell is said to be 1 to 100 million times keener than humans' (that is why dogs are used for drug detection), and bats accurately measure the distance to nearby objects by emitting ultrasonic waves and hearing the echoes.

Scientists are developing advanced sensors based on what they have learned from superior animal sensors. For example, they are developing a sensor using Insects' sense of smell as a model.

Insects are sensitive to certain smells as much as dogs. Males of the silkworm moth can sense pheromones released by a female moth several kilometers away and fly toward the female.

A part of insect antennae functions as olfactory receptors. When substances of a specific smell attach to the receptors, electrical signals are generated and travel to the brain, which tells the insect to fly to the source of the substance. Some insect receptors have been found to respond to only one or a few kinds of odor substances. It is feasible to genetically manipulate these receptor cells so that they become responsive to different odor substances. Using this technique, research has been underway for the development of sensors useful in various areas such as detection of narcotic drugs and land mines and search of disaster victims.

It would be very convenient if such sensors are abundantly available in the environment and provide us with all sorts of information.

Some people predict that sensors will be disseminated everywhere across the world in the near future as an information revolution takes place in the form of the Internet of Things (IoT).

This future movement is referred to as the era of a trillion sensors. The state of the world in which a trillion sensors are disseminated is called a trillion sensor society. This quantity is 100 times the current number and means 150 sensors become available per person.

The concept of a trillion sensor society was first proposed by an American entrepreneur, Janusz Bryzek, four years ago, who said that humans should establish a huge sensor network in society using over one trillion sensors every year, in order to resolve global-scale social issues. Data sent from sensors accumulates and turns into "big data." By analyzing it using artificial intelligence (AI) or supercomputers, big data is expected to be applicable to diverse fields including medicine and electronics.

People involved in this initiative hope to put this concept into practice by around 2023. To achieve this, it is necessary to develop methods for mass producing sensors at low cost.

Eventually, AI will surpass human brains, the IoT will be popularized around the world, and sophisticated sensors will be disseminated globally. I envisage that human wisdom will play an even greater role in creating a new world by applying these revolutionary technologies.

Akio Etori: Born in 1934. Science journalist. After graduating from College of Arts and Sciences, the University of Tokyo, he produced mainly science programs as a television producer and director at Nihon Educational Television (current TV Asahi) and TV Tokyo, after which he became the editor in chief of the science magazine Nikkei Science. Successively he held posts including director of Nikkei Science Inc., executive director of Mita Press Inc., visiting professor of the Research Center for Advanced Science and Technology, the University of Tokyo, and director of the Japan Science Foundation.

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