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Spin Dynamics

from Keio's Faculty of Science and Technology

Spin control technology toward
the creation of innovative electronic devices.

Yukio Nozaki

Associate Professor
Department of Physics

Introducing Researchers

Featured in this issue is Associate Professor Yukio Nozaki, whose research focuses on the development of new electronic devices based on magnetic substances.

Dedicated to electronic device innovation through the pursuit of spin electronics

Contributing to the development of nanoelectronic device technology

Electronic spin is the smallest form of magnet. Electronic spin has two directions; the difference in these two directions produces N and S poles of a magnet. Moreover, the two kinds of electronic spin are under the strong influence of magnetic fields and electric currents, which sometimes cause the directions to be switched. Spin electronics takes note of relationships between magnetic fields, electric currents and electronic spin. A relatively new research field, yet spin electronics is a focus of attention among researchers worldwide. We visited Associate Professor Nozaki who addresses spin electronics research for its practical applications.

Electronic spin as the source of magnetism

"Magnets refer to substances that have N and S poles, and the source of their magnetism is a phenomenon known as electronic spin. This spin phenomenon enables electrons themselves to function as a small permanent magnet" says Associate Professor Yukio Nozaki as he explains the basic principle of a magnet.

Then what is electronic spin? While admitting that there are still many unknowns due to its extremely microscopic nature, Dr. Nozaki continues, "Electronic spin is a strange rotational motion that won't return to its original position until it completes two rotations. Since it has the magnetic moment, it performs precession motion within a magnetic field (Fig. 1). You may compare its image to a spinning top wobbling with its rotation axis aslant. However, unlike a top whose rotation will stop with the lapse of time due to friction, electronic spin continues to rotate indefinitely. This is because electrons have properties of a wave. The magnetic field produced by that electronic spin serves as the source of magnetism of a magnetic substance."

Spin electronics is a research area aiming to control the direction of electronic spin as one likes, thus attracting the attention as a technology that can remarkably enhance the performance of electronic devices (Fig. 2).

Electronic spin with these properties, when magnetic field, electric field, heat, and/or microwave are given as stimuli, shows greater precession and eventually reverses the spin direction – in other words, the N pole and S pole of the substance interchange with each other. Also known as magnetization reversal, this phenomenon is applied, for example, to the hard disk drive (HDD: a magnetic data recording device based on binary assignment of 1 or 0 to the direction of magnetization). HDDs currently in use employ magnetization reversal via magnetic field for rewriting digital data. Some specialists, however, point out that the use of this method is reaching its limits in terms of power saving and recording density enhancement for HDDs. In response to this challenge, Dr. Nozaki noticed magnetization reversal via electric current and is moving forward with research on a technology that can control electronic spin reversal with less energy consumption and at high speeds.

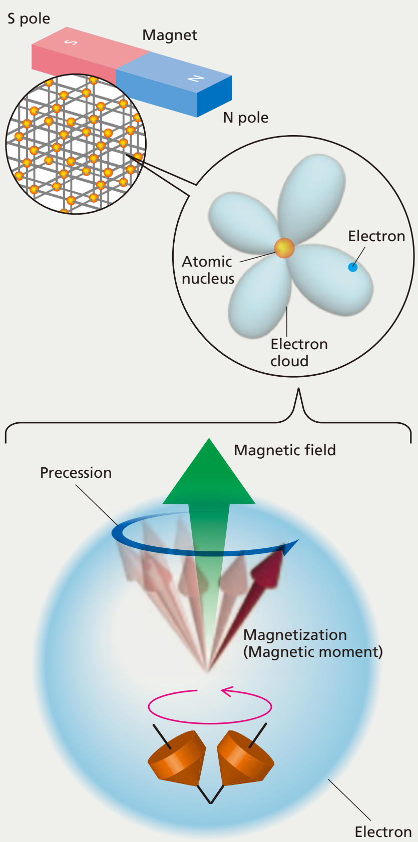


Fig. 1 Electronic spin is a magnet in the microscopic world
As electrons around the atomic nucleus spin, magnetization (magnetic moment) occurs and functions as a permanent magnet. There are two kinds of electronic spin in terms of direction – up spin and down spin – and this direction determines N or S pole.

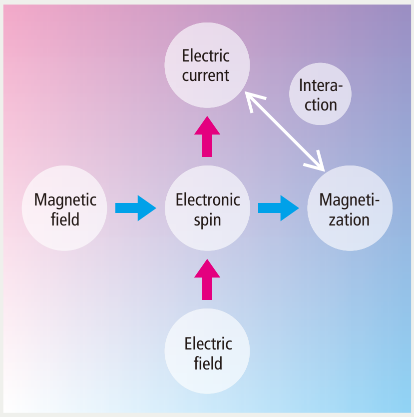


Fig. 2 Concept of spin electronics
Within a given substance, electric current induced by the electric field interacts with magnetization induced by the magnetic field. Using this interaction, it is possible to control magnetization by electric current and vice versa.

Elucidation of 4 types of torque is the key to effective control of electronic spin

Key to effective control of electronic spin is the force (torque) that works on electronic spin. This torque comes in four types: (1) damping torque; (2) precession torque; (3) spin transfer torque; and (4) non-adiabatic torque (Fig. 3). When magnetic field and/or electric current are given as stimuli to electronic spin, these four torques work to reverse electronic spin. This is already theoretically confirmed. Especially when it comes to the relationship between torque's action and magnetization reversal when magnetic field is given as a stimulus,

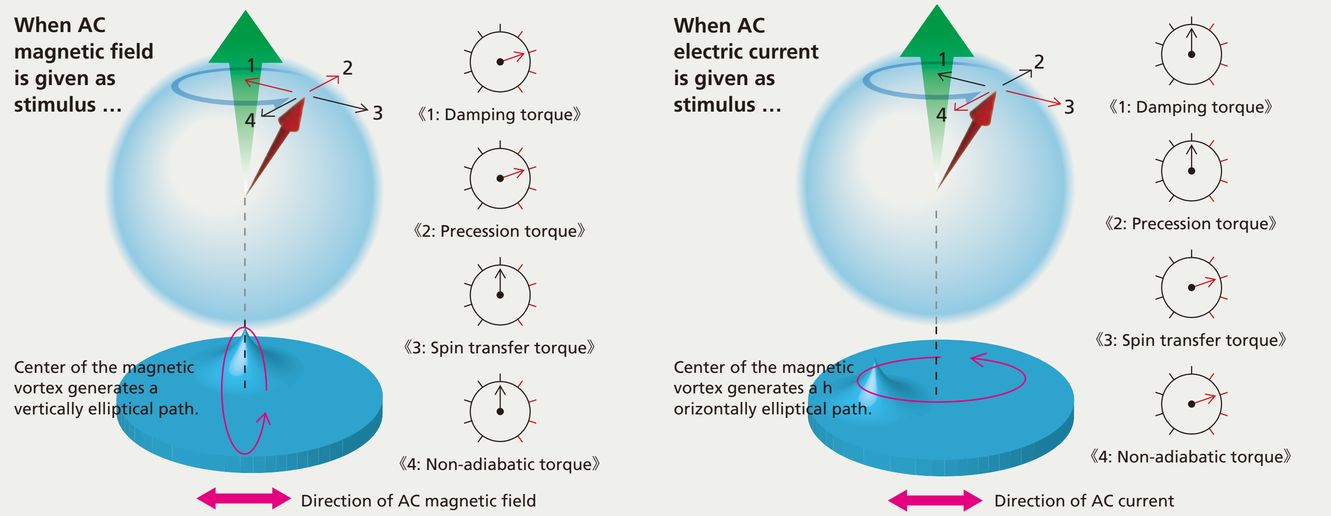


Fig. 3 4 torques that act on electronic spin

Four torques act on electronic spin. These are regarded as factors that determine the direction and motion of the magnetic moment. Since all of these torques directly interact with the magnetic moment, they can alter the direction of the magnetic moment without changing the moment' s magnitude. If frequencies of the magnetic field and electric current given as stimuli are changed, the torques change their respective actions, which will appear as changes in the turning path of the magnetic vortex. This means that by analysis of changes in the stimuli given and changes in the magnetic vortex it is possible to quantify changes in each torque relative to stimuli given.

there are prior research works as seen in the example of HDDs mentioned above. “By contrast, research into magnetization reversal via electric current has just begun, with few research endeavors being made. Unlike magnetic field-based magnetization reversal, magnetization reversal via electric current is highly efficient as it can directly access individual ferromagnetic devices, thus realizing high-speed motion of tens of GHz with limited power consumption,” remarks Dr. Nozaki explaining advantages of electric current-based control.

What Dr. Nozaki pursues is research into how to quantify each torque that results when electric current has been used as a stimulus. And his aim is not only to reverse the spin but also to reverse it most efficiently – at even higher speeds and with less stimuli.

So he attempted to shed light on how effectively each of the four torques, when electric current is given as a stimulus, would work on magnetization reversal. However, the subjects are too small to observe changes in individual electronic spins and to analyze actions by each of the four torques. This led Dr. Nozaki to notice a magnetic structure comprised of multiple electronic spins and make the most of its characteristics.

“Between adjoining electronic spins there is interaction to maintain their directions parallel to each other. If you reduce the size of magnetic devices to the nanometric scale, therefore, it becomes possible to analyze the behavior of an individual electronic spin by judging from the collective behavior of the electronic spins as a whole. For example, by reducing the size of a given material to something like 100 nanometers, it is possible to realize electronic spin in which all the individual electronic spins move in unison with each other. Furthermore, by arranging individual electronic spins in the shape of a disk, the electronic spins seek to harmonize with each other and form a magnetic vortex as a result,” remarks Dr. Nozaki. These magnetic structures are extremely high in stability and show simple and linear reactions to stimuli given, making it easy to analyze the four torques. However, when the size of the collective electronic spin exceeds 10 micrometers, the spin tends to take a stable structure at several different locations, making the overall structure complex.

Potential applications ranging from magnetic memory to logic devices

“Research into macrospin and magnetic vortex is making rapid progress, shedding light on the behavior of electronic spin,” Dr. Nozaki says with a smile.

“For example, if you use AC current as a stimulus to a magnetic vortex, the center of the magnetic vortex resonates with the stimulus and begins to rotate in a concentric manner. It has been well known that at this time, the linewidth of resonance spectrum has much to do with (1) damping torque, and the resonance frequency with (2) precession torque, respectively. However, a discovery was made of late that a significant change in the frequency of electric current given as a stimulus transforms the vortex’s path from a concentric shape to an elliptic one. After further detailed calculations, it has also been found that from the shape of the elliptic path it is possible to obtain (3) spin transfer torque and (4) non-adiabatic torque (Fig. 3). I’m now moving forward with verification tests for this theory,” he continued.

Elucidation of relationships between the four torques and stimuli will pave the way not only for quantitative determination of magnetization reversal via electric current, but also for development of new applications, such as high-speed magnetic memories and rewritable spin logic devices (Fig. 4).

“As electronic spin control increases in speed, it will come to be used as a micro switch that switches electric current ON and OFF. It will also make a post-semiconductor device technology a reality, which will enable an all-purpose electronic circuit capable of rewriting data into diverse functions, for example.”

Indeed, electronic spin is a focus of attention today as a technology that will lead to the development of epoch-making devices.

(Reporter & text writer: Kaoru Watanabe)

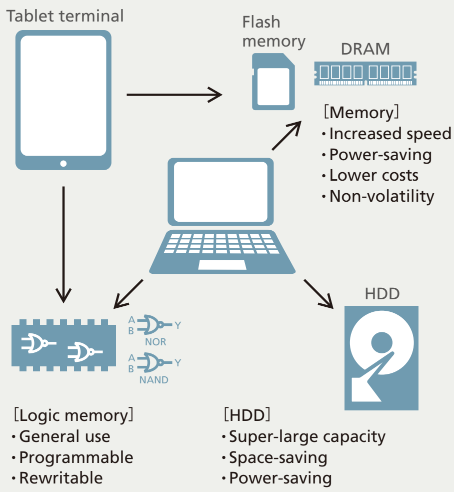


Fig. 4 Application electronic spin to devices

Expectations are high for electric spin for applications to magnetic memories that enable zero consumption of standby electricity, and electronic devices capable of rewriting into various functions.

Thorough pursuit of your target theme will reveal true fun of learning

Mr. Nozaki says that in his high school days he liked chemistry more than physics. But as a university student he studied under Professor Miyajima and associated with physics-minded friends and overseas researchers, which awakened his interest in physics. His interest in physics continues to grow even today. Especially, standing in front of his students in the classroom as a teacher gives him an impetus, making him more and more aware of the depth of this area of learning. His students are attached to and respect Mr. Nozaki as a strict yet gentle teacher.

As a small child was there anything special you were crazy about?

According to my mother, I was a child who liked disassembling mechanical things. Since my parents were self-employed, they were usually away from home most of the day. And also because I was an only child, I used to play alone. One day, mother returned home and found me disassembling a camera.

If I remember correctly, I wanted to know about the camera's mechanism rather than simply disassembling the camera for fun. Yes, I remember I was curious about what kind of mechanism makes it possible to take photos, and why the camera makes a click when the shutter is pushed. These questions were wonders and caught my interest. Presumably, the camera's back cover might have come off as I repeatedly opened and closed it in an attempt to look inside – the beginning of disassembly. By the time mother came back home, the camera might have been reduced to screws, parts and so on. I was bitterly scolded.

Because of all these events, it seems to me that mother found me definitely suitable for science and technology. Then she switched her policy: instead of things being disassembled, she gave me plastic model toys, which allowed me not only to disassemble but also reassemble them. From this time on, I also became interested in making things.

Did you like scientific subjects at school as well?

I wonder. Rather than love of scientific subjects, what occurred to me above all else was awareness of my weakness or dislike of liberal arts-oriented subjects. I liked mathematics and science because I could think and work out answers on the spot. But I was poor in subjects that require day-after-day constant learning (particularly by rote). My performance in writing kanji characters to dictation was truly miserable! Although I could somehow manage these subjects by last minute cramming for examinations up to the end of junior high school, such a makeshift technique didn't work at all in senior high school. Naturally I stayed away from liberal arts subjects and set my mind toward scientific subjects like mathematics and chemistry. But physics was an exception. Back in those days, physics was a subject totally lacking a sense of reality (as it seemed to me). I could little appreciate the true fun of physics.

By contrast, in chemistry, you can reenact a reaction before your eyes if you combine chemicals just as described in the chemical formula in question. It seemed to me chemistry is more realistic or interesting.

You mean chemistry is more interesting as it can explain the realistic world?

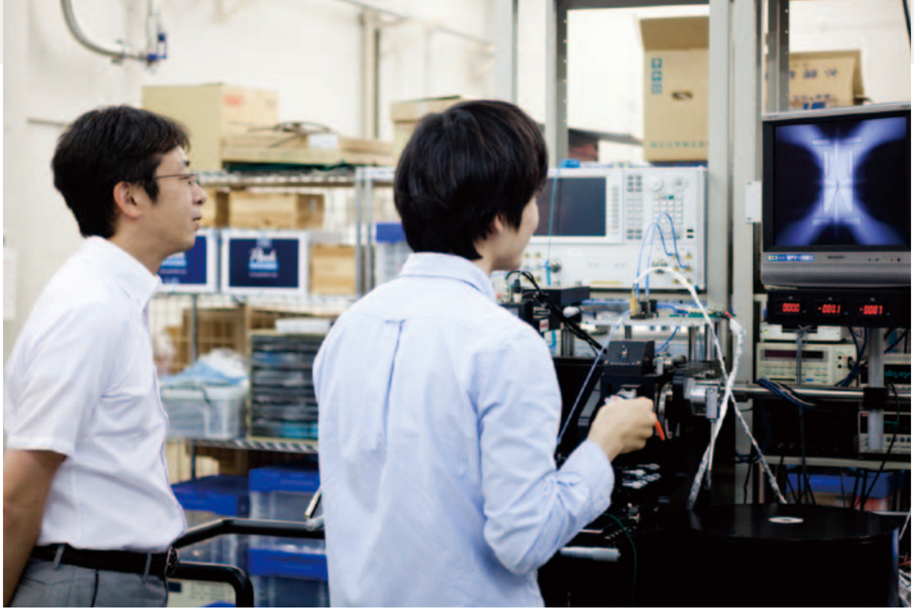
Well, compared with physics that seems somewhat disconnected from reality, chemistry appeared to be simple and straightforward, allowing the cause and effect to be directly connected. This is why I was attracted more to chemistry in high school. Chemistry even appeared to me as approaching straight into the essence of things.

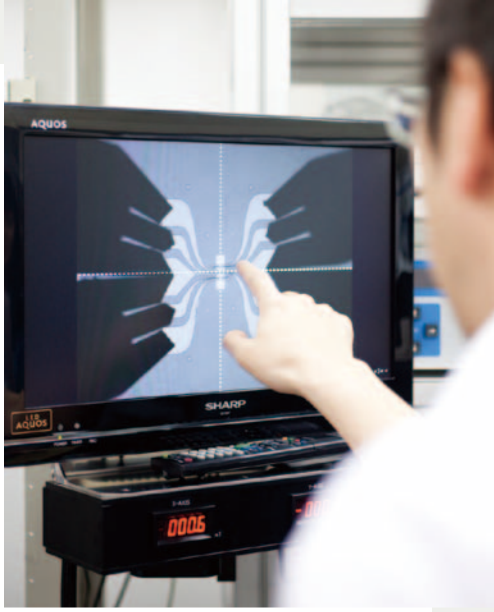
To tell the truth, I became aware of the fun of physics only after I was admitted to Keio University. The impetus was a friend I became acquainted with on campus. I was influenced by him stressing that physics is excitingly interesting and pursuits other than physics are not worthy of learning. At that time I thought I would keep physics as one of my options. What determined my course of life was a class on electrodynamics by Dr. Hideki Miyajima (now Prof. Emeritus). Dr. Miyajima's teaching was free of unreality – it was easy to understand and interesting, which made me think that physics might be fun to study. It was when I was a sophomore. Frankly speaking, I wish I became aware of this a little earlier.

About when did you make up your mind to choose a researcher career?

I became serious about becoming a researcher after I belonged to Dr. Miyajima's lab and began to study in the master's course. When I was looking for a research theme, a research associate of our lab, who was about to visit France for research purposes during the summer holidays, happened to be looking for a student who would accompany to assist him. I raised my hand the moment I heard of this offer. Since nobody else volunteered to do so, my visit to France was decided.

Through the two-month period of devoted research work in a foreign country like France and surrounded by highly motivated foreign researchers, I became aware of the delight of concentrated





research. I found research activity exciting enough even for an assistant like myself. Then how wonderful would it be if the research work were for my own sake? This was my impression, which urged me to choose a researcher career.

Is distinction between research and your private life difficult?

Before marriage, research work was everything in my life. But after I got married, I changed my lifestyle and became able to distinguish my private life from research work, especially with the birth of my first child. Because preparing for lectures for the following day is demanding and time-consuming, I sometimes have to do it at home. But I completely enjoy private time when communicating with my children. In fact, dealing with children is a great task itself and my hands are full. Frankly speaking, physics is the last thing I can think of. I have little idea of what my children are thinking of, and their thinking is not logical at all. But their pointlessness and unmanageable behavior are fun, maybe. For sure, children are a matter of greatest interest for me.

What do you want your students to learn?

As advice based on my own experience, I'd like my students to identify a research theme they find intriguing. The field doesn't matter. If there are some who have already identified their themes, they should proceed that way. For others who have not found their themes yet, I'd like them to focus on something at hand even for the time being, by suppressing their mind that is indecisively wandering this or that way.

As students, you may have to deal with many things aside from academic learning. But please remember to concentrate on something especially when you are at a loss of what to do or which way to go. I'm sure that by doing so you will have a moment when things formerly in question get interrelated with each other and emerge as something convincing before your eyes. I'd like all my students to capture such a moment.

◎ Just a word from a student ◎

● While in the general education course, my impression of Mr. Nozaki was one of a strict teacher. But this impression changed completely when I joined his lab. When I asked a question during research work, not only did he give me the correct solution, but he also explained step by step how to climb the stairs of understanding while encouraging us to think on our own. His approach often convinced me, the questioner, as well as other members of the seminar. Thanks to Mr. Nozaki's educational approach, it became possible for me to address and understand difficult challenges.

(Reporter & text writer: Kaoru Watanabe)

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

Concentrate to find a breakthrough, especially when you are at a loss for which way to go.

Yukio Nozaki

Mr. Nozaki's specialties are spin dynamics and spin electronics. His current research theme is the control of spin angular momentum dynamics that is strongly coupled, in ferromagnetic metals, with electronic and electron-phonon systems. He is developing his research work from basic research to applied research for practical applications. In 1998, after acquiring a doctorate (physics), he became a postdoctoral research assistant for Kyushu University's Graduate School and Faculty of Information Science and Electrical Engineering, assuming the position as an associate professor in 2006. In 2010, he assumed the current position as an associate professor for Department of Physics, Keio University Faculty of Science and Technology.

Yukio Nozaki's path to becoming a researcher

Here Mr. Nozaki looks back at his path to becoming a researcher, focusing on his early nine years – after graduation from high school, followed by entrance into Keio University, acquisition of doctorate, and becoming a research associate at Kyushu University.

High school days

As a high school student, I only studied my favorite subjects (mathematics, chemistry and a bit of physics), almost neglecting all the other subjects. Like other friends around me, I wished to go on to a medical university. But studying scientific subjects one-sidedly naturally didn't suffice. So I wavered in my decision on which course I should choose. One day I happened to find a notice on a school billboard saying that Keio University Faculty of Science and Technology would invite school-recommended students for admission. This moment marked the beginning of my life at Keio.

Admitted to Keio and enrolled in Department of Physics at the invitation of a friend

Japan's bubble economy was at its heyday when I was admitted to Keio; the Hiyoshi Campus was bright and lively. I was invited to the tennis circle, where I met a colleague who wanted to be enrolled in the Department of Physics. Persuaded by him, I soon found myself enrolled in the Department of Physics as well. My campus life was a busy one, pressed by preparation of reports on my specialized subjects day after day. It was our rule to have a "self-examination" meeting (in fact, a "drinking party") at "Hiyoura" (Japanese pub) twice a week after physics experiments.

Joining Miyajima lab

Intrigued by "superconductivity" that shows interesting phenomena, such as zero electric resistance and magnetic levitation, I belonged to the Miyajima lab specializing in superconductivity and magnetism. Just before submitting my graduation thesis, I underwent a lung operation and was hospitalized due to a hole in my lung due to too much singing (at a "karaoke" sing along music studio). But somehow I could graduate thanks to warm support from my teacher, friends and parents.

Master's course

Hearing that Dr. Otani, the assistant professor of our lab, would visit France during the holidays to participate in experiments at a French national institute (in Grenoble), I volunteered to accompany him (never thinking of myself as a potential burden!). Living together with my teacher's foreign colleagues (photo), I devoted myself to analyzing results of experiments using superconducting thin-films.

An unforgettably horrible experience

Surrounded by rugged and rocky mountains, Grenoble is well known as a rock-climbing paradise. I have exceptional acrophobia (fear of heights) but a French researcher persistently invited me for a rock-climbing tour. I finally I agreed to his offer as a memory of my stay in France, and tried climbing a snowy mountain. He said it was a mountain for beginners, but it was nothing but a horrible, unforgettable experience; I really thought I was on the brink of death.

Doctoral course

Dr. Otani, an outstanding research scientist whom I had been aiming at, left Keio to assume a post elsewhere. With this event as an impetus, I began to tackle a new research theme. After experiencing a number of failures, I could finally succeed in the micro-processing of ferromagnetic film, and acquired a doctoral degree for research into the analysis of its magnetic structure. I'm still truly thankful to younger students at the lab who encouraged me at an "all-you-can-eat" Korean barbecue restaurant when I was down due to a deadlock in research.

私の本棚
My favorite books

Spin Electronics –The Foundation of Next-Generation Memory MRAM

This book introduces new technology, spin electronics (spintronics), in an easy-to-understand way. Since the book contains few difficult formulas, I think even high school students will be able to appreciate the ambience of this new technological domain.

(Extra 1) Doctor for Animals

The lab's atmosphere (especially the advising teacher's atmosphere) depicted in this book is very similar to that of the lab I belonged to during my student days. You may call it close to a documentary. When young, I thought all labs are similar to this one more or less, but after graduation I found reality was much different.

(Extra 2) DVD of Seikima II's "Black Mass" (Concert) at breakup of the band

This DVD is a complete record of "Black Mass" (concert) at the December 1999 breakup of the Seikima II rock band led by ("His Excellency") Demon Kogure. As a faithful follower (fan) of His Excellency since my student days, I had never missed listening to their performance on the All-Night Nippon radio program. This means I always lacked sleep on Tuesday mornings. Even today, I enjoy this DVD for diversion from time to time though my family members cannot appreciate the good points of Seikima II.

Biography of Kotaro Honda

This book is a biography of the late Dr. Honda, a scholar who was highly respected as the "God of Iron." I borrowed this book from one of my seniors who strongly recommended it as being "very useful for managing a lab!" The book depicts pioneering research into magnetism at the dawn of Japan's electrodynamics while fostering a number of up-and-coming researchers. I was deeply impressed by his sincere attitude – sparing no efforts in conducting difficult trail-blazing experiments, always tackling problems face-to-face and without seeking easy shortcuts. I really want every researcher-to-be student to read this book. Some day we'd also like to develop a personality similar to Dr. Honda who was respectfully nicknamed "human magnetism."

***Spin-wa-Meguru* (The Story of Spin)**

This book introduces the circumstances where electronic spin, the source of magnetism, was discovered. It vividly describes geniuses (later to win Nobel Prizes), such as Wolfgang Pauli, Paul Dirac and Werner Heisenberg, boldly meeting the challenge of shedding light on the internal structure of the atom. It contains a number of interesting episodes, including the circumstances in which the relativistically contradictory assumption "spin is electron's rotation" was published as a thesis.

Spin Dynamics in Confined Magnetic Structures I ~ III

This series is a scrupulous compilation of recent developments in spin dynamics, my specialty. For example, it introduces a new technology that can measure high-speed spin in the gigahertz to terahertz bands by frequency domain and time domain.

Intuitive Approach to Physical Mathematics

When I was assigned to take charge of a lecture at Kyushu University for the first time, I heard that ferrodynamics is an extremely unpopular subject among many students because its mathematical approach seemed to be an unmanageable hurdle to them. So I was worried about how to teach vector analysis, Fourier analysis and Taylor expansion, a professor of the neighboring lab introduced this book. Reading it, I could now understand the meaning of the key formulas that I had simply learned by heart formerly – like having my eyes reopened after prolonged blindness. This book is a must for students who are lost in a maze of mathematics.

Basics of Magnetics: Physics of Ferromagnetism

This textbook is a Bible for ferrodynamics beginners. I make it a rule to have seniors study it first and foremost. Learning ferrodynamics requires complex knowledge of quantum mechanics, statistical mechanics and electrodynamics; this textbook offers an easy-to-understand explanation of all these three fields of learning.

Industry-academia collaboration in science and technology

Endeavors of individual scientists and engineers of outstanding ability produced formerly new scientific concepts and new products. Today, however, the era of individuals is over and is superseded increasingly by industry-academia or industry-government-academia collaboration.

Associate Professor Yukio Nozaki, featured in this issue, is currently collaborating with businesses is conducting verification of behavior of recording modes to develop the next-generation hard disk with a recording density exceeding 1 terabit (10^{12} bits) per square inch. Behavior tests using mass-produced hard disk media have confirmed the validity of the recording mode now being studied. The next step is to conduct experiments with next-generation recording media capable of magnetic recording of even smaller bits.

If this becomes a reality, it will provide a major momentum to the development of the next-generation recorder capable of extended recording of ultra high-definition video image (its resolution being 16 times that of the current full HD). Expectations are also high for this technology, as it will contribute to making significantly smaller and much more power-efficient data centers currently operated by businesses to store enormous volumes of data.

Mr. Nozaki remarks, "To spread our new recording system as a standard system for next-generation hard disks, it is also necessary to develop compatible recording media and new signal processing technology in addition to the development of recording/playback heads. In the days ahead, I want to realize practical use of this system by promoting research hand-in-hand with the businesses concerned."

In order to promote such collaboration, Keio University Faculty and Graduate School of Science and Technology maintain the Keio Leading-edge Laboratory of Science and Technology (KLL) as a unit of liaison for industry-government-academia collaboration. Not only does KLL disseminate research seeds, but it also plays an active role in the promotion of joint research projects by bridging researchers' desires for realizing practical development, like Mr. Nozaki's case, with needs of interested businesses.

Furthermore, KLL offers the annual KEIO TECHNO-MALL science and technology exposition and industry-academia seminars as opportunities for interaction with the industry. With these events as impetuses, businesses approach Keio for establishing tie-ups, which leads to the start of new joint research projects and various other positive activities.

In the academic year 2011, these activities resulted in as many as over 300 industry-government-academia collaboration projects.

Science and Technology **Information**

Proceedings of the "Strategic Management Chair for Creating Innovations (a Sony - donated chair). Open Symposium 2011: Toward a New Phase of Development of Humankind and the Future, III" compiled by Mario Tokoro, Chairman and CEO of Sony Computer Laboratories, Inc. To be put on the market August 31, 2012

http://www.keio-up.co.jp/

This series of symposia – "Toward a New Phase of Development of Humankind and the Future" – was launched in 2009 in a joint project between Keio University and Sony Corporation with the aim of fostering up-and-coming scientists and engineers. To conclude the 4-event series of symposia held during the academic year 2011, the last volume of the proceedings of the symposia will be published soon. Orders are accepted via the above Keio University Press URL.

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Other Events on the Agenda

- October 19 (Fri.), 2012: The 15th KLL Industry-Academia Collaboration Seminar
- December 7 (Fri.), 2012: The 13th KEIO TECHNO-MALL
- February 22 (Fri.), 2013: The 16th KLL Industry-Academia Collaboration Seminar

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/).

Editor's postscript

This is the 10th issue of the new "Kyurizukai" since this bulletin was launched in 2009. Compared with the previous issues, from this issue on we will include something new on the front cover: a photo of the featured researcher having something in his or her hand. For this particular issue, we used a photo of Associate Professor Nozaki holding a toy gyroscope in connection with his research theme "spin."

For photographing, Mr. Nozaki himself wound a string around the gyroscope. When doing so, he looked just like a young boy playing with a spinning top. Naturally, the atmosphere there became relaxed and the photo could capture a relaxed expression just like Mr. Nozaki's.

Mr. Nozaki seems to represent an agreeable image (my image) of Keio Faculty of Science and Technology researchers – earnest, gentle, and serious about both education and research work. He is readily accessible by phone because he spends most of the time at his lab. Though he is conscious of engagement, he sometimes forgets a deadline when too busy. But he responds in haste (and willingly) when urged.

A total of ten researchers appeared in the ten issues (including this one) published so far. Though they vary widely in their personalities and fields of research, they seem to collectively convey the atmosphere unique to our Yagami Campus. I hope that our readers will read all of them again and appreciate that atmosphere. The new "Kyurizukai" will continue to introduce attractive profiles of our proud researchers.

(Saori Taira)

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