NICT NEWS

National Institute of Information and Communications Technology

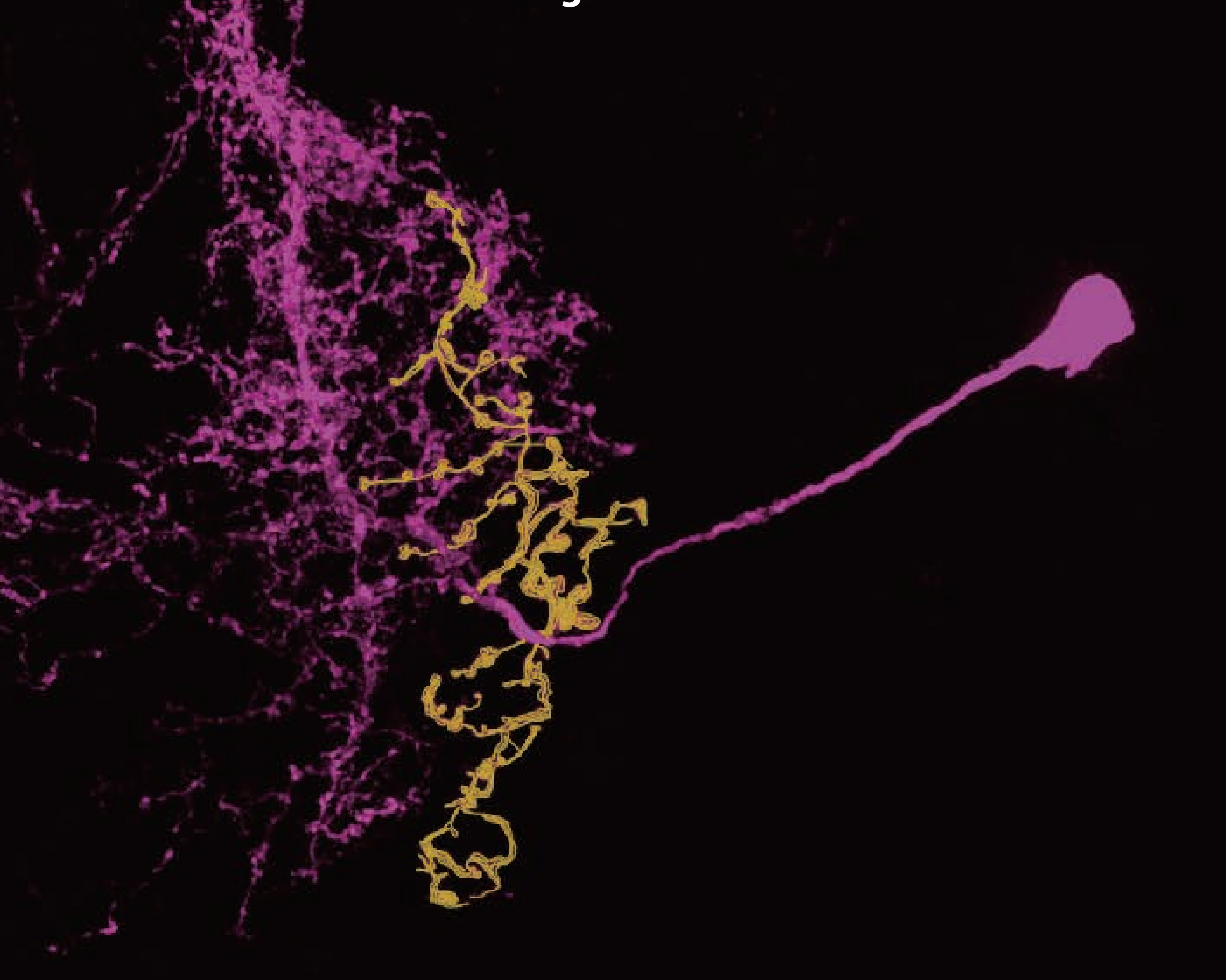
No.4 2019
Vol. 476

FEATURE

Frontier Researches to Pave the Way for the Future ICT

Interview

Sowing the Seeds for the Future and Paving the Way to New Fields through Innovative Basic Research



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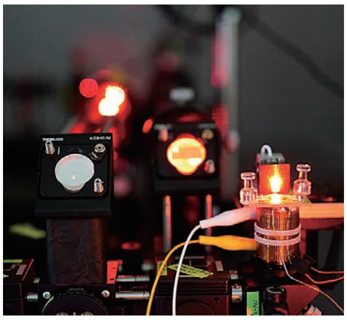


Cover photo:
Front cover: "Feeding neuron," a pivot that controls feeding behavior in the brain of a vinegar fly (*Drosophila melanogaster*). Most information related to the control of feeding behavior is integrated in the Feeding neuron. Neuronal branches digitally traced with magenta receive sensory inputs (such as taste), whereas branches shown in yellow command motor outputs for feeding. It is expected that the causal link between synaptic plasticity (micro changes in information processing in the brain) and memory (changes in macro brain functions) is directly observed in this neuron.

Upper-left photo:
Above left: Optical tweezers (stage part) with temperature control capable of measuring force at the molecular level. This is a new method that allows the accurate reconstitution of biological systems, making it a powerful tool for studying biological network control.

FEATURE

Frontier Researches to Pave the Way for the Future ICT

—Special Issue on Advanced ICT Research Institute—

Interview

Sowing the Seeds for the Future and Paving the Way to New Fields through Innovative Basic Research

Advanced ICT Research Institute

Iwao HOSAKO

Director General
Advanced ICT Research Institute

After completing a doctoral program, Iwao HOSAKO worked for NKK Ltd. (currently JFE). In 1996, he joined the Communications Research Laboratory, Ministry of Posts and Telecommunications (currently NICT). He has been engaged in research and development of terahertz semiconductor devices and various application systems. Ph. D. (Science).

ICT has been evolving at breakneck speed. The integration of semiconductor circuits is on the verge of reaching its limit, and the huge amount of information contained in big data, which cannot be processed by the human brain, is starting to be processed by AI.

What lies ahead in the future of information communication? How will ICT overcome this flood of information? We interviewed Director General Hosako of the Advanced ICT Research Institute, a research institute that stands out even within NICT, where basic research is carried out in preparation for the future.

——ICT has been evolving at breakneck speed. What lies ahead in the future?

Hosako: I think "30 years" is one of the key points. The Advanced ICT Research Institute was established in Kobe in 1989, exactly 30 years ago. It was during the Japan-U.S. economic friction when Japan was criticized for not engaging in any basic research, but simply riding on the back of U.S. research. This was what prompted the Japanese government to invest effort into basic research. There was a need to carry out basic research in the information communication field too, which led to the founding of the Advanced ICT Research Institute. But the institute came to be pressured into achieving results faster. I think it was because of this that the number of papers being published in Japan has plummeted considerably in recent years, compared to countries overseas. This is how the system for technological research changed, weakening the foundations of science and technology. But even so, I think it was the seeds that were sowed at the start that led to the series of Nobel prizes that have been won recently.

Learning from the past 30 years, I think the most important thing is to sow the seeds for new ideas, then make sure they are cultivated continuously for over 30 years.

The Three Key Technologies That Will Pave the Way to the Future 30 Years from Now

——What kind of technologies are there that will pave the way to the future?

Hosako: We believe there are three key technologies. One of them is quantum technology. Quantum information processing technology, in particular, is very important. A spectacular increase in computation speed is what will lead to advances in the performance of ICT. I think it will still be a while before a quantum computer is developed, but one thing I can say is that they will not be used individually like today's supercomputers but will be like accelerators developed for a specific purpose. They will be like the graphic boards of PCs. So, when they are used for a specific purpose, they will achieve incredible results that will be incomparable to today's supercomputers.

We have many people engaging in quantum technology research at our institute. They include researchers involved in superconducting devices, ion traps, quantum cryptography, and quantum sensors. I want to make effective use of these resources.

——What is the second key technology?

Hosako: It is the biological information communication system. Insects and bacteria are the organisms that have thrived the most on Earth. Looking at bacteria for example, they have sensors through which information is inputted, and actuators through which information is outputted (system of turning energy into movement. This may be the flagellum in bacteria), and in between, they have an information processing (computing) system. In other words, information is inputted, computed, then outputted, just like in a comput-

Interview

Sowing the Seeds for the Future and Paving the Way to New Fields through Innovative Basic Research

er. So, we can learn a lot from this system. These organisms require very little energy to move. In a normal temperature environment, they process information in a world that barely rises above the level of noise. It has only been around a hundred years since humans recognized this ingenious system and began biomimicry, but bacteria have existed on this planet for 3 billion years. So, we believe the functions of bacteria are extremely refined.

We have also been focusing on learning from the mechanisms of the brain. The human brain contains around 100 billion neurons. In recent times, the fMRI has enabled the elucidation of brain functions at resolutions on a scale of around 1 mm, realizing major advances in neuroscience. However, a cubic millimeter of brain tissue contains a huge number of neurons. What we see is no more than the functions of groups of neurons. So, what do we have to do to look at the functions of individual neurons? The answer can be found in insects. In the Memory Neurobiology Project and the Neuro-network Evolution Project, we are studying the fruit fly whose brain is around 1 mm in diameter. Their brain consists of around 200,000 neurons. It's extremely small compared to the brain of a human being. Moreover, the insect's eye, known as a compound eye, has a resolution of around 800 pixels in the case of fruit flies. According to one theory, the human eye is said to have a resolution of around 576 million pixels, so the eye of the fruit fly is far inferior to the point of being almost impossible to compare. But the insect is able to fly, navigate, find food, and find mates on this sensory input. Their sensors and information processing capabilities are basic, but they are still more capable than drones. This simple, lightweight information processing capability is ideal for IoT.

——What is the third key technology?

Hosako: You may think "why now?" but the third key technology is to make optical fibers and wireless communication faster. We are focusing on short-range communication. There is a need for superfast communication that does not need to be long-distance, for example, the communication between sensors and a control computer inside a vehicle. Working toward superfast communication will give rise to a variety of spinoffs. For example, in our Nano scale Functional Assembly Project, we are looking at using organic EO devices for superfast, short-distance optical fiber communication. There is the possibility of being able to apply this technology in realizing a LiDAR (laser radar) for use in sensors with no mechanical moving parts for preventing collisions in automobiles.

——Will you use terahertz waves for wireless communication?

Hosako: Terahertz waves have extremely short wavelengths, and in wireless communication over extremely short distances, they can achieve superfast communication of 100 Gbps. This technology was developed through joint research between Panasonic and Hiroshima University, and it was announced in February at ISSCC2019, an international conference on semiconductor technology. Other than that, the technology can also be used to diagnose important cultural properties before beginning repair work on them, or for controlling the thickness of special coatings for absorbing radio waves. At the moment, it can be used in fields in which you don't need to worry about costs, but to get people to use the technology more extensively, there will be a need to cut costs dramatically.

The Need for Long-Term Research

——So, it takes time for technologies to become useful in society?

Hosako: After launching research into new technology, it takes around 20 to 30 years for it to appear on the market. Right now, a representative example of the results of NICT's research being used throughout society is our multilingual speech translation system. The fundamental R&D for this technology was originally begun 30 years ago at the KARC (current Advanced ICT Research Institute), which was opened as a center for carrying out basic research on information communication. The institute was set up with three systems for engaging in research on information, physical properties, and biological systems.

——What do you envisage for the future of the Advanced ICT Research Institute, 30 years from now?

Hosako: I think amount of information will continue increasing in the future with no end in sight. But ironically, this huge volume of information will lead to congestion on the internet, requiring the excessive use of information processing and communication resources. So, we need technology to control this huge volume of information. Once again, the secret to solving this problem can be found in organisms. The behavior of animals in large groups is interesting. A huge school of fish consisting of tens of thousands of individuals can change direction simultaneously in an instant, or it can chase away enemies by making it appear to be a single large organism. In doing this, the tens of thousands of individuals are not all communicating with one another at once. Neither is there a leader in the middle of the school giving out orders. At best, they are each only looking at about three other adjacent individuals and acting independently. I think we will be able to do some interesting things if we could develop the technology for this kind of autonomous control. Swarms of bees too, act autonomously, and they start small, but ultimately make huge hives. If we could study and make use of such functions, we might for example be able to build bases on the moon using swarms of robots working autonomously, using very little energy.

——The Advanced ICT Research Institute has a research laboratory and development centers, but what is the difference between them?

Hosako: There are three centers; the Quantum ICT Advanced Development Center, Green ICT Device Advanced Development Center, and DUV ICT Device Advanced Development Center. These are research groups within our institute that are close to developing practical applications for our technologies or have successfully acquired major external funding. On the other hand, we only have one research laboratory. It's the Frontier Research Laboratory, consisting of around nine research units, which engage in anything that may become the seeds for achievements in 30 years' time. They engage in pure basic research.

Two New Ideas

——Apart from the three key technologies we talked about, are there any other new fields?

Hosako: They are not fields, but we have two other ideas. They are for super sensing and super control. For example, bacterial (E. coli) sensors are genuine super sensors. There are only two types of receptors (sensors) in bacteria (E. coli), but they use them to differentiate between a variety of chemicals. Using this super sensing technology allows the ascertainment of differences between carbonated beverages with almost 100% accuracy, which is difficult for humans to do. It can also ascertain the region where rice was grown from just the water used to wash it. Another example of super control is found in the Phased Array laser radar (LiDAR) with no moving parts. There is a need for free controlling of the laser beam in the LiDAR. In a lot of cases, a method is used in which a mirror is moved to control the beam direction. If a phased array using an array-type optical waveguide could eliminate moving parts, it would lead to reduced costs due to fewer breakdowns. If the unit cost could be reduced to several thousand yen, it would become possible to install them even in mini motor vehicles.

——Can you tell us about the Advanced ICT Research Institute's ambitions for the future?

Hosako: The trend among research institutes throughout Japan is that everyone is focusing on short-term research only, and I think fewer institutes are involved in the sowing of seeds for the future. People tend to believe that it is more efficient to achieve results in a short time by setting goals that can be attained easily, but in fact, setting long-term goals that may not even be attained is the way to give birth to numerous by-products and boost efficiency, as well as the level of research.

Moving forward, I want to continue sowing numerous seeds for long-term goals, and if the research is successful, I want the organization to split off from the Advanced ICT Research Institute to find practical applications for the technology. I want to strive in sowing such seeds, or cultivating the saplings for such research, and deepen ties between a variety of research fields in order to pioneer new fields in basic research.

Column

Holding of the "Advanced ICT Research Institute 30th Anniversary Symposium"

Photo of the symposium venue (in Kobe City)

To commemorate the 30th anniversary of the Advanced ICT Research Institute, the "Advanced ICT Research Institute 30th Anniversary Symposium" was held on June 7 in Kobe City. Around 150 industry-university-government researchers and associates gathered at the venue to take part in the event.

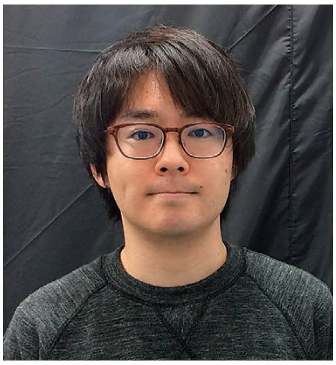
At the symposium, President Hideyuki TOKUDA of NICT gave an opening speech, which was followed by congratulatory speeches by guests, Director-General Hideyuki OHASHI of the Kinki Bureau of Telecommunications at the Ministry of Internal Affairs and Communications and President Shojiro NISHIO of Osaka University. (The latter guest speech was read by Executive Vice President Yasushi YAGI.) After that, a movie titled, "30 years at the Advanced ICT Research Institute" was shown, enveloping the audience in a peaceful atmosphere.

Director General Iwao HOSAKO of the Advanced ICT Research Institute gave a talk titled, "Advanced ICT Research Institute today and in the future," referring to the fact that the institute has created numerous outstanding research results with the number of paper citation accounting for 35% of overall NICT. (The percentage of its staff number is 12%.) He also stated that cutting-edge technology research will be disseminated as "from Kobe" brand in NICT, which many of the participants seemed to show their understanding for. Distinguished Researcher Kazuhiro OIWA of NICT, introduced the activities of young researchers at the institute, and the audience seemed to take great comfort in knowing that the seeds for new research were being sown at the institute.

In the latter half of the symposium, Director Shizuo TOKITO of the Research Center for Organic Electronics at Yamagata University gave a speech introducing the cutting-edge research for organic electronics and its future prospects, as well as on the importance of basic research in Japan, a technology-intensive nation. This was followed by a speech by Director Toshio YANAGIDA of the Center for Information and Neural Networks on the latest results of research carried out at the center in commemorating the 10th anniversary of the conclusion of a basic agreement with NICT and Osaka University.

The intellectually stimulating symposium came to a close at around 4:30 p.m. The event was a huge success, with participants enveloped in an atmosphere of greater expectations for the dissemination of research branded "from Kobe" of the Advanced ICT Research Institute.

Connecting Synaptic Plasticity to Memory at the Single Cell Level



Akira SAKURAI

Advanced ICT Research Institute
Frontier Research Laboratory
Senior Researcher

After completing his thesis studies, he did postdoctoral work at University of Massachusetts Medical School, Massachusetts Institute of Technology and Tohoku University. In 2014, he joined NICT. He is interested in the molecular and cellular basis of changes in circuit connections underlying memory formation at the single cell level. Ph. D. (Life Science).

In recent years, artificial intelligence (AI) and machine learning has made remarkable progress, and the ideas of neuroscience have largely contributed to this. Given such historical background, it might be imagined that the mechanism of learning and memory of the brain have already been fully understood. However, at many universities and research institutions throughout the world, lots of people are still working on the neural mechanism of learning and memory with the aid of huge funds. Regarding the biggest problem of memory study, it has been pointed out that there is a deep gap between the study of memory at the molecular and cellular (micro) level and that at the brain function, behavioral (macro) level. We are trying to fill the gap between micro and macro to elucidate how memory is formed in the brain at the single cell level with our original methodology.

Computers with brain-inspired strategy

Recently, there have been high expectations for the development of brain-inspired computers, which differ from the conventional von Neumann architecture. Computers with von Neumann architecture read an algorithm as a program and execute algorithms one by one through an established procedure, whereas computers inspired by the way of information processing in neurons are capable of parallel processing and learning with a large number of elements, and do not require a specific program. Because of this property, brain-inspired computers exhibit great performance in the case that an algorithm is not understood or difficult to be written (such as pattern recognition of sounds or letters). Especially, their importance is recognized in analyzing big data with high accuracy, which is getting important today. For example, IBM in the United States developed the computer chip named "TrueNorth" by imitating the physiological properties of a single neuron in information transmission in detail, and reported it in *Science* (Merolla *et al*., 2014) and already started to sell it. Compared to computers with von Neumann architecture, TrueNorth consumes less energy to conduct pattern recognition with better precision. Furthermore, it exerts the highest level of performance in machine learning. These facts suggest the effectiveness of the

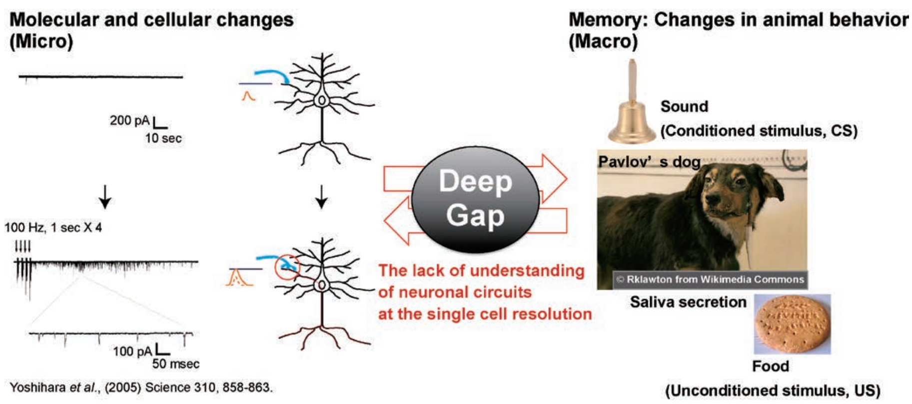


Figure 1 The gap between micro and macro in the study of memory

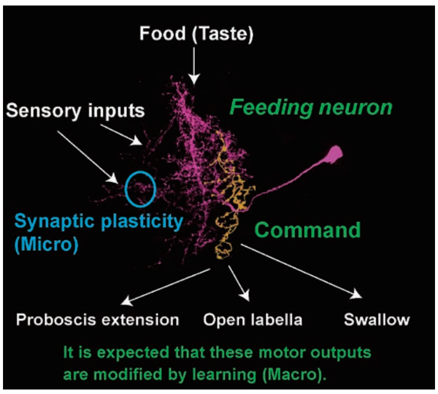


Figure 2 The "Feeding neuron" for connecting micro and macro. It is suggested that the most of information about feeding is integrated in the dendrite colored with pink, and all of the motor outputs for feeding are commanded from the axon colored with yellow.

strategy in which the properties of a single neuron are applied to design AI. Neurons can do only two things: "transmit" and "store" information. The mechanism with which a single neuron transmits information is well understood and actually applied in TrueNorth, whereas the mechanism of "store" is still an enigma. In order to make further dramatic progress in the performance of AI, we are trying to elucidate the "store" mechanism, in other words the mechanism of memory formation, at the single neuron level.

Micro and macro in the study of memory

It is believed that memory is formed by micro plastic changes in specific connections of neurons (synapse). However, it has been pointed out regarding the causal link between synaptic plasticity and memory that "currently, the biggest problem standing in our way is that the method for connecting a deep gap between micro studies and studies of macro brain functions is not necessarily clear (Nakaakira TSUKAHARA, Brain plasticity and Memory)." Although a dog can learn that food is given after bell ringing and secrete saliva in the famous "Pavlov's dog" experiment, we cannot understand which synaptic connection in the brain is changed (micro) to let a dog salivate (changes in macro brain functions) because there is no map of neuronal circuits that function during Pavlovian conditioning at the single cell resolution (Figure 1). Thus, one of the major factors causing the gap between micro and macro is the complexity of brain circuits. To investigate potential neurophysiological mechanisms of memory formation, we need a simple neuronal network to correlate behavior with the underlying neuronal circuit dynamics.

The "Feeding neuron" connecting the micro and macro

In order to fill the gap between micro and macro, we are using *Drosophila melanogaster* as a model. *Drosophila* shows various kinds of behavior and has a great ability for learning, even though the number of brain neurons is much smaller than that of human being. Therefore it is a useful model for the detailed study of mechanisms underlying brain functions. The "Feeding neuron" was found as a pivotal neuron that controls feeding behavior and reported in Nature* by our group (The Chief Senior Researcher is Motojiro YOSHIHARA). There is one Feeding neuron in each hemisphere of the brain. Activation of them induces the entire sequence of feeding behavior, while on the other hand ablation of them completely eliminates feeding behavior induced by food presentation. These results suggest that the most information related to the control of feeding behavior is integrated in the Feeding neuron (Figure 2). Thus, it is anticipated that if a new synaptic connection is formed to activate the Feeding neuron, memory about feeding will be formed as was seen in Pavlov's dogs.

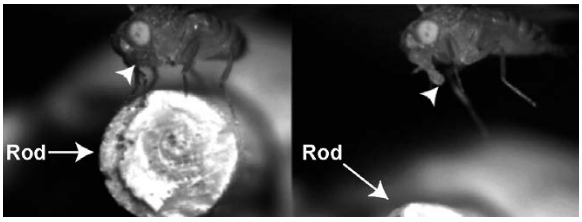


Figure 3　A Pavlov's fly extends its proboscis when a rod is released.

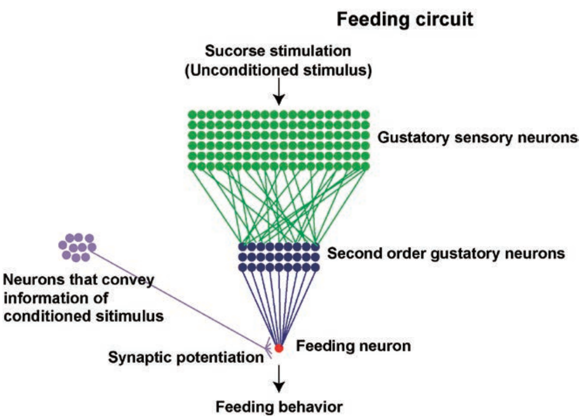


Figure 4　New connections that activate the Feeding neuron are created.

Pavlov's fly

To take advantage of the Feeding neuron in the study of memory, we have now established a novel conditioning experiment in which a fly learns that sweet sucrose solution is given immediately after releasing a rod from legs of a fly (a fly is holding a rod at first) just like Pavlov's dogs learned that they were given food after ringing a bell. After repeated presentation of the rod release stimulus followed by sucrose stimulation, flies extended their proboscis (a part of feeding behavior) in response to rod release alone (Figure 3), whereas they did not before conditioning. In calcium imaging experiments, we recorded the activity of the Feeding neuron in real time while getting the fly to learn and found that the rod release stimulus alone activated the Feeding neuron after the conditioning, whereas it did not before the conditioning. These results suggest that a new connection that activated the Feeding neuron was created at the Feeding neuron and/or upstream of the Feeding neuron (Figure 4). To pinpoint where the new connection is generated, we inactivated the Feeding neuron by using the optogenetic technique during conditioning, leading to suppression of proboscis extension by the rod release stimulus (memory). These results suggest that the new connection responsible for memory formation was created, at least partly, on the Feeding neuron.

Toward real-time observation of plastic changes in a single neuron during memory formation

Through electrophysiological recording and two-photon live imaging, we can monitor the plastic changes possibly occurred in the Feeding neuron in real time when memory is formed. Furthermore, at this time it is possible to manipulate gene functions to elucidate how micro changes at the molecular and cellular level make macro behavioral changes (memory) without any gap. Based on the findings obtained in this way, we will develop a mathematical model to design silicon circuits by a collaborative study. Our results open an avenue for the systematic analyses of the molecular and cellular basis of changes in circuit connections underlying memory formation at the single cell level by connecting micro and macro.

* Information presented in *Nature*
Flood, Iguchi, Gorczyca, White, Ito & Yoshihara. *Nature*. 499:83-87. 2013

Understanding the Mechanism of Spontaneous Oscillation that is Driven by the Collective Activities of Biomolecular Motors

Akane FURUTA

Advanced ICT Research Institute
Frontier Research Laboratory
Cooperative Visiting Researcher

After receiving her Ph.D. Akane FURUTA Joined NICT in 2011 and has been engaged in research on the mechanism of biomolecular motor. Restart Postdoctoral Fellowship (RPD). Ph. D. (Science).

The development of new network systems based on distributed processing by numerous components, taking a hint from living organisms, has been accelerating in recent years. These systems are totally different from conventional systems of top-down network control. However, the algorithm behind how local interactions between components lead to the overall desired behavior has yet to be elucidated. This led us to focus on the spontaneous oscillation phenomena (ciliary and flagellar beating) created by thousands of biomolecular motors that many cells have, and to set out to develop an experimental system for understanding the mechanism behind this cooperativity phenomena by artificially reconstituting the beating system.

Taking a Hint from the Self-Organization of Network Structure in Living Organisms

In recent years, there has been growing expectations for a society in which everything in the environment, including humans, will become connected to the network as in sensor networks, IoT, IoH (Internet of Human), and smart materials. However, if such networks were to be built as a centralized system with a control center as in current railway and telephone infrastructure, how would our future turn out? There is no such thing as flawless software, no matter how much care is taken to design it. A tiny error at the control center may lead to a large-scale system failure as is often reported in the media. As networks become increasingly convenient and an indispensable part of our daily lives and bodies, the damage from a failure may become immeasurable.

The above problem has heightened the focus of researchers on the use of algorithms employed by living organisms as a countermeasure. A system of mutual communication between numerous components at all levels, from molecules to molecular aggregates, cells, tissues, and individuals, is often seen in living organisms, and that is what enables localized responses, and the transmission of the results to a higher level. For example, the slime mold, *Dictyostelium discoide-*

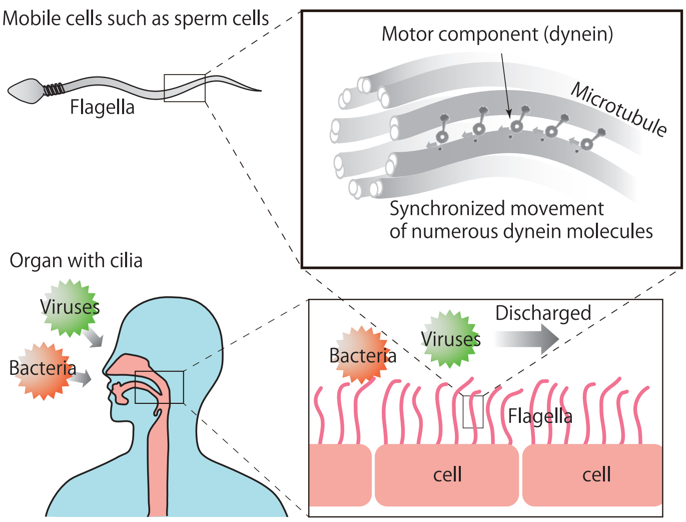


Figure 1 A schematic diagram of a flagellum and cilia. There is a row of motor components, dynein, on the surface of the microtubule framework. Synchronized oscillation is achieved through the coordinated movement of numerous dynein on the surface of the microtubule.

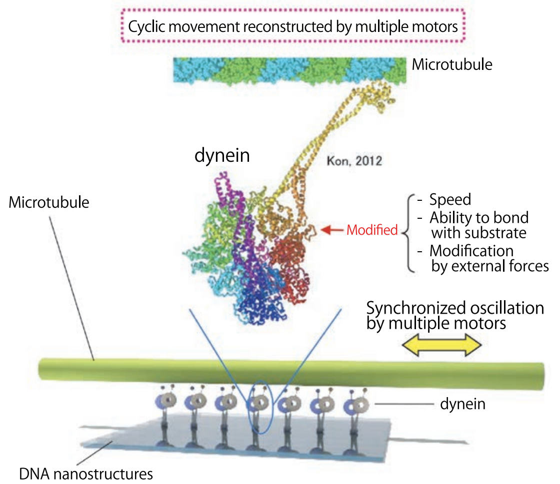


Figure 2 Schematic diagram of high-precision protein placement technology based on templates of DNA nanostructures. A micrometer-sized actuator mimicking a flagellum is made by placing dynein (biomolecular motors) at regular intervals along a rail.

um, normally exists as individual cells, but when faced with starvation, they accumulate to form a large sporocarp, which scatters spores for passing on the baton of life to the next generation. Moreover, flagella and cilia seen universally in living organisms, are formed by the self-assembly of numerous components including biomolecular motors, which are periodically placed on a scaffold of microtubules. They beat in a coordinated manner by interacting with nearby motors despite the lack of a centralized control system. There are great expectations for this self-organization and coordinated operative system of organisms to be applied to a network system based on a new bottom-up-style principle. But attempts to describe such phenomena in rational terms have always been difficult due to the complexity of biological phenomena based on hierarchical systems.

The Spontaneous Oscillation of Flagella and Cilia Triggered by Biomolecular Motors

To deal directly with this issue, we focused on ciliary and flagellar beating, in which the components are relatively easy to modify (Figure 1).

Flagella and cilia are long, hair-like structures that extend from the surfaces of cells. They are motile organelles that undergo cyclic beating motions, providing the driving force needed for cells to swim, or transport substances in vivo. As seen in the flagellar beating of a sperm cell as it swims toward the ovum, or the discharging of foreign matter by cilia on the epithelial cells of the trachea, flagella and cilia are indispensable to the biological activities of organisms, and these special structures have been retained in organisms from single-celled protists to humans. Inside these flagella and cilia are rows of numerous biomolecular motors known as dynein. These biomolecular motors act on the rails causing them to bend as the rails slide over each other. These bends are then transmitted along the entire rail, generating a controlled oscillatory motion that reaches frequencies of several dozen hertz. The oscillatory mode of the flagellum is able to change instantaneously on time scales in the order of magnitude of milliseconds, depending on environmental conditions. But when this happens, no clear signals are sent out to individual biomolecular motors to synchronize their timing in accordance with a particular frequency. Instead, they are believed to operate individually in independent cycles, but they gradually become synchronized through mutual interaction. In other words, it is a true system of bottom-up control. It is natural to expect that there are close relationships between individual biomolecular motors and the overall system, and their collective behavior is believed to be programmed entirely into the properties of individual motors, but the mechanisms behind this have yet to be elucidated.

Wind Tunnel Tests on Reconstituting Living Organisms

With the aim of elucidating the mechanism behind the "self-organizing cooperative phenomenon," which is a characteristic of living organisms, we are carrying out research into artificially reconstructing the structure of flagella. The biggest issue in carrying out such research was building the experimental system. The flagellum is made up of extremely complex structures including the biomolecular motor, which is the smallest motor component, rails, and numerous spring components, and because of its complexity, it is difficult to predict the relationship between the properties of individual motor components and the macroscopic behavior they result in, even when using a very large-scale computer. Just as wind tunnel tests are indispensable even today in the designing of airplanes and bullet trains, understanding the coordinated movements of flagella will require repetitive experimental cycles in which the motor components are modified to see how the changes affect their collective behavior.

This led us to actually make a minimalistic "oscillating biological machine" simulating the structure of a flagellum by placing dynein biomolecular motors at regular intervals along a rail, just as in real flagella, by using high-precision protein placement technology we developed based on templates of DNA nanostructures (Figure 2). If we could ascertain how behavior is affected by which components being placed where, it will allow us to carry out experiments similar to those carried out in the wind tunnel. Prior research revealed that a single molecule of dynein is only capable of making weak movements, and it is only when numerous molecules work in unison that they are able to function properly. However, the relationship between a single molecule of dynein and the overall behavior of the flagellum has not been elucidated. At this stage, one of the most convincing hypotheses based on circumstantial evidence is that the function of individual components is designed to be modified greatly by the mutual movement of the components. This modification is fed back mutually, and as the components affect one another, they become synchronized, this is what is believed to lead to overall spontaneous oscillation.

Future Prospects

We will make full use of the technology we developed for integrating biomolecular motors with DNA nanostructures, and optical tweezers (Figure 3) capable of making measurements at the molecular level, to actually reconstitute biological systems. By doing so, we hope to elucidate the mechanisms behind how the dynamic, coordinated oscillation phenomenon by numerous molecules is generated spontaneously. We hope that using these new methods to study the essence of how organisms form these networks will allow us to apply the knowledge to a variety of fields, such as in energy-efficient, autonomous distributed computers based on new principles, and network control technologies that were difficult to develop through top-down methods. We are on the verge of achieving numerous results, so you can look forward to a revolution in biology emanating from the NICT.

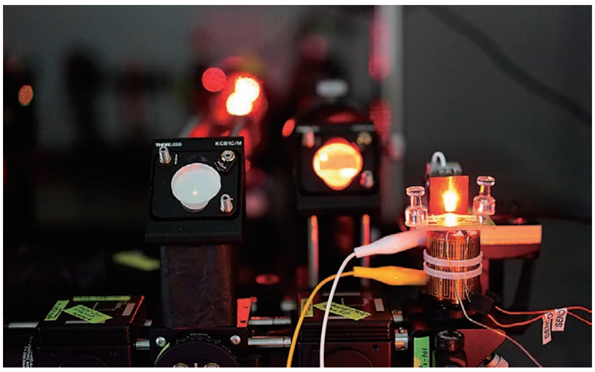
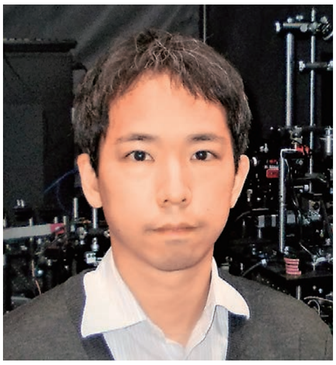


Figure 3 Stage part of optical tweezers with temperature control (refer to contents page).

Investigation of Nano- and Quantum-Structures Based on the Single-photon Counting Method

Toward the realization of higher performance colloidal-dot quantum emitter



Toshiyuki IHARA

Advanced ICT Research Institute
Frontier Research Laboratory
Researcher(Tenure-Track)

After getting his Ph.D. in Physics, he worked at Institute of Industrial Science in The University of Tokyo and Institute for Chemical Research in Kyoto University. He then joined NICT in 2017. His primary research interests are in developing advanced technologies of microscopic spectroscopy for understanding the physics in nanostructures and quantum emitters. Ph. D. (Science).

Research and development into quantum technology is accelerating throughout the world in preparation for a revolution in info-communications and information processing. Using microscopic, nano-sized materials allows easy manufacturing of "quantum emitters" that emit special light with non-classical properties. Quantum emitters can be used for a variety of purposes, including use in info-communications. This has led to research being carried out all over the world with the aim of making them brighter, more stable, capable of room temperature operation, etc. In this article, we introduce the characteristics of colloidal-dot quantum emitters made from a semiconductor nanoparticle material known as colloidal quantum dots, and an original measurement system we developed for accurately evaluating the emitter performance.

Nano-Sized Quantum Emitter, the Key to Quantum ICT

In recent years, researches are being carried out all over the world on a variety of emitters capable of generating non-classical light, which cannot be explained by concepts of classical waves. Examples include emitters that generate a series of single photons, which cannot be split any further, and emitters that generate quantum-correlated entangled photon pairs and indistinguishable photons. These emitters have the potential to realize tap-proof communication through quantum cryptography, or be used in, high-speed information processing technology that is overwhelmingly superior to existing computers. Among emitters capable of generating non-classical light, the nano-sized quantum emitter is one of the most expecting candidates to achieve outstanding performance. Nano-sized quantum emitters are emitters made of microscopic, nano-sized materials, and are characterized under the laws of quantum mechanics. As competition heats up around the world to develop cutting-edge "quantum ICT technology," the development of nano-sized quantum emitters, which are efficient at generating non-classical light, is also accelerating dramatically.

The Characteristics of Colloidal Quantum Emitters

Our research focused on a material known as the colloidal quantum dot (CQD), and we are carrying out experiments to investigate its performance as easily quantum emitters.

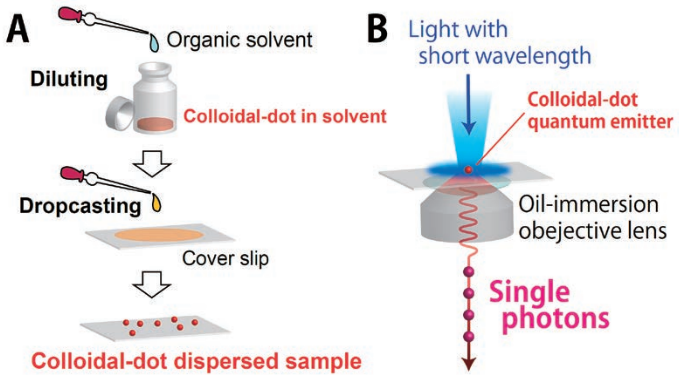


Figure 1 A: How a colloidal quantum dot (CQD) dispersed sample is made. It is diluted to a low concentration using organic solvent, then dropcast onto a cover slip. B: How single photons are generated using the CQD dispersed sample. Irradiating it with a short wavelength light results in the emission of single photons with long wavelengths. This system is characterized by its ability to be operated at room temperature.

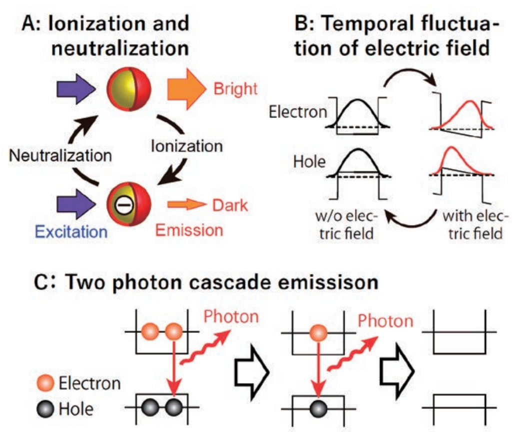


Figure 2 Examples of physical phenomena that affect the performance of the colloidal-dot quantum emitter.

The CQD is a semiconductor nanoparticle that exhibits high luminescence efficiency at room temperature, and it is a material that allows the low cost manufacturing of quantum emitters. The particles are around 2 – 10 nanometers in diameter, and they are characterized by dramatic changes in their properties, such as the color of the emitted light (wavelength), depending on their size, shape, material quality, etc. In this research, we set up our colloidal-dot quantum emitter (a quantum emitter made from CQD) according to the procedures shown in Figure 1.

Irradiating dispersed, low-concentration CQD with a short wavelength light causes the CQD to emit single photons with long wavelengths. The single photons emitted from the CQD have low directivity, but a microscope component known as an "oil-immersion objective lens" can be used to reduce loss, realizing greater brightness.

Recent researches have revealed that various physical phenomena affect the performance of the colloidal-dot quantum emitter as shown in Figure 2. Figure 2A shows the neutralization and ionization of a single CQD, which is one of the causes of temporal fluctuation (photoluminescence blinking) in the strength of emissions. Figure 2B shows how the presence or absence of an electric field inside the CQD results in a phenomenon in which the wave function of electrons changes, leading to temporal fluctuation in the color of emissions. Figure 2C shows the process in which two photons are emitted sequentially from a single CQD in a phenomenon known as "two-photon cascade emission." It is not just the case of CQD, but the performance of many nano-sized quantum emitters is affected strongly by these physical phenomena. The development of a high-performance nano-sized quantum emitter will require a deeper understanding of the mechanisms behind how these phenomena occur, and advanced technologies to control them.

Analyzing Emitters Using the Single-Photon Counting Method

To observe and analyze the variety of physical phenomena as shown in Figure 2, this resaerch utilizes the "single-photon counting method." The use of this counting method enables us to record the times of single-photon detection, at a high temporal resolution of around 10 picoseconds, in a text file. Figure 3 shows a schematic diagram of the measurement system developed for this research. A low-noise, high-sensitivity super-conducting nanowire single-photon detector is used, to analyze the characteristics of temporal fluctuation in the strength of emissions and two-photon cascade emissions with extreme precision.

In this system, the generated photons are passed through an optical element (beam splitter) to split the beam into half before they are passed through two optical fibers to measure what is known as their intensity correlation. If the single photons are being generated in an orderly manner at regular intervals, the probability of the two split photon beams entering the optical fibers at the same time will be 0%. So, the signal indicating the delay time between two photons being zero will be eliminated when using a two-channel single-photon detector to measure the coincidence count. Figure 4 shows an example of actual data of the intensity correlation obtained through experiments. The data shows that the ratio between the maximum coincidence count value and the value when the delay time between two photons is zero is around 0.01. The lower the value, the higher the performance, and tha value of 0.01 indicates its top-class performance as a single-photon emitter among all emitters around the world operable at room temperature.

Data obtained through recent experiments suggests that performance can be improved even further by making use of the characteristics of super-conducting nanowire single-photon detectors. We expect that the further experiments will prove the limitation of performance improvement of nano-sized quantum emitters at room temperature.

Future Prospects

This research proved how easy it is to make a high-performance single-photon emitter (colloidal-dot quantum emitter) by making use of CQD. If technology could be developed in the future to efficiently generate not only single photons, but also entangled photon pairs and indistinguishable photons, we can expect a dramatic spread in the practical application of ICT technology using non-classical light throughout society. Meanwhile, experiments using the advanced single-photon counting method have also made it clear that it is possible to quantitatively evaluate the non-classical properties and optical characteristics of a variety of nano materials, including CQD. In the next stage of research we will involve R&D into further improving the performance of nano-sized quantum emitters, while also aiming to ensure the advanced use of the single-photon counting method, and the extensive application of non-classical properties seen in nano and quantum structures.

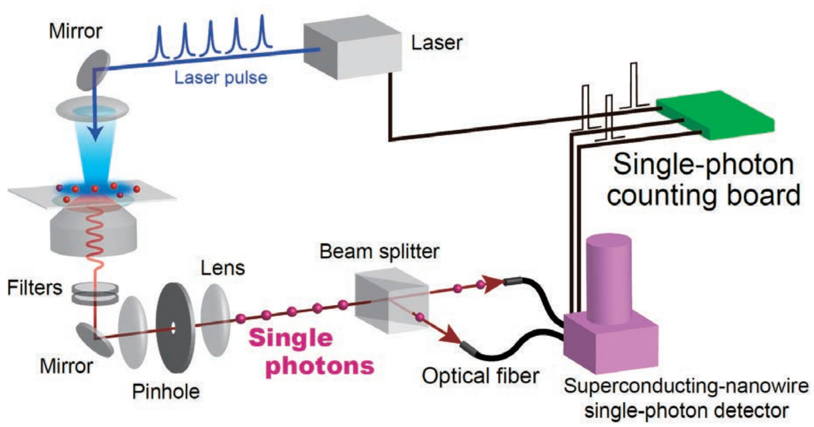


Figure 3 Schematic diagram of the counting system developed for this research. The generated single photons are detected by a super-conducting nanowire single-photon detector, and the signals are recorded by a single-photon counting board.

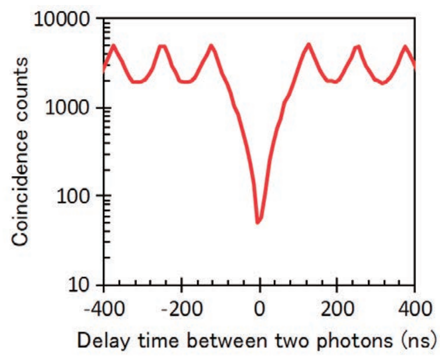


Figure 4 Example data on the coincidence count of single colloidal quantum dot emissions. It shows that the ratio between the maximum coincidence count value and the value when the delay time between two photons is zero is around 0.01, which is indicative of its ability to achieve top-class performance in the world.

Development of Normally-off Gallium Oxide Transistors

Toward the realization of safe and high-efficiency power devices

Takafumi KAMIMURA

Advanced ICT Research Institute
Green ICT Device Advanced Development Center
Senior Researcher

After completing graduate school, Takafumi KAMIMURA became a Research Fellow of the Japan Society for the Promotion of Science, and then joined NICT in 2013. Senior Researcher since 2014. Engaged in research on gallium oxide devices mainly for power device applications. Ph.D. (Engineering).

At a time when global energy demand is increasing year by year, the consumption of limited resources is continuing to grow. This problem is also related to environmental problems such as global warming, etc. and an energy saving has become an urgent issue throughout the world. The Green ICT Device Advanced Development Center is working toward the practical realization of a gallium oxide power devices that can contribute to energy saving using high-efficiency power conversion. Another essential characteristic for power devices is normallly-off, the electric current does not flow when a circuit fault , etc has occurred. It is necessary to realize fail-safe control of power devices. Recently, we have newly developed and demonstrated a device structure that can obtain the normally-off characteristic with good reproducibility, which was difficult to be realized so far.

Gallium oxide realizes high-power and high-efficiency power devices

Power devices are semiconductor devices that can handle high voltage and large electric currents. They play a major role in the control and supply of electric power by the functions of converting AC to DC , and changing voltage or frequency.

In recent years, wide-gap semiconductors which have a large band gap*1 compared to silicon (Si) have been gaining attention. This is because it is expected that wide-gap semiconductors will be able to achieve high power conversion efficiency in high power domains, which is not capable of the currently mainstream Si power devices. In particular, gallium oxide (Ga_2O_3) has an even larger band gap than gallium nitride and silicon carbide, the typical wide-gap semiconductors, so it is expected that it can deliver a better performance than using those materials.

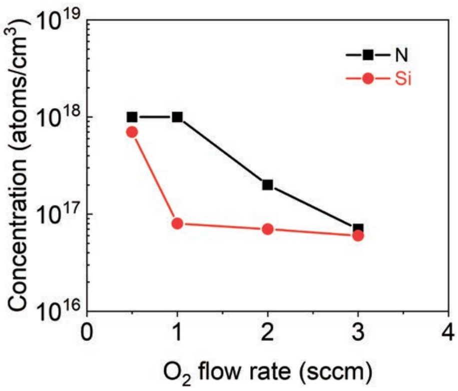


Figure 1 Relationship between O_2 flow rate in single-crystal Ga_2O_3 thin film growth and concentrations of incorporated N and Si in grown films. Each concentration is obtained by secondary ion mass spectrometry measurement.

Fail-safe – the necessity of the normally-off characteristic –

In addition to high-efficiency power conversion, another requirement with respect to the performance of power devices is that they be fail-safe. This indicates control that can safely block the electric current and avoid danger from the device running out of control in unforeseen circumstances such as failures, malfunctions, etc., because power devices have to handle high electric power safely. The device characteristic that realizes this control is the normally-off. So far, there are some reports about the normally-off characteristic of the Ga_2O_3 metal-oxide-semiconductor field-effect transistor (MOSFET*2), but production with good reproducibility was difficult due to residual electrons in a channel region of the MOSFET caused by unintentionally doped impurities in the materials.

In this study, we aimed for development of a process and device structure that can realize the highly-reproducible normally-off characteristic in Ga_2O_3 MOSFET.

Development of a method of controlling the concentrations of nitrogen and silicon in Ga_2O_3 single-crystal thin films

In Ga_2O_3 MOSFET, electrons are carriers of electric current. In the case that the electron concentration in the channel is high, the drain current flows even if the gate voltage is not applied, therefore it is necessary to lower this electron concentration. Prior to the beginning of this study, we had already known that Si atoms and nitrogen (N) atoms were incorporated into a single-crystal Ga_2O_3 thin film when the thin film was grown on a substrate using plasma-assisted molecular beam epitaxy (MBE). We consider that these elements are probably derived from the quartz components in the MBE machine and from the residual N_2 in the high-purity oxygen (O) gas cylinder which is the O source for the Ga_2O_3 growth respectively. In the Ga_2O_3 Si atom functions as a donor which give off electron, wheres the N atom functions as a deep acceptor which captures electron and reduces their concentration. When a MOSFET is fabricated using this single-crystal thin film, if the concentration of N is sufficiently greater than that of Si, the channel is depleted or the hole concentration becomes much higher than the electron concentration leading to a conversion from an *n*-type into a *p*-type. Therefore, if the electrons are not induced in a channel by a positive gate bias, the drain current does not flow due to lack of charge carriers, which means the realization of the normally-off characteristic.

Firstly, we conducted research into the crystal growth conditions to aim to obtain the relationship in impurity concentrations that N concentration was higher than Si concentration. Figure 1 shows the correlations between the oxygen flow rate during the single-crystal Ga_2O_3 thin film growth and the concentrations of incorporated Si and N in the film. In consequence of exploring O_2 flow rate in the growth condition, we found that when the O_2 flow rate was 1 sccm*3 the N concentration showed a ten times higher value than the Si concentration. Due to our discovery of this growth condition, we were able to realize single-crystal thin films that could be expected to realize the normally-off characteristic.

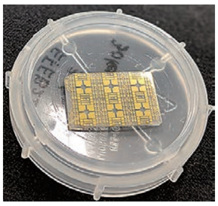


Figure 2 Picture of a device fabricated on Ga_2O_3 substrate. The size of substrate is 10 mm × 15 mm. The gold patterns correspond to electrode patterns, which correspond to each device and test pattern to evaluate material properties and electrode patterns to evaluate the devices and grown thin film are embedded on the substrate.

Demonstration of a normally-off Ga_2O_3 MOSFET

Next, we fabricated the Ga_2O_3 MOSFET using the single-crystal thin film grown under the aforementioned condition and evaluated its electric characteristics. (Figure 2). A structural schematic diagram of the Ga_2O_3 MOSFET is shown in Figure 3. Figure 4 shows the electric characteristics of the fabricated device. Figure 4(a) shows the relationship between the applied drain voltage and drain current density, and each plotted line corresponds to the case in which a different gate voltage was applied as indicated in the plot. The drain voltage-drain current density characteristics represent the typical *n*-type MOSFET characteristics in which electrons work as majority charge carriers. Figure 4 (b) shows the relationship between the applied gate voltage and the drain current density at the constant drain voltage of +5 V. At the gate voltage of 0 V to +5 V, the drain current density was sufficiently below the lower limit of measurement of the measuring device and was not observed. In other words, when the gate voltage is 0 V, the drain current flow is completely blocked due to the lack of the charge carriers, hence the normally-off characteristic was realized. Based on this fact, it was demonstrated that the residual electron concentration in the channel could be lowered successfully by the N doping. Moreover, if the applied gate voltage was increased exceeding +5 V, the drain current density started to rise exponentially and the transistor was transitioning to an on-state. However, at a gate voltage of over +8 V the gate leakage drastically increased and a normal transistor operation could not be possible, therefore it is supposed that this gate leakage can be reduced by replacing the gate insulator material with other materials, therefore the gate leakage is not expected to be a major obstacle to a future development of Ga_2O_3 MOSFETs.

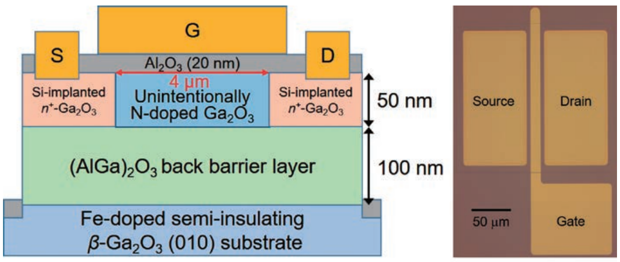


Figure 3 Cross-sectional schematic diagram of Ga_2O_3 MOSFET structure (left) and photomicrograph taken from the surface of device (right)

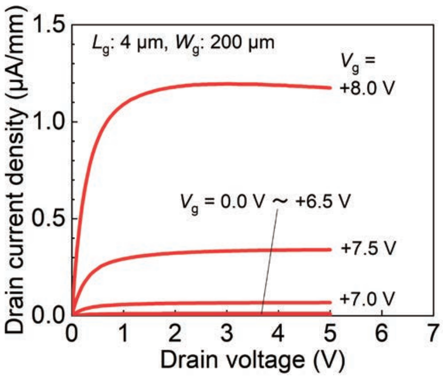


Figure 4 (a) Output characteristics of Ga_2O_3 MOSFET with a N-doped channel. This shows the *n*-type MOSFET characteristic in which as the gate voltage positivey increases electrons as charge carriers are induced into the channel and accordingly the drain current density increases.

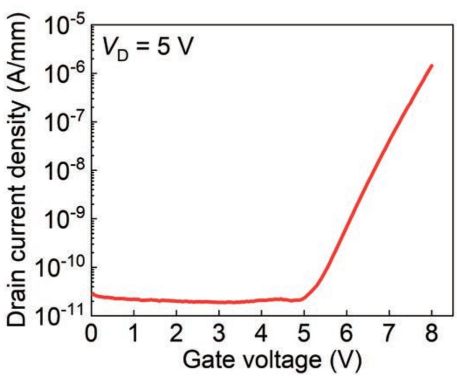


Figure 4 (b) Transfer characteristic of Ga_2O_3 MOSFET with a -doped channel. It exhibits the normally-off characteristic in which the drain current starts to rise from a gate voltage sufficiently higher than 0 V. Accordingly, no drain current flow is observed at the gate voltage of 0 V, meaning normally-off characteristic.

Future prospects

In this study, we performed the demonstration of the normally-off characteristic in the Ga_2O_3 MOSFET with N doped channel. Due to the establishment of this elemental technology, we have greatly increased the prospect that fail-safe control of power modules using the Ga_2O_3 devices will be possible.

Going forward, we will continue to advance research and development toward early practical realization of the Ga_2O_3 power devices. Since the Ga_2O_3 is a material that started to attract attention from 2012 when NICT showed the possibility of the power device application of Ga_2O_3, there are still some of unclarified physical property values. We also advance to reveal the physical properties of the Ga_2O_3 through the developments and demonstrations of the Ga_2O_3 devices.

(The results concerning the growth of single-crystal thin film were mainly efforts by Senior Researcher Yoshiaki Nakata at the Green ICT Device Advanced Development Center.)

***1 Band gap**
The energy difference in the energy band structure of a crystal from the top of the highest energy band occupied by electrons to the bottom of the lowest empty band. The band gap is also called the forbidden band. It is one of the most important physical property values in semiconductor materials.

***2 MOSFET: (MOS transistor)**
A MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) is one type of field-effect transistor. It has a structure that sandwiches oxide insulator film between the gate metal and the semiconductors. Due to this oxide insulator film a MOSFET can greatly reduce gate leakage current and as a result it realizes high efficiency.

***3 sccm**
Standard cc/min. A unit of flow rate that indicates how many cubic centimeters of a fluid flows per minute. It is normalized at 1 atmosphere and a constant temperature as the standard conditions.

The Challenge of Realizing Physical Layer Cryptography in Free-space Optical Communications

- Secure communications utilizing the properties of light -

Hiroyuki ENDO

Researcher
Quantum ICT Advanced Development Center
Advanced ICT Research Institute
Ph.D. (Science).

Biography

1989: Born in Saitama Prefecture
2012: Graduated from Department of Physics, School of Advanced Science and Engineering, Waseda University
2013: NICT Cooperative Visiting Researcher (enrolled in Waseda University Graduate School)
2017: Completed a doctorate program at Waseda University Graduate School and then joined NICT. Appointed to current position.

Awards, etc.

Fiscal year 2015 Technical Committee on Satellite Communications Award, The Institute of Electronics, Information and Communication Engineers (for an organization)
"Physical layer security in free-space optical communications"
Fiscal year 2019 National Institute of Information and Communications Technology award (Outstanding Performance Award)
"Physical layer cryptography in free-space optical communications"

Q&As

Q What do you like the most about being a researcher?

A I think that one of the real thrills of this work is being able to directly speak with people whose names I had only known from textbooks and academic papers before, and to be able to build things together with them.

Q If you were reborn, what would you like to be?

A If I could become a researcher again, this time I would like to conduct research into subjects like the ancient Orient, Japanese novelist/scientist Kenji Miyazawa, or owls; something which is not very closely related to my current area of research.

Q What do you think is your worst personal failure to date?

A I fail in some way every day, every week, and every month, in matters both large and small, but I was truly depressed when I broke the mug I had received as a memento from an international conference in the airplane on my way home.

"Free-space optical communications" is wireless communications using laser beams and is attracting attention because it is capable of high-speed, large-capacity communications. In particular, the sender and the receiver face each other to send information with highly directional laser beams, so it is said that these communications have a higher level of security than wireless communications using radio waves.

The physical layer cryptography that I am researching is a cryptographic technology that utilizes the characteristics of free-space optical communication. Under the assumption that eavesdroppers cannot eavesdrop using a method of a kind that would be discovered by the sender and receiver, it can use appropriate signal processing to realize secure communications that absolutely cannot be deciphered with a computer.

While I was enrolled in Graduate School, I continued my research into physical layer cryptography at NICT as a Cooperative Visiting Researcher. The demonstration experiments using the 7.8 km free-space optical communications testbed between NICT and the University of Electro-Communications revealed that unpredictable information leakages occur due to atmospheric fluctuations. Recently, I have turned these natural phenomena that are unpredictable to me to my advantage to search for methods of improving the performance of physical layer cryptography.

After I took up my position as a researcher, I broadened the scope of my research to techniques for creating secure random numbers from physical phenomena. Furthermore, I am utilizing the findings I developed through these studies in large projects in the laboratory. These projects are quite challenging, because it is necessary to forge a convergence of opinions among various people, but they give me a great sense of achievement.

Due to the high level of power efficiency of free-space optical communications itself, physical layer cryptography is suitable for communications using unmanned aerial vehicles, such as satellites and drones, etc.

However, this research has still only just started and there are many hurdles that must be overcome both theoretically and in terms of the devices. I am endeavoring every day to steadily solve these problems one at a time in order to achieve the practical application of physical layer cryptography.

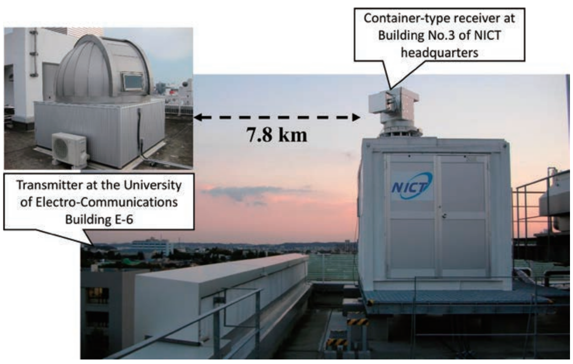


Figure: The free-space optical communications testbed with a total line length of 7.8 km that connects the University of Electro-Communications to NICT

The Maejima Hisoka Award was established with the aim of commemorating the achievements of Hisoka MAEJIMA, who founded the telecommunication industry, and of encouraging the transfer and growth of his spirit. It is awarded to those who make outstanding contributions to the advancement and growth of the information and communications (including postal services) or broadcasting industries, and in the 64th Maejima Hisoka Award this fiscal year, NICT won three awards including those for joint research.

*The titles and organizations of the recipients are those at the time they won their awards.

Tsushinbunka Association 64th Maejima Award

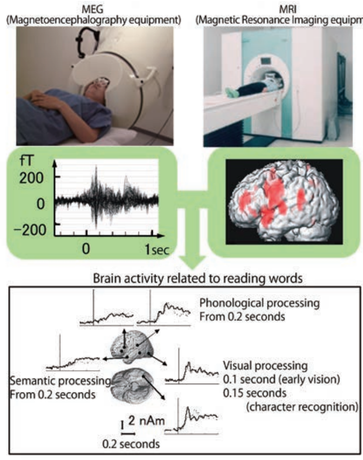
Norio FUJIMAKI

Manager (now, Expert researcher)
Brain Function Analysis and Imaging Laboratory
Center for Information and Neural Networks

Overview ●Description: Construction of MRI and MEG measurement systems for fusion research of brain information and communications

●Date: April 10, 2019

Comments from the Recipient: I am glad to receive the prize, because it represents high evaluation of our linguistic brain function measurements and safe operation of brain measurement systems in CiNet, which is a collaborative research center of NICT and Osaka University that started six years ago. It has now five MRI and MEG facilities to measure safely two-thousand subjects in a year for brain information research including marketing and medical applications. I thank all of the related persons.



Visualization of brain activity using MEG with a fine temporal resolution, and MRI with a fine spatial resolution

Hiroshi HARADA

Executive Visiting Researcher
Strategic Program Produce Office
Social Innovation Unit
Open Innovation Promotion Headquarters

Fumihide KOJIMA

Director of Wireless Systems Laboratory
Wireless Networks Research Center

Overview ●Description: R&D, standardization and promotion activities on wireless communication system for the smart meter use.

●Date: April 10, 2019

Comments from the Recipients: This is our great honor to receive the 64th Maejima award, owing to our contributions to the smart meter wireless communication system that were developed by NICT and globally standardized and promoted via the suitable collaborations with the domestic companies. We are going to provide safe and relieved society by ICT.

Wi-SUN certified device (from left: Radio device, Internal radio module, Communication IC)

Fumihide KOJIMA (left) and Hiroshi HARADA (right)

Akifumi KASAMATSU

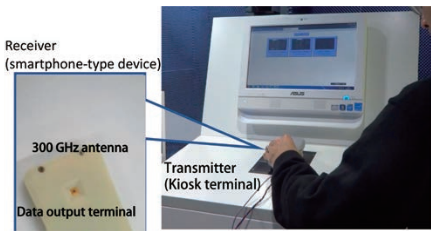
Executive Researcher
Frontier Research Laboratory
Advanced ICT Research Institute

Overview ●Description: [R&D in terahertz wave wireless transmission technology] They developed the world's first compact, terahertz wave (300 GHz-band) transmitter and receiver, achieving a data transmission speed of 40 Gbits per second. Using this device, they demonstrated a system capable of downloading data equivalent to that contained in a single DVD in around 3 seconds, from a kiosk terminal to a smartphone-type device. They also contributed to the laying down of global standards for the 300 GHz-band and the development of measuring technology.

●Date: April 10, 2019

●Co-Recipients: Makoto YAITA (Nippon Telegraph and Telephone Corporation), Yasuhiro NAKASHA (Fujitsu Laboratories Ltd.)

Comments from the Recipient: This award was won by those representing the three companies (NTT, Fujitsu and NICT) jointly consigned to develop the 300 GHz-band technology. We won the award thanks to not only the winners, but also all those who took part in the joint research. NICT was able to make use of the device technology of the Advanced ICT Research Institute, and the measuring technology of the Applied Electromagnetic Research Institute. We would like to express our gratitude to all those who gave us their support.



300 GHz wireless downloading demonstration experiment

NICT NEWS 2019 No.4 Vol. 476

Published by **Public Relations Department, National Institute of Information and Communications Technology**

Issue date: July 2019 (bimonthly)

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ISSN 2187-4050 (Online)