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Quantum-Mechanical Optoelectronics

from Keio's Faculty of Science and Technology

New horizons of optoelectronics opened up by quantum mechanics.

Junko Hayase
Associate Professor
Department of Applied Physics and Physico-Informatics

Featured in this issue is Associate Professor Junko Hayase, who is in pursuit of a quantum leap in the innovation of informatics. Associate Professor Hayase strives toward realizing practical use of quantum-mechanical optoelectronics.

Applying principles of quantum mechanics to semiconductors and photonics

Possibility of "A world with 0 and 1 used simultaneously"

In the extreme micro-world of atoms, molecules, electrons and elementary particles, phenomena that cannot be explained by classical mechanics often take place. This is the field of study quantum mechanics handles. A century has passed since the theory of quantum mechanics was established. As its correctness is verified through experiments, quantum mechanics has made rapid progress and grown into a technology within the reach of humankind for practical use. Associate Professor Hayase is tackling the practical application of quantum-mechanical optoelectronics by pioneering technologies to control quantum-mechanical characteristics of light and semiconductors.

Creating new technology by combining pulsed light and semiconductors

"Quantum-mechanical informatics is a focus of attention today as the greatest application of quantum mechanics. Effective and advanced use of quantum-mechanical characteristics enables many wonderful things that conventional informatics couldn't even imagine previously – things, such as quantum teleportation capable of communicating information to remote places in an instant; a quantum computer that can solve extremely demanding tasks in an instant via super-parallel computing – a task that would take hundreds of millions of years for currently available computers to perform; and a quantum cryptographic system that is absolutely safe against eavesdropping," remarks Dr. Hayase.

Dr. Hayase's specialty is quantum-mechanical optoelectronics. The focus of her studies is on systems based on a combination of pulsed light and nanostructured semiconductors that can freely control quantum-mechanical characteristics of photons* and electrons.

"Today our information-oriented society is supported by optoelectronics, but it's far from perfection in terms of effective application of the principles of quantum mechanics. If we succeed in making the most of quantum-mechanical characteristics, it would be possible to create totally new technologies that revolutionize our common knowledge. One such example is quantum informatics," she adds.

What is "quantum superposition" – a state with 0 and 1 in a state of stack alignment?

As you may know, all information we handle on our PCs, cellular phones, the Internet, and so on is represented by sequences ("01101 …") of binary numbers of "0" or "1" with a "bit" as the minimum unit (see Fig.1). It is the intensity (ON/OFF) of light or electric current that expresses "0" or "1." However, this technology merely constitutes a part of the characteristics of light and semiconductors. Therefore, scientists around the world are expecting much of quantum-mechanical informatics. The truly wondrous phenomena of "0 can be 1 simultaneously" that can take place in the world of quantum mechanics are said to enable a new horizon of informatics no one had ever dreamed of previously.

"It is the famous 'Schrödinger's Cat' experiment (Fig.2) that well illustrates the concept of quantum mechanics. In this experiment, a cat is put in Chamber A in which a poisonous gas generating device is set up. On the other hand, with Chamber B, a randomly operating switch is connected to it. When the Chamber B switch is turned ON, the gas generating device in Chamber A is actuated. Until one looks into either one of the chambers after a certain lapse of time, it is impossible to know whether the cat is alive (0) or dead (1). This state is referred to as "quantum superposition" – a state where 0 can be 1 simultaneously. A quantum computer uses this superposition as a unit of information (quantum bit). Since one quantum bit is capable of 0 and 1 processing simultaneously, numerous quantum bits enable super-parallel computation."

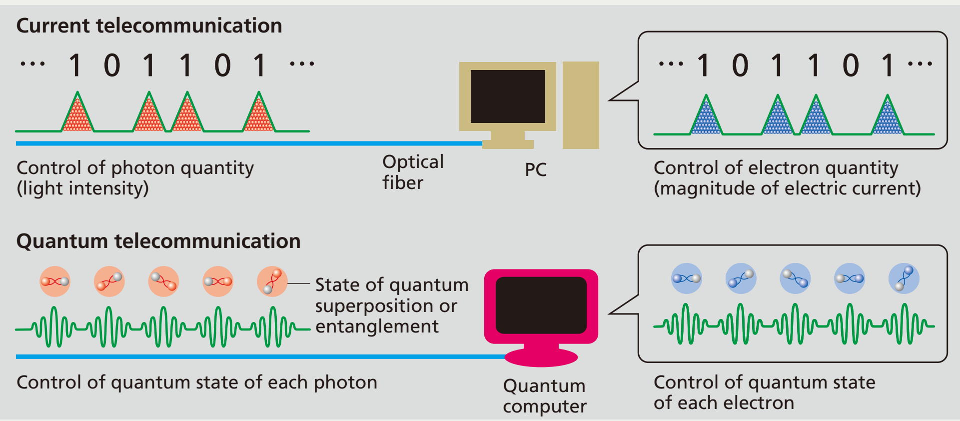


Fig.1 Quantum-based future information technology
With current information technology, information (0 or 1) is represented via control of light intensity (quantity of photons) or the magnitude of electric current (quantity of electrons). By contrast, if we can take advantage of "quantum superposition" or "quantum entanglement," revolutionary information technologies, such as quantum teleportation, quantum computers, and quantum cryptographic systems will become a reality.

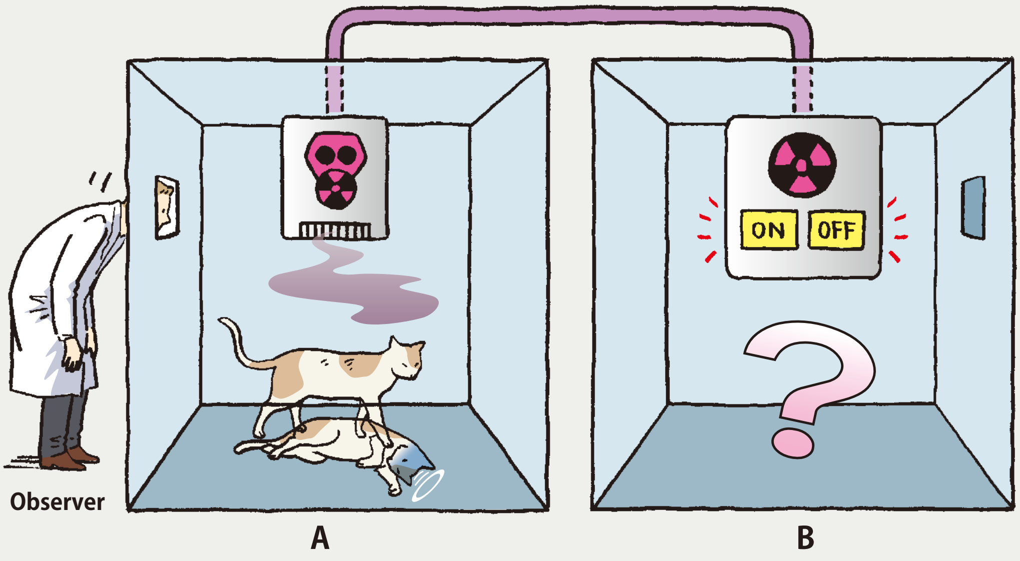


Fig.2 Schrödinger's Cat
The illustration of the famous 'Schrödinger's Cat' experiment is an easy-to-understand explanation of the wondrous world of quantum mechanics. Being alive (0) or death (1) of the cat remains unknown until the observer looks into Chamber A – a state known as "superposition." Also, before the Chamber B switch is turned ON (B=0), the cat in Chamber A is alive (A=0), whereas the cat is dead (A=1) if the switch has been turned ON (B=1), which remains unknown until the inside of either Chamber A or B is checked. This state is known as "quantum entanglement."

Another important concept is "quantum entanglement." The cat is alive (A=0) before the switch is turned ON (B=0), while it is dead (A=1) after the switch has been turned ON (B=1). In other words, it is either "if A is 0, B is 0" or "if A is 1, B is 1." But you cannot tell which is which until you actually observe it. This state is known as quantum entanglement. If Chambers A and B are placed at separate locations, the state of Chamber B becomes definite the moment Chamber A is observed, making it possible to communicate information between two remotely distant locations. This is the principle of quantum teleportation.

More than one quantum state, such as superposition and entanglement, remain coexisting possibilities until being revealed. Once revealed, a particular quantum state becomes definite. In other words, this means that quantum states as possibilities are broken once you observe them.

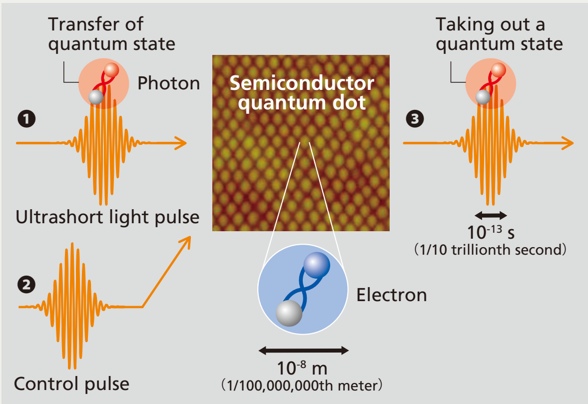


Fig.3 Quantum-mechanical exchange of information between photons and electrons
Photons' quantum-mechanical information (quantum state) is transferred to electrons within the semiconductor by irradiating ultrashort light pulses to semiconductor quantum dots ❶. After a certain lapse of time, control pulses are irradiated ❷ to allow the transferred quantum-mechanical information to be taken out ❸ in the form of photons.

"The photon is useful for cryptography partly because it is the smallest particle that cannot be further divided. It is also because eavesdropping can be easily revealed since quantum states fail if someone attempts to eavesdrop (= observe) on a particular piece of information. Furthermore, the ultimate in energy-saving telecommunication is possible because quantum-mechanical telecommunication works with only an extremely small amount of energy," Dr. Hayase added.

Combining semiconductor quantum dots with ultrashort light pulses

Working energetically to achieve quantum optoelectronics, Dr. Hayase is currently engaged in experiments – exchanging quantum states between semiconductor electrons and photons, controlling these states, and so on (Fig.3). However, numerous problems are encountered to convey quantum-mechanical information to semiconductors.

"A quantum state is so fragile that it can be rapidly broken . Therefore, information needs to be controlled and transferred while maintaining the quantum state, which is extremely difficult."

Coming to the fore as a possible solution are semiconductor quantum dots – a type of semiconductor suitable for maintaining and controlling quantum states. Quantum dots are ultrafine particles of semiconductor whose size is 10^{-8} meter. With this semiconductor, electrons can be confined in a very small area, making that area work as if it were an atom. This makes it easy to control and maintain the quantum state of each one of the electrons.

"What's outstanding about quantum dots is that their characteristics can be controlled freely according to their size and shape. My research team employs a special technique to produce quantum dots that can interact strongly with the light used in optical fiber communication. We have also succeeded in retaining the state of superposition much longer than those developed by other groups."

That said, it is unavoidable that quantum states are constantly being broken every moment. So, as an ultrafast flash, Dr. Hayase uses ultrashort pulse laser capable of emitting light instantaneously in an incredibly short period of 10^{-13} second. This enables her team to make use of nonlinear phenomena that cannot take place under ordinary light conditions, which in turn makes it possible to control superposition and quantum entanglement.

Given the extremely weak intensity of light that corresponds to one photon, it is very difficult to cause intended effects between photons and electrons. So Dr. Hayase is looking for a method of collecting many quantum dots that could enhance interactions between photons and electrons.

"What makes quantum mechanics intriguing is that it has virtually unlimited potential. I'm tackling research activities with the hope of achieving a fantastic discovery that could revolutionize the world in decades ahead."

(Reporter & text writer: Madoka Tainaka)

*Photon: Photon is the smallest unit of light energy. Speaking from a quantum-mechanical viewpoint, light has properties as both waves and particles (photons).

Requisite for pursuit of research are a challenger spirit and the ability to concentrate.

Ms. Hayase is one of the few female researchers in Japan specializing in quantum-mechanical optoelectronics. Though it is difficult to imagine from her soft and gentle appearance and manners, as a high school student she belonged to her school's rowing club and was powerful enough to place fourth in the national high-school competition. Using her bodily strength and power of concentration nurtured through club activities, Ms. Hayase has forged her own way as a researcher.

How did you spend your childhood? Were you good at science as a young schoolgirl?

Though I have little memory of my childhood, my parents often said that I had been a very inquisitive girl always asking "why?", but I'm sure I was not particularly good at science.

I was born in Fukushima Prefecture where everything is easy and slow. So I remember that I didn't study hard as an elementary schoolgirl. In my junior high school days my family moved to Saitama Prefecture and I went on to a prefectural senior high school. An encounter with a physics teacher was inspiring and marked a significant turning point in my life.

He was different from other physics teachers. In our physics class, conducting an experiment was an integral part of study, which made students think about "why." When it comes to regular examinations, the teacher rarely gave calculation-oriented problems but instead posed questions like "Describe why so." As a thinking type of student by nature, my encounter with this teacher awakened my interest in physics. That said, becoming a researcher still remained an almost unreachable dream for me back in those days.

This is because as a member of my high school's rowing club, I had spent most of my time for club activities including participation in the inter-high school rowing competition. Up until September of my third year in high school (when the National Athletic Meet was held), I had literally devoted myself to club activity. So I studied little to prepare for university entrance examinations. Instead, I was admitted via recommendation to the Department of Physics, Sophia University.

But you couldn't be recommended by your high school unless your day-to-day performance was good, could you?

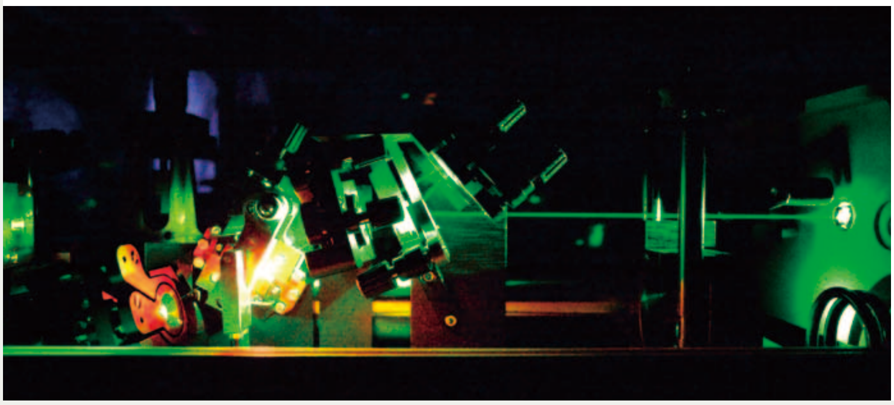
Maybe it was thanks mainly to my increased physical strength and enhanced power of concentration that was developed through my club activities. I used my strength and power of concentration to the fullest to steer through the vital high-school examination. To tell the truth, I had never attended a cram school. And I received a trial university entrance examination only once.

Just about when did you make up your mind to become a researcher?

When I was a senior at my university, I decided to join the lab of Professor Kazuhiro Ema who was then only in his second year of arrival in his post. The lab was focused on nonlinear spectroscopy using ultrashort light pulses – a forefront field of study leading the world. Until the end of the year as a junior, I had learned theories and experiments the answers of which are known and provided. But at the Ema lab we took up the challenges of experiments no one in the world had ever conducted, and could produce innovative results. My life with the Ema lab was both challenging as well as very fulfilling. We often carried out experiments all night long, but it was not troublesome at all. Once concentrated on something, I'm not satisfied until I carry it out to the very end.

Having put myself in such an environment, my yearning to become a researcher must have grown stronger and stronger. People often say that I appear to be a quiet type at a glance, but I find myself rather stubborn and uncompromising once I've decided to do something (laughter). My parents advised me, saying "It's best to find employment with a company after graduation and marry a suitable young man." But I gave no ear to their advice and decided to go on to graduate school for a doctoral course.

After earning my doctor's degree, I joined the RIKEN institute to become an academic research scientist. It was a position as a postdoctoral fellow with a term of three years. I applied for RIKEN by proposing a research theme of my own, which was luckily adopted by the



Ultrashort pulse laser emits light instantaneously for an incredibly short period of 10^{-13} second. This equipment is packed with a plethora of leading-edge optical technologies.

My lab enjoys a fresh and friendly atmosphere, where more than half of its members are undergraduate seniors. After research activities, all of us often go out for dining and drinking together.

institute. The theme is a bit different from my current theme, but had things in common in that it would handle light and nanostructured semiconductors. Following my service with RIKEN, I moved to the National Institute of Information and Communications Technology (NICT), where I encountered quantum dots. It just happened that at NICT there was a research team engaging in the making of characteristic quantum dots, which I found intriguing. I belonged to NICT for about four and a half years. With the NICT as well, I obtained a position for myself through job-seeking activity.

I approached one research institute after another to obtain necessary research funds and secure a stable research environment. During my service with the NICT, I was successfully chosen as an eligible researcher by the Japan Science and Technology Agency's (JST) "PRESTO (Sakigake in Japanese)" competitive research funding system that targets individual research projects, surmounting a highly competitive ratio of one in 15 applicants. What was particularly good about the "PRESTO (Sakigake)" system was that the adopted researchers and advisers on the screening side get together in semiannual boarding sessions to engage in discussions in an unrestricted atmosphere. On these occasions, the participants make presentations on the progress of their respective research projects. Each participant is subjected to unreserved opinions and criticism from others – a coveted opportunity for obtaining an extremely high level of advice, which provided me with nourishment for future growth.

Using participation in the "PRESTO (Sakigake)" system as momentum for stepping up my career, I then became a teacher for the University of Electro-Communications by taking advantage of the tenure-tracking system (a system that encourages young researchers to accumulate experience as independent researchers under employment with a term and obtain stable employment after passing rigid screening). And last year, at last, I could find a permanent position at Keio University. Now I'm in a position to operate my own lab, with six students, undergraduate and graduate, under my care. I feel great responsibility for this duty, which is fulfilling as well.

As a female researcher, have you experienced any particular hardship or benefit?

I'm not particularly conscious of advantage or disadvantage in terms of gender. Most of the time the consciousness as a female didn't come to mind. Naturally, I always see myself as a person and not as a woman. The only good thing about me being a woman is that as a minority I can be easily remembered by others. I may be also benefiting as a woman because of recently introduced systems aimed to support female researchers. But if I'm benefiting from such systems, I feel obliged to return the benefit I received by producing suitable results. It's my feeling of responsibility not as a female but as a researcher…

What about diversion from your research work?

Since I'm usually leading a restless life, I try to enjoy a relaxed lifestyle when I'm not working, going shopping with my husband, taking trips and so on. Proper rest and relaxation are definitely necessary because research work demands physical strength and energy as well as power of concentration. Likewise, I'd like my lab students to lead a life punctuated with rhythms of hard work and relaxation.

◎ Just a word from . . . ◎

● **A student: I'm always impressed with Dr. Hayase's toughness. Whatever trouble occurs, she comes in punctually and proceeds to research work in a concentrated manner. I admire her as a mirror of research scientists. Just as an attempt to follow her pattern, I've begun to develop my physical strength.**

(Reporter & text writer: Madoka Tainaka)

For the full text of this interview
http://www.st.keio.ac.jp/kyurizukai

YouTube: Keio University channel's research introducing video
http://www.youtube.com/watch?v= D3wvAgDzPQc

I'd like to maintain a mindset for always embracing new challenges.

Junko Hayase

(pen name: Junko Ishi-Hayase)

Dr. Hayase's specialty is quantum optoelectronics. Specifically, she engages in studies regarding optical properties of nanostructured semiconductors based on the use of ultrashort light pulses, quantum control, and application of quantum information. Ms. Hayase acquired a doctor's degree (science) at Sophia University. Before being assigned to the current position as an associate professor of Keio University's Faculty of Science and Technology in 2010, Dr. Hayase served as a fellow researcher at RIKEN's basic science laboratory, a fellow researcher at the National Institute of Information and Communications Technology (NICT), a researcher at the Japan Science and Technology Agency's (JST) "PRESTO (Sakigake)" system, and a research associate professor at the University of Electro-Communications' Education and Research Center for Advanced Studies. In 2009, she was awarded the "Young Scientist's Prize" by the Minister of Education, Culture, Sports, Science and Technology.

How the Hayase Lab came into being

The Hayase lab started in April 2010. Let's see how it originated.

April 2010

Our lab made its start from a totally empty space. To begin with, air-conditioning and electrical work was installed to provide the basic environment for making experiments. I visualized the room layout, imaging a picture of our lab's future by myself.

July 2010

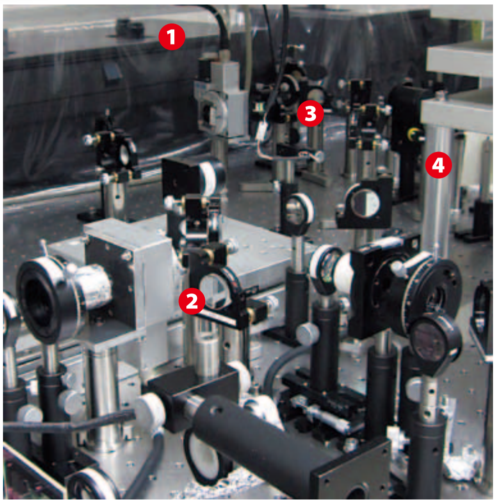
We purchased pieces of experimental equipment one by one, using the hard-won funds. Delivery of a special laboratory table for optical experiments is shown here.

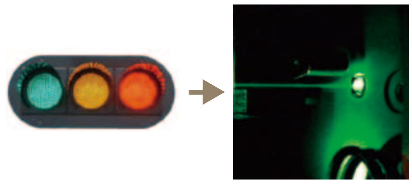
June 2011

Our students have assembled all of these optical components arranged on the laboratory table on their own. We are highly motivated to produce great research results, using our original measuring systems.

Points the Hayase Lab is particular about!

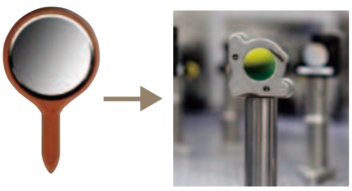
We'd like to introduce some of our equipment by comparing them with our everyday items.





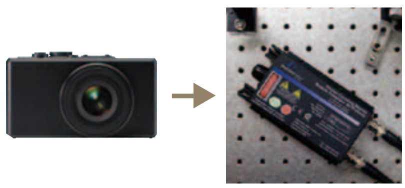
1 Ultrashort pulse laser

This laser is indispensable for conducting optical experiments. What makes this laser markedly different from LED and solar light is that it can generate light with a uniform wave phase (coherent light). Of particular interest is that the ultrashort pulse laser used in the Hayase lab is capable of emitting an intense light instantaneously within an amazingly short period of 10^{-13} second – an extremely short period of time in which light that can travel seven and a half times around the Earth per second is allowed to advance only by a distance equivalent to the thickness of a hair.



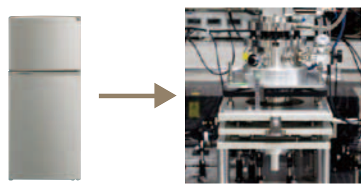
2 Dielectric multilayer mirror

Mirrors we typically use are coated with aluminum (metal) and have a reflectance of approximately 80%. Meanwhile, the mirror we use in optical experiments is of a special construction made by stacking layers of an electrically insulated substance known as dielectric. According to design, its reflectance can be freely adjusted from nearly 0% to 100%.



3 Single photon detector

This ultra-high-sensitive detector counts photons (the smallest unit of light energy) one by one. The amount of energy held by one photon is equivalent to 1/10 billionth that of an LED lamp. It can capture one single photon, using a special semiconductor device with a sensitivity 1,000 times that of the latest digital camera.



4 Cryogenic cryostat

This cryostat is used to cool semiconductor quantum dots. Cooling is necessary to retain their quantum-mechanical properties over a long period of time. The cryostat realizes a cryogenic environment of -270°C, using liquid helium that is even lower in temperature than liquid nitrogen. You may be able to imagine that cryogenic condition if you compare it with household-use freezers (approximately -18°C).

私の本棚

My favorite books

Ultrafast Spectroscopy of Semiconductors and Semiconductor Nanostructures –In English

Offering numerous case studies, this book provides a review of ultrafast nonlinear spectroscopy in semiconductor nanostructures. It allows you to have a glimpse of the depth and diversity of semiconductor research activities. With "atoms" it is easy to obtain just-as-expected experiment results, while with "semiconductors" it is rather difficult to establish precise theories where experiment results often differ from initial predictions. Semiconductor quantum dots are highly intriguing nanostructured semiconductors with which you can enjoy intellectual stimulus of both atoms and semiconductors simultaneously.

Nonlinear Optics – In English

This is my textbook on nonlinear optics. I've been using this textbook for years ever since I first learned nonlinear optics as an undergraduate senior during a rinko session. When I was a first grader in the master's course, I participated in an international convention where I just happened to meet the author Dr. R. W. Boyd, which made me feel excited and highly honored. He was very frank and friendly even with a young researcher like me. It was a truly memorable occasion because I knew that as researchers we could discuss equally beyond each other's social status and career.

"Galileo, the Detective" Series – In Japanese

I like Keigo Higashino's novels and enjoy reading his books during my free time. Of the many interesting Higashino novels such as "The Secret" and "A Journey Under the Midnight Sun," the "Galileo, the Detective" series are unique science-oriented suspense novels. In this series, the author gives full play to his flexible imagination that combines laws of natural science with tricks behind various crime cases, which truly impresses me. As I reviewed Keigo Higashino's personal profile, I found that he graduated from a department of electronic engineering and once worked as an engineer himself. No wonder he is well versed in physics.

Physics in the Mirror – In Japanese

The author of this book is Dr. Shinichiro Tomonaga, a winner of Nobel Prize in Physics. This book explains, in a clear and easy-to-understand way, the wondrous as well as "difficult-to-understand" world of quantum mechanics. It contains a short story entitled "Mitsuko on Trial" which is a must for readers. The story humorously explains the wave-particle duality of light by staging a trial with "Ms. Mitsuko Namino" (symbolizing light) as the defendant. I'd like those who are prejudiced against physics as being difficult to read this book.

Quantum Optics from the Basics – In Japanese

"Quantum optics" is a research field that takes a quantum-mechanical approach to light itself as well as interactions between light and substances. This comprehensive textbook is recommended to beginners of quantum optics as it covers the basic theories of quantum optics as well as the latest endeavors toward practical utilization of quantum informatics. This book is memorable for me as I was involved in writing (only one chapter though) for the first time in my life. In addition to myself, two Keio University teachers can be found in the list of co-authors.

The Forefront of Quantum Dot Electronics – In Japanese

This book provides an overview of the latest results of quantum dot electronics research in Japan. Quantum dot is a field of nanotechnology initiated by Japanese researchers. As such, a number of Japanese researchers are actively at work in the world's forefront – a field representing the comprehensive scope of Japanese science and technology. Since I wrote one chapter of this book as one of the co-authors, I have special attachment to this book.

Young researchers and competitive research funds

"Competitive research funds" are plans aimed to provide financial support to research activities at universities.

Under a competitive research funding system, a researcher applies for a grant by making a presentation on his or her research activity plan for several years to come. Several researchers evaluate the proposal and decide on eligibility of the proposal. While the best known among competitive research funds is the Grants-in-Aid for Scientific Research, the JST-sponsored "PRESTO (Sakigake)" is worthy of mention as a plan specifically aimed at supporting innovative research by young and upcoming researchers.

In the foregoing interview, Associate Professor Hayase mentioned that frank exchange of opinions with other young researchers and advisers during the boarding session under the "Sakigake" system provided her with nourishment for growth as a researcher. In fiscal year 2010, Dr. Hayase presented a research theme entitled "Implementing a quantum interface between single photons and the collective excitation of electron spins in semiconductor quantum dots" which was also adopted by the "Funding Program for Next Generation World-Leading Researchers."

On one hand, these competitive research funds play a significant role in fostering young researchers whose research environment often falls short of that of well established researchers. On the other hand, themes publicly invited by these funds tend to seek solutions for contemporary problems and expect results to be produced in a relatively short period of time. So there are opinions that these funding systems should be improved to invest more in basic research activities from a long-range perspective.

In the wake of the Great East Japan Earthquake of March 11, 2011, the minister in charge of science and technology promotion announced the policy entitled "About the government's current policy for science and technology" (issued on May 2, 2011) with the aim of reviewing the government policy in light of changing circumstances. It is a focus of attention among interested parties.

Science and Technology **Information**

Strategic Management Chair for Creating Innovations (a Sony-donated chair)
Open Symposia Series 2011: Toward a New Development Stage for Humankind and Society
"The 1st symposium: Innovation and Employment"

Date: October 14 (Fri.), 2011 18:00 ~
Place: Fujiwara Hiroshi Memorial Hall, Kyosei-kan Bldg. on Keio Hiyoshi Campus
Admission free; Prior applications required
http://www.koukai-sympo.net/portal/

This year as well, Keio University plans to hold a three-session series of open symposia offered by chairs donated to the Faculty of Science and Technology. Please apply for participation in these events via the foregoing URL.

※ Please note, however, that the schedule may be changed due to power consumption measures and other unavoidable reasons.

Information updates will be notified via respective websites.

Scenes from Open Symposium 2010.

Other Events on the Agenda

- October 28 (Fri.), 2011: The 12th KLL Seminar on Industry-Academia Collaboration
- December 9 (Fri.), 2011: The 12th KEIO TECHNO-MALL
- February 24 (Fri.), 2012: The 13th KLL Seminar on Industry-Academia Collaboration

Details of these events will be uploaded on Keio University's Leading-edge Laboratory of Science and Technology's (KLL) website (http://www.kll.keio.ac.jp/).

WEB site Navi

We express our heartfelt sympathy for all those who suffered from the Great East Japan Earthquake. We have set up a portal site that introduces Keio University's research activities related to recovery from the earthquake. Please access the following URL: **http://www.rcp.keio.ac.jp/srp/20110624.html**

Editor's postscript

The Hayase lab is quite young. One student puts it this way, "Making our own lab is challenging. Even doing miscellaneous errands is fun for us." The inside of the lab is neatly in order where removing footwear is the rule. As a power-saving initiative, air-conditioning has been kept at 82°F and each member is provided a mini-electric fan instead. Reflecting Associate Professor Hayase's gentle personality, an atmosphere of mutual trust is felt in the lab.

Bright sunlight comes in through windows on the other side of the semi-dark corridor, symbolizing fresh and creative ideas that are radiant within the campus. Yes, our Yagami Campus is in the power-saving mode.

(Saori Taira)

We at the New "Kyurizukai" editing committee launched our Twitter page: http://twitter.com/#!/keiokyuri

It will disseminate episodes during data collecting activities, information on the Faculty of Science and Technology, and media-related information.

We welcome your response to the #7 (August 2011) issue!

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