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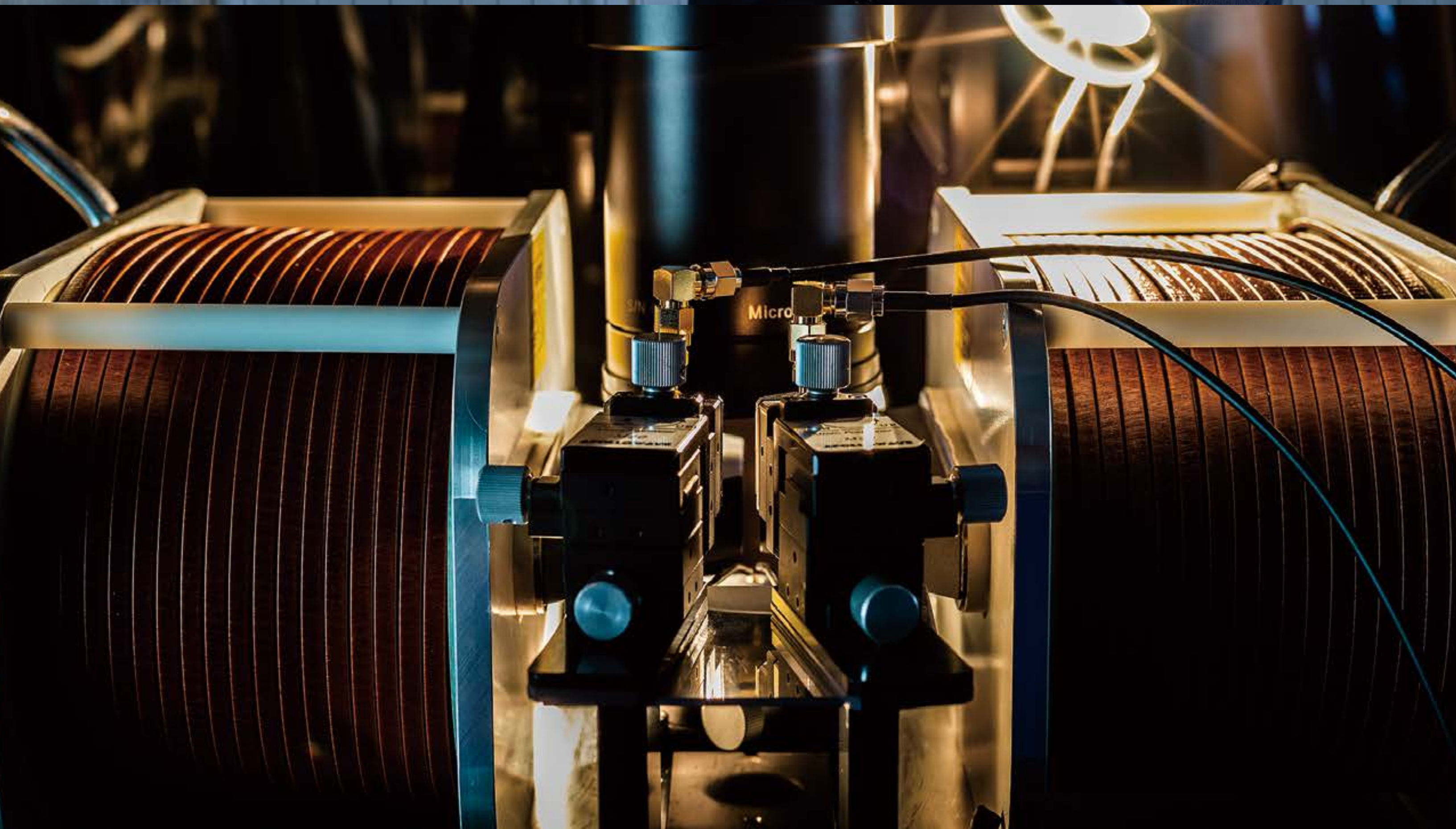
Research Center for Magnetic and Spintronic Materials (CMSM)

Bringing order to random spin

Challenges in controlling electron spin, the source of magnetic force



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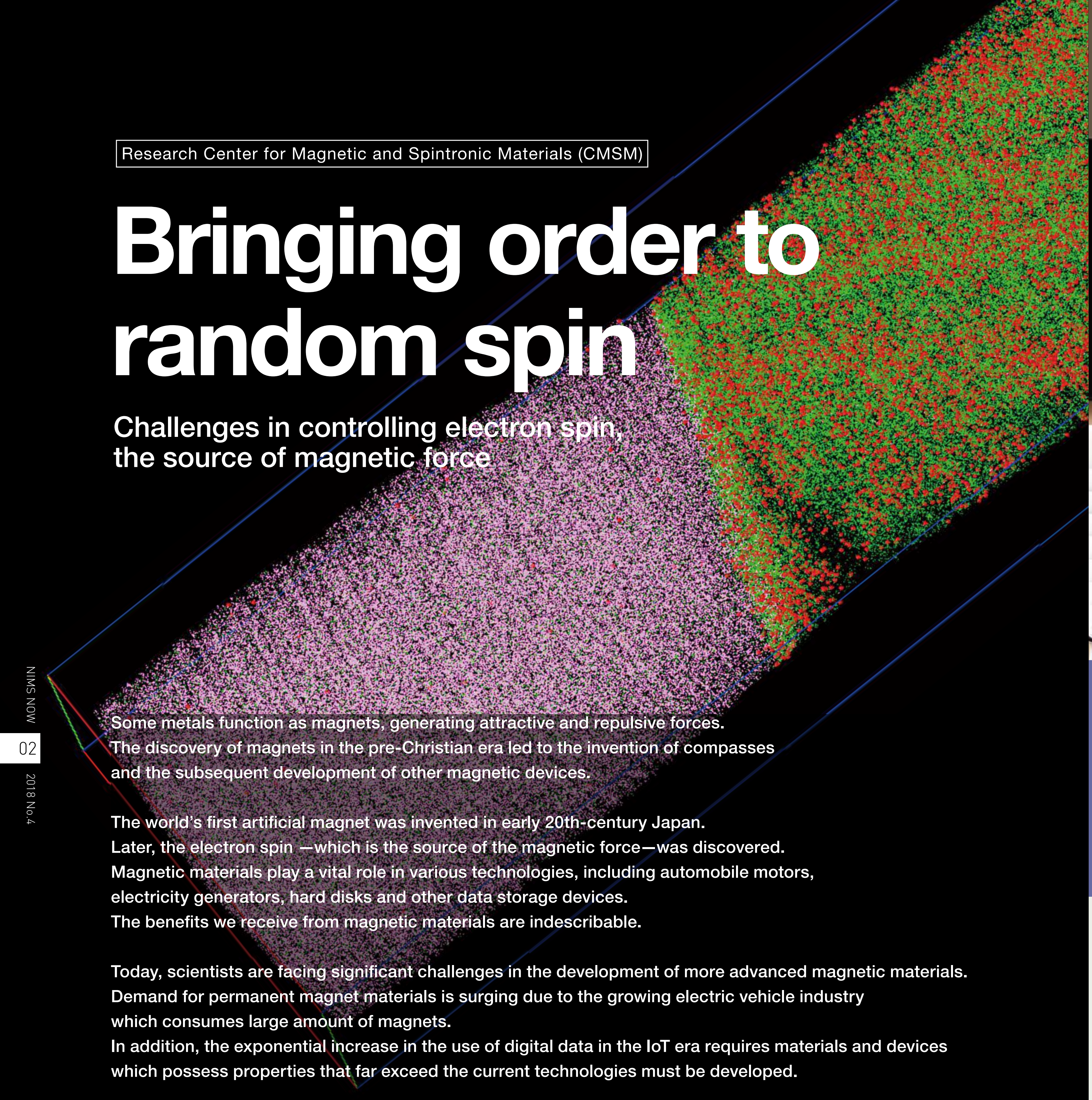

Some metals function as magnets, generating attractive and repulsive forces.
The discovery of magnets in the pre-Christian era led to the invention of compasses and the subsequent development of other magnetic devices.

The world's first artificial magnet was invented in early 20th-century Japan.
Later, the electron spin —which is the source of the magnetic force—was discovered.
Magnetic materials play a vital role in various technologies, including automobile motors, electricity generators, hard disks and other data storage devices.
The benefits we receive from magnetic materials are indescribable.

Today, scientists are facing significant challenges in the development of more advanced magnetic materials.
Demand for permanent magnet materials is surging due to the growing electric vehicle industry which consumes large amount of magnets.
In addition, the exponential increase in the use of digital data in the IoT era requires materials and devices which possess properties that far exceed the current technologies must be developed.

Solutions to these issues lie in technologies that allow micro-, nano- and atomic-scale control of the structural and magnetic properties of magnetic materials.
The NIMS Research Center for Magnetic and Spintronic Materials (CMSM) addresses these challenges by integrating advanced expertise in material fabrication, analysis and theoretical calculation.

This NIMS NOW issue focuses on the latest research on magnetic and spintronic materials, which may lead to the development of innovative technologies.

Photo: Atomic distribution within a dysprosium-free neodymium magnet determined through three-dimensional atom probe analysis
The distributions of neodymium (Nd: green), iron (Fe: purple) and copper (Cu: red) atoms is shown. NIMS succeeded in developing powerful Nd magnets without using the rare earth element dysprosium. This was achieved by forming a non-ferromagnetic layer containing many Nd and Cu atoms between ferromagnetic phases containing many Fe atoms, thereby breaking the magnetic linkage between them. (Photo provided by the Magnetic Materials Analysis Group, p. 15)

NIMS AWARD 2018 NIMS Award Interview

Invention of the world's strongest magnet and the dawn of spintronics

Masato Sagawa

Advisor for Daido Steel Co., Ltd.

Sagawa earned his doctoral degree from Tohoku University in 1972. After working at Fujitsu Limited and Sumitomo Special Metals Co. Ltd., he founded Intermetallics Co., Ltd. He has been serving as an advisor for Daido Steel since 2016. He is also an advisor for the Elements Strategy Initiative Center for Magnetic Materials (ESICMM), an outgrowth of a national project.

Terunobu Miyazaki

Professor Emeritus at Tohoku University

Miyazaki earned his doctoral degree from Tohoku University in 1972. He has been a professor at Tohoku University since 1991 and became a professor emeritus in 2007. From 2007 to 2013, he was a principal investigator at the Advanced Institute for Materials Research (AIMR) at Tohoku University, which was established by the World Premier International Research Centers Initiative (WPI).

Kazuhiro Hono

Director of the Research Center for Magnetic and Spintronic Materials (CMSM), National Institute for Materials Science (NIMS); also a NIMS Executive Vice President

Hono earned his doctoral degree from Pennsylvania State University in 1988. He has been the Director of CMSM at NIMS. He became the Executive Vice President of NIMS in 2018. He also serves as the Project Leader of the Characterization and Analysis Group at ESICMM.

The 1917 invention of "KS steel" by Kotaro Honda of Tohoku University represented the world's first artificial magnet. Since then, Japanese researchers have made major achievements in magnetic materials and related fields. Particularly notable achievements include the development of neodymium magnets—the world's strongest permanent magnets—by Dr. Masato Sagawa, and the observation of tunneling magnetoresistance (TMR) at room temperature by Dr. Terunobu Miyazaki, which led to development of technologies based on TMR devices and the rise of spintronics.

Dr. Kazuhiro Hono, Director of the NIMS Research Center for Magnetic and Spintronic Materials (CMSM), interviewed Sagawa and Miyazaki, co-winners of the 2018 NIMS Award for their outstanding accomplishments in materials science.

Honor of winning the NIMS Award

Hono: "The true value of materials is in their use"; this is one of our guiding principles at NIMS. The NIMS Award is bestowed on researchers who have either developed a material with significant practical use or made a breakthrough in basic research which led to such a development. Dr. Sagawa and Dr. Miyazaki, congratulations on being co-winners of the 2018 NIMS Award.

Dr. Sagawa, you invented the novel neodymium magnets in 1982. They remain the world's strongest permanent magnets today and are used in various electronic products and hybrid automobiles.

Sagawa: The magnet I created is composed of neodymium, iron and boron. I came up with this idea 40 years ago while participating in a symposium held by the National Research Institute for Metals, a predecessor of NIMS. At the symposium, I heard Dr. Masaaki Hamano—then a research assistant at the Institute for Materials Research, Tohoku University—say, "Compounds consisting of rare earths and iron do not become ferromagnets because the iron atoms are too closely distributed

> I believe that my experience in materials syntheses was the decisive factor to achieve the world's strongest permanent magnets.——
>
> Masato Sagawa

within them." This comment inspired me: I thought that the spacing between the iron atoms could be widened by adding chemical elements with small atomic radii such as boron or carbon. It is flattering to receive this NIMS award, as it seems like the foundation for it was laid at the symposium.

Hono: Dr. Miyazaki, you have developed room temperature high-output TMR devices. I think your invention demonstrated the practical applicability of spintronics to the public because these devices enabled the development of various memory devices including hard disk drives (HDDs) and non-volatile magnetic random access memory (MRAM).

Miyazaki: I started my research on TMR devices with the goal of getting funding from the government. Fortunately, my research results ended up facilitating the growth of spintronics into a major discipline. Although my contributions to spintronics were limited to the very early stages of its evolution, I am delighted to receive the NIMS Award.

Just 13 days ahead of a US researcher! Story behind the development of neodymium magnets

Hono: Researchers at the NIMS CMSM—where I serve as a director—are indeed carrying out research projects derived from both of your earlier accomplishments. Can you tell us how this field of research was perceived around the world at the time?

Sagawa: When I worked at Fujitsu in 1978, I was able to spend a limited amount of time developing magnets because it was not my primary research project. Nevertheless, I managed to continue the project, relying only on the idea I came up with while listening to Dr. Hamano's presentation. After about a year, I found that a combination of neodymium, iron and boron offered a promising composition for a permanent magnet. I then spent another three years studying the microstructures of magnetic materials in order to create more powerful magnets. After moving to Sumitomo Special Metals and spending three months there, I created the neodymium-iron-boron magnet, the world's strongest permanent magnet, in July 1982. When I presented the results at an international conference in the United States in 1983, I received an overwhelming response.

Miyazaki: I remember that you presented your results at the Conference on Magnetism and Magnetic Materials (3M); I was there but was unable to enter the meeting room to listen to your presentation because the room was packed.

Sagawa: I found out later that four different American research groups were fiercely competing in research similar to what I was doing at that time. I learned that Dr. John Croat at the General Motors Research Laboratory had been carrying out strikingly similar research and both he and I applied for a patent for similar magnets; I was ahead of him by only 13 days in filing my patent.

Hono: What do you think led you to win the competition?

Sagawa: I believe that my experience in materials syntheses was the decisive factor. Among the various approaches to synthesizing magnets, I chose sintering based on my knowledge of materials which I had built up over the course of many years. Although Dr. Croat and I developed magnets with the same composition, he used a rapid liquid quenching technique while I used a sintering technique. As a result, my magnet was much stronger than his. This gave me a strong appreciation for the importance of my experience in materials syntheses.

The origins of the high-output TMR devices indispensable to today's HDDs

Hono: Dr. Miyazaki, when the world's highest TMR values were less than 1%, you achieved a TMR value of 18% by using amorphous aluminum oxide (Al_2O_3) as the insulating layer material. This was a complete surprise to scientists around the world. Can you tell us what led to the discovery of the large TMR?

Miyazaki: Dr. Sagawa's efforts in developing neodymium magnets were driven by high demand for strong permanent magnets composed primarily of iron, a low-cost material. By contrast, when I started my TMR research around 1989, only a small number of scientists were interested in the subject. This was evident from the fact that I could easily cover all of the research on TMR back then by reading only a few papers. I was looking for a research topic that would attract funding, and I learned that TMR can be observed only at low temperatures and that the effect disappears at room temperature.

With the state-of-the-art techniques available today, TMR devices composed of many nanometer-thick layers can easily be fabricated. The TMR devices used in modern technologies are based on these stacks of ultrathin films. However, it is sufficient to stack three such layers to study the possibility of generating a sizable TMR effect at room temperature. This doesn't require sophisticated equipment or substantial funding. I did not expect the TMR effect to become such an indispensable technology when I started this research.

Sagawa: I know that some industry researchers were interested in the TMR effect. When I was working at Fujitsu, I was approached by some people from the magnetic recording industry who asked whether the magnetoresistance effect (a phenomenon in which the electrical resistivity of a material changes in response to external magnetic fields) could be increased.

Hono: I can understand the industrial interest in TMR. Dr. Miyazaki's development of TMR devices that operate at room temperature was a milestone in spintronics research. Without it, HDDs would not have reached their current level of development.

Miyazaki: The term "spintronics" was still new to the public when I published our results on the TMR effect in 1995. Spintronics—a discipline combining magnetic materials and nanotechnology—uses an engineering approach to exploit both the charge and spin of electrons in solids. Whatever the applications may be, I consider spintronics to be based on magnetism, and I hope that researchers in this field continue to understand the importance of gaining a solid understanding of and experience with magnetism.

Further enhancement of the strongest magnet and search for new magnetic materials

Hono: Internet of Things (IoT) systems use many HDDs to store large amounts of data. Increasing the magnetoresistance effects allowed miniaturization of HDDs by increasing their areal recording density. Among the various magnetoresistance effects discovered and applied to HDD technologies, I believe the discovery of the TMR effect by Dr. Miyazaki had the greatest impact. Neodymium magnets, on the other hand, are used in HDD actuators and spindle motor components. I must say that today's IoT systems would not have been possible without your respective accomplishments.

Sagawa: Demand for neodymium magnets will further increase when electric vehicles and robots become prevalent. However, to secure a continuous supply of neodymium magnets, we must resolve the issues related to the availability of dysprosium—an element required to stabilize the magnets.

Hono: The Element Strategy Initiative (see p. 8) was launched in 2012 by the Ministry of Education, Culture, Sports, Science and Technology to address this very issue. Although I had been interested

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>
> Terunobu Miyazaki

in research on magnets for many years, I had the impression that there was not much left to do in this field. However, things changed when China stopped exporting rare earths to Japan in 2010 due to the Senkaku Islands dispute; researchers started to consider developing high-performance permanent magnets without using rare earth elements like dysprosium.

The large difference between research today and when the two of you were actively engaged in it is the dramatic improvement of the characterization tools available. With three-dimensional atomic probe tomography and the electron microscopes, now we can now seamlessly analyze materials in detail from atomic scale to micron-scale resolution. These tools enabled us to identify the underlying mechanism of coercivity in magnetic materials. With modern computer simulations, we can also easily predict the magnetization reversal process.

Sagawa: Since the performance of neodymium magnets is known to be influenced by their microstructures, I have great expectations for the atomic-scale microstructural analyses at which NIMS excels. Of course, neodymium magnets have performance limitations, so it is also important to look for materials with better characteristics.

Hono: I agree. We are currently making such efforts in the lab. We process various materials into thin films and examine their potential as effective permanent magnets. Some have shown magnetic properties better than those of the $Nd_2Fe_{14}B$ compound, the main constituent of the neodymium magnet.

I expect NIMS to lead research and development efforts in magnetic materials by using state-of-the-art characterization tools and developing theoretical models to deepen understanding of the fundamental properties of permanent magnets. NIMS should also commit to a continuous search for magnetic materials other than the neodymium magnet.

Expanding the scope, finding new applications

Miyazaki: Analyses and theoretical modeling are becoming essential in the development of spintronics, as they have been in other fields of study. I used to believe theoretical studies to be somewhat meaningless. However, the theoretical predictions of Professors William Butler and J. Mathon on the use of magnesium oxide (MgO) as a more effective insulating layer than the Al_2O_3 originally used in my TMR devices is now used in today's technologies, leading me to believe that theoretical studies are a vital component of materials synthesis.

Hono: I expect that NIMS will be able to play a major role in theoretical modeling, which has proven to be very effective in advancing spintronic research.

Miyazaki: Spintronics can be used to enhance the performance of various forms of MRAM. It is also important to explore other fields in which spintronics could be applied. For example, efforts are underway to use magnetoresistive devices in magnetoencephalographic and magnetocardiographic sensors. I hope that young researchers conduct a wide array of research.

Hono: Spintronics is currently a hot topic. The field has attracted many talented researchers, leading to the discovery of a succession of new physical phenomena. It is therefore critical that we find practical/industrial applications for spintronic research to prevent its current popularity from fading.

My discussion today with the two of you has further increased my awareness of the role NIMS should play in research. Your research is so highly esteemed because of how significantly our society has benefitted from it. I personally believe that your achievements are worthy of the Nobel Prize.

(by Akiko Ikeda, Sci-Tech Communications)

> I expect NIMS to search for new magnetic materials using state of the art analytical tools and develop theoretical models that will lead to a deeper understanding of magnetic properties.——
>
> Kazuhiro Hono

Activities at the Elements Strategy Initiative Center for Magnetic Materials (ESICMM)

Development of permanent magnets containing no critical elements

It has been five years since the 2012 launch of the Element Strategy Initiative, which is led by the Ministry of Education, Culture, Sports, Science and Technology. We interviewed ESICMM Director-General Satoshi Hirosawa to learn about current activities and issues being addressed at ESICMM, a research center aiming to develop high-performance permanent magnets to replace the neodymium magnets currently in use.

Satoshi Hirosawa
Director-General, ESICMM, NIMS

Search for a successor to neodymium magnets

Neodymium magnets ($Nd_2Fe_{14}B$) have been used in a variety of ways all over the world. Demand for these magnets has grown rapidly in recent years due to their use in hybrid and electric vehicles. Their use in wind power generation is also expected to increase demand for the magnets. Dysprosium is added to neodymium magnets to assure stable performance at high temperatures. However, global dysprosium reserves amount to only about 10% of the amount of neodymium available, and China's dysprosium production represents more than 90% of the world's supply. It is therefore an urgent task to develop magnets that do not contain scarce elements, like dysprosium, to satisfy the increasing demand for powerful permanent magnets.

ESICMM consists of three groups: the Electronic Theory and Computation Group, which is specialized in theoretical and computational sciences, the Structural and Property Characterization Group, which analyzes the structure-property relationships through thorough characterization of magnetic materials, and the Materials Synthesis and Processing Group, which fabricates magnetic materials. The 15 member organizations of ESICMM have been closely collaborating on research and development activities.

In the first half period of the initiative, we were able to demonstrate the renewed potential of samarium-iron-cobalt (Sm-Fe-Co) magnets.[1] We fabricated high-purity magnetic films with optimized crystalline structure based on theoretical predictions and microstructural analyses. These films exhibited stronger magnetization than any other permanent magnets temperatures higher than room temperature. Temperature dependence of the magnetic properties are a critical factor in evaluating the performance of permanent magnets. This is because magnets integrated into automobile motors, for example, are required to function without issue at temperatures as high as 200°C. We compared the magnetization and magnetic anisotropy of Sm-Fe-Co magnets and neodymium magnets at 200°C and found that both were higher for Sm-Fe-Co magnets. We are currently attempting to increase the performance of Sm-Fe-Co magnets to the theoretical limit based on the material's intrinsic properties by synthesizing dual-phase structures. We are striving to develop Sm-Fe-Co magnets into practical use.

Bringing materials exploration to a new level through theoretical calculation and analysis

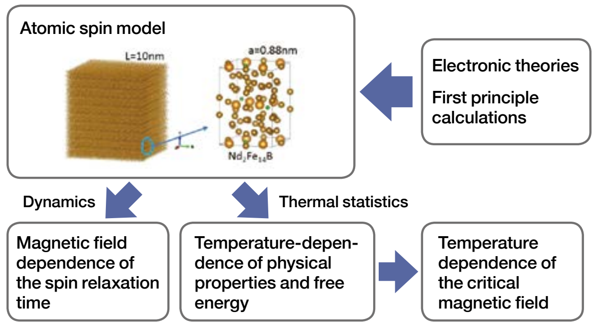
Theoretical calculation will be indispensable in developing of Sm-Fe-Co permanent magnets into practical use. With regard to theoretical studies, we are developing a "thermodynamic database," which serves as a reference in the fabrication and processing of materials, and an "atomistic theory of coercivity," which serves as a guide to control the microstructures of materials.

The thermodynamic database is useful in that it allows various factors—such as the diffusion coefficient of each element, surface energy, and so on —to be taken into account in elucidating and predicting the microstructures of materials. We have been improving the quantity and the quality of our thermodynamic data base by combining information obtained through theoretical calculations and equilibria experiments. We hope to eventually build a machine learning system enabling estimation of the thermodynamic properties associated with target materials using structural information.

In addition, we are developing an atomistic theory of coercivity by making significant changes to the conventional theory of coercivity and by using atomistic models that account for the temperature dependence of the magnetic properties of individual atoms within a magnet. This theory is expected to facilitate the prediction of temperature-related changes in the collective coercivity phenomena in a magnet (Figure).[2]

A high-performance magnet is not a homogenous material; it is a composite material in which several materials with different magnetic properties distribute in a complex manner. Thus, many issues associated with this structural complexity need to be addressed in order to increase the performance of such magnets. The Structural and Property Characterization Group and the Electronic Theory and Computation Group are working together to resolve these issues. New models and theories developed through their collaboration give direction to the design of magnet fabrication processes and thereby support the Materials Synthesis and Processing Group in producing prototypes of practical magnetic materials. The ESICMM framework thus allows the three groups to work effectively. We will continue our research endeavors in pursuit of the discovery of innovative magnet materials.

Example. Computation of the momentum of approximately 83,000 atomic spins within a 10-nm cube



Construction of an atomic model-based coercive force theory

Neodymium magnet ($Nd_2Fe_{14}B$) study as an example:an atomic spin model—which takes account of magnetic moments at individual lattice points—is constructed using first principles calculations for interactions among atomic spins and used for calculation of both dynamics and thermal statistical quantities, such as magnetization and anisotropy values. In addition, these steps enable calculation of energy barriers to magnetization reversal and discussion of coercive force.

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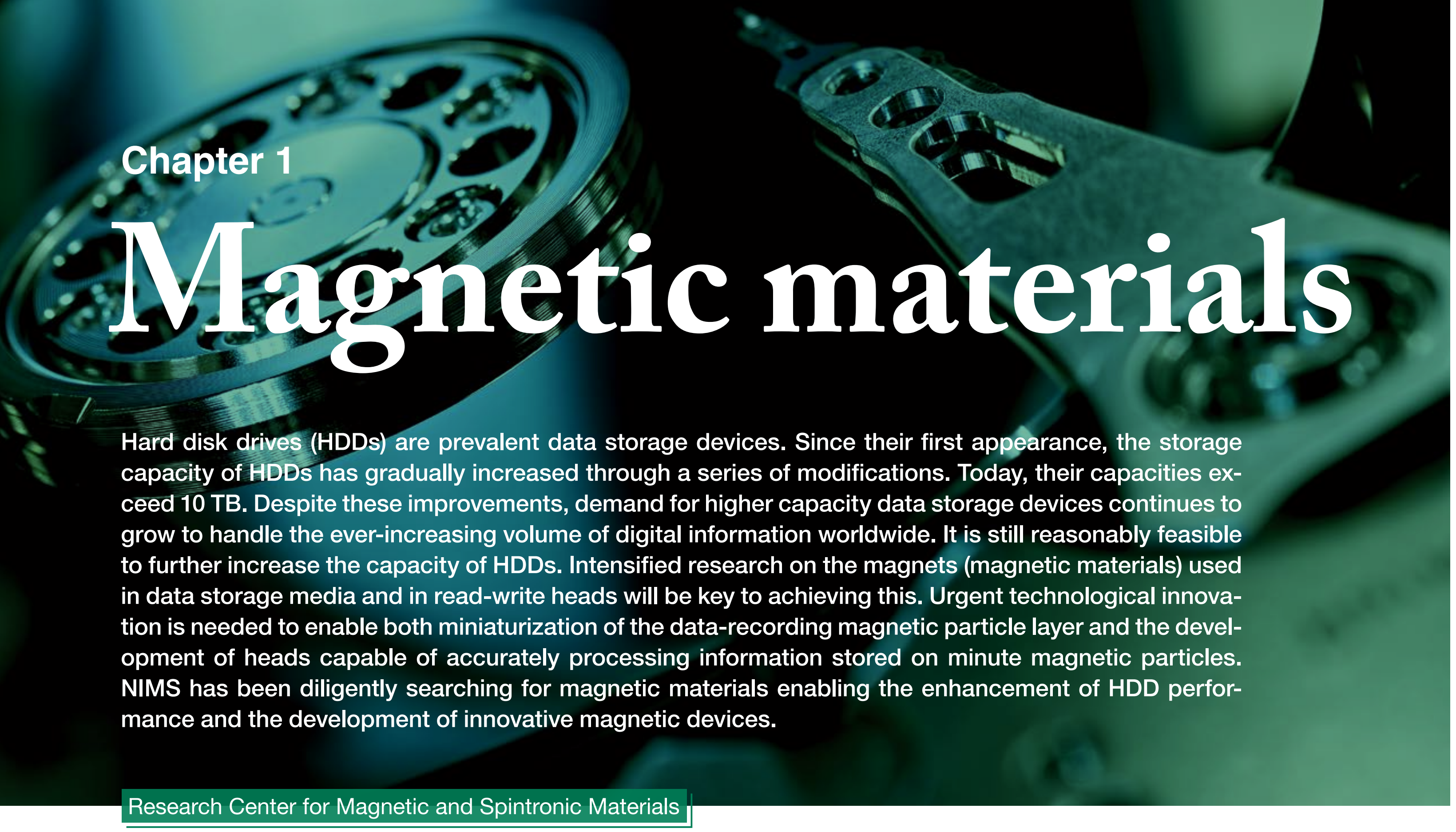
[1] Y. Hirayama, Y.K. Takahashi, S. Hirosawa and K. Hono, Scripta Mater. 138, 62 (2017).
[2] S. Miyashita et al. Scripta Mater. 154, 259 (2018)



Chapter 1

Magnetic materials

Hard disk drives (HDDs) are prevalent data storage devices. Since their first appearance, the storage capacity of HDDs has gradually increased through a series of modifications. Today, their capacities exceed 10 TB. Despite these improvements, demand for higher capacity data storage devices continues to grow to handle the ever-increasing volume of digital information worldwide. It is still reasonably feasible to further increase the capacity of HDDs. Intensified research on the magnets (magnetic materials) used in data storage media and in read-write heads will be key to achieving this. Urgent technological innovation is needed to enable both miniaturization of the data-recording magnetic particle layer and the development of heads capable of accurately processing information stored on minute magnetic particles. NIMS has been diligently searching for magnetic materials enabling the enhancement of HDD performance and the development of innovative magnetic devices.

Research Center for Magnetic and Spintronic Materials

Investigation of new technologies capable of reading and writing vast amounts of information

Half-metallic Heusler alloys as promising next-generation read/write head materials

Limitations of current read heads

The surface of HDD storage media is coated with a layer of minute magnetic particles. Multiple magnetic particles are needed to store a single bit of data, the smallest data storage unit. The magnetization directions (up or down) of individual magnetic particles are translated into digital signals of 0 and 1 for each particle group storing a single bit of data. Application of an electric current to a write head composed of electromagnets generates a magnetic field which induces magnetization reversal in the magnetic particles on the data storage medium. The read head—which reads the disk—employs a TMR (tunneling magnetoresistance) device consisting of two ferromagnetic layers separated by an insulator (see the upper left diagram on p. 12). When the read head approaches magnetic particles, the magnetization direction within the TMR device's ferromagnetic layers changes, leading to changes in the tunneling current intensity due to the TMR effect. The read head exploits this effect to read data.

The recording density of HDDs—expressed in terms of the number of bits per square inch (bit/in^2)—was 10 gigabits/in^2 around 2000. The recording density has since increased by a factor of 100 to the current 1 terabit/in^2. Although efforts to increase the recording density are expected to continue, as Sakuraba pointed out, “Once the density exceeds 2 terabits/in^2, current read heads will no longer be adequate.”

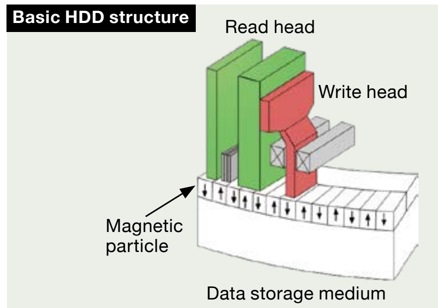
A smaller bit size is required to further increase recording density. The read head size also needs to be reduced to remain compatible with the smaller bit size. However, head size reduction necessitates miniaturization of the TMR device within the head. The response speed of smaller TMR devices decreases due to increased electrical resistance caused by the tunneling effect at the junction between the ferromagnetic and insulating layers. To address this issue, “current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) devices” are drawing attention as promising next-generation read heads.

Overcoming a weakness in next-generation read heads

A CPP-GMR device consists of two ferromagnetic layers separated by a non-magnetic metal. Unlike TMR devices, CPP-GMR devices are associated with low electrical resistance because they are composed entirely of metallic layers. This structure enables CPP-GMR devices to maintain their high-speed response capability even at sizes of several tens of nanometers. However, “CPP-GMR devices have a problem when used as read heads,” Sakuraba said. “Their sensitivity to the magnetic field is low because of low magnetoresistance ratio.”

If the bit density of HDDs is increased, the sensitivity of read heads needs to be increased to enable them to detect weaker magnetic fields generated by smaller magnetic particles. However, the sensitivity of CPP-GMR devices—which employ common ferromagnetic materials, such as iron (Fe) and cobalt (Co)—is too low, as indicated by their low magnetoresistance ratios (only a few percent) at room temperature. “Half-metals provide a solution to this issue,” Sakuraba said.

Basic HDD structure



An HDD consists of a disk-shaped recording medium and read-write heads. The magnetization directions of individual magnetic particles coating the medium are translated into digital signals of 0 and 1.

Electrons have both charge and spin properties and their spin states can be categorized as spin-up and spin-down. When an electric current is applied to a general magnetic material, electric current has a different number of spin-up and spin-down electrons, i.e., conduction electron is spin-polarized. The degree of spin-polorzation is less than about 50% for general magnetic materials. By comparison, half-metals exhibit 100% spin polarization (Figure 1). “The higher the spin polarization value of the ferromagnetic layers used in a CPP-GMR device, the higher the magnetoresistance ratio of the device,” Sakuraba explained. “For this reason, the use of half-metals as ferromagnetic layers should lead to the development of highly sensitive read heads.”

Among the various half-metals available, half-metallic Heusler alloys are particularly promising ferromagnetic materials for CPP-GMR devices because they may be capable of exhibiting nearly 100% spin polarization even at temperatures much higher than room temperature. The Magnetic Materials Group thoroughly studied various combinations of chemical elements, their ratios and thermal treatment temperatures, etc. and eventually succeeded in developing a half-metallic Heusler alloy, Co$_2$FeGa$_{0.5}$Ge$_{0.5}$. The group subsequently developed a CPP-GMR device composed of ferromagnetic layers made of this alloy separated by a non-magnetic nickel-aluminum (Ni-Al) layer. “Our device exhibited magnetoresistance ratios of 280% at low temperatures and 82% at room temperature. These values represent the current world records for CPP-GMR devices,” Sakuraba noted.

Sakuraba acknowledges the contributions of the Magnetic Materials Analysis Group and theorists both of the Research Center for Magnetic and Spintronic Materials—in making these achievements. Detailed observation of the atomic distributions within materials ensured the attainment of desirable crystalline structures (Figure 2). Theoretical studies of the relationship between the composition, crystalline structures and magnetoresistance ratios of materials allowed the formulation of strategies to increase the magnetoresistance ratio. “We are currently investigating the causes of the decrease in magnetoresistance ratios from 280% at low temperatures to 82% at room temperature,” Sakuraba said. “Once these causes are identified, we should be able to find methods of increasing room temperature magnetoresistance ratios.”

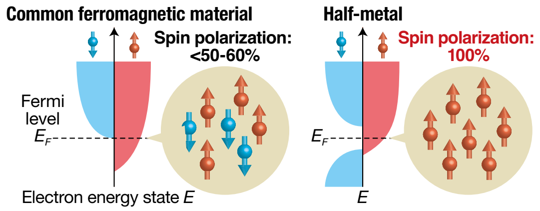


Figure 1. Schematic diagrams comparing the electronic state densities of a common ferromagnetic material and a half-metal

In half-metals, only electrons with one spin direction exist above the Fermi level,* which forms the basis of electrical conduction. Thus, half-metals may be capable of generating completely (100%) spin polarized electric currents.

* Fermi level: The highest energy state occupied by electrons in a solid material. Only electrons near the Fermi level contribute to the electric current.

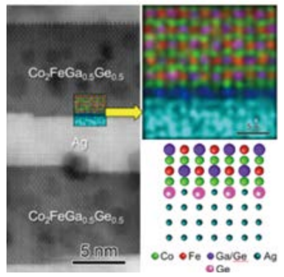


Figure 2. CPP-GMR device that employs the half-metallic Heusler alloy

The device consists of ferromagnetic layers composed of the half-metallic Heusler alloy (Co$_2$FeGa$_{0.5}$Ge$_{0.5}$), and a non-magnetic Ag layer. (Left) A scanning transmission electron microscope image of the Co$_2$FeGa$_{0.5}$Ge$_{0.5}$ and Ag layers. (Upper right) A mapped image of these layers based on energy dispersive X-ray spectrometry. The interfacial states of the Co$_2$FeGa$_{0.5}$Ge$_{0.5}$ and Ag layers can be observed at atomic resolution. It had been known that the use of non-magnetic Ag enables only electrons of one spin direction to scatter at the interface, resulting in high spin polarization. Sakuraba's group searched for non-magnetic metals that facilitate greater levels of spin-dependent scattering at the interface and eventually found such a material: Ni-Al. The group also determined that the optimum thickness of the Ni-Al layer is one and a half atoms.

Writing data with the assistance of microwaves

Innovative data writing technologies also need to be developed to achieve recording densities greater than 2 terabits/in^2. Concurrent with efforts to decrease the size of magnetic particles for increasing recording density, it is vital to use new magnetic materials whose magnetization direction remains stable under the influence of heat. Magnetization of such magnetic particles, however, is difficult to reverse using only the magnetic field generated by a write head. To solve this issue and promote the reversal of magnetization directions in magnetic particles with high thermal stability, assisted magnetization switching technologies are been developed that use lasers or microwave irradiation to locally heat magnetic particles.

Sakuraba said, “Half-metallic Heusler alloys may also serve as ideal materials for use in the microwave generating component of the assisted magnetization switching technology.” When an electric current is applied to a CPP-GMR device, spin polarization takes place within one of the ferromagnetic layers, generating a spin-polarized current. The spin-polarized current then induces spin torque in the other ferromagnetic layer, causing magnetization precession (resembling the motion of a spinning top, in which the gravitational field produces torque) within the ferromagnetic layers. As a result, microwaves are generated. Because ferromagnetic materials with high spin polarization are able to generate microwaves at low electric currents, half-metallic Heusler alloys may serve as effective CPP-GMR device materials.

Sakuraba's group has confirmed at the laboratory level that use of the half-metallic Heusler alloy reduces the electric current density necessary to generate microwaves by half when compared to the use of common magnetic materials. “A microwave generator needs to be inserted into an approximately 20-nanometer gap between two magnetic poles within an HDD write head,” Sakuraba said. “Our next goal is to fabricate a thinner device capable of stably and continuously generating microwaves.”

“Half-metallic Heusler alloys are fascinating materials,” said Sakuraba. “Their application is not limited to magnetic storage devices; they may serve as effective thermoelectric materials, magnetic refrigeration materials and other functional materials. I would like to continue studying the diverse functionalities of these alloys while taking advantage of our unique research settings, which allow close integration between experimental, analytical and theoretical approaches.”

(by Shino Suzuki, PhotonCreate)

Yuya Sakuraba

Group Leader,
Magnetic Materials Group,
Reseach Center for Magnetic and Spintronic Materials

J. W. Jung et al., Applied Physics Letters 108, 102408-1-102408-5 (2016) DOI: 10.1063/1.4943640
S. Bosu et al., Applied Physics Letters 110, 142403-1 142403-4 (2017) DOI: 10.1063/1.4979324

Research Center for Magnetic and Spintronic Materials

Maximizing the capacity of data storage media

High density recording media, towards 4 Tbit/in² HDD

Further reducing the size of magnetic nanoparticles

"To increase the recording density of recording media, the area of one bit needs to be reduced," Takahashi said. The magnetic recording media is consisted of uniformly dispersed FePt grains in a carbon matrix. Data can be written on these grains by reversing their magnetization directions using a magnetic field generated by a write head. In current HDDs, a group of 10 magnetic grains of approximately 8.5 nanometers (nm) stores a single bit of data, the smallest data storage unit. "Reducing the area of one bit without changing the size of the grains increases the noise. To prevent this, further reduction of magnetic grain size is necessary."

A global goal has been set to achieve a recording density of 4 Tbit/in² by 2022. In today's technology, the magnetic grains are composed of cobalt-chromium-platinum (CoCrPt) alloys and are approximately 10 nm in diameter. To achieve the global goal, these grains need to be decreased to 4 nm in diameter. However, Takahashi noted a problem with this approach. "The magnetization directions of 4-nm CoCrPt grains fluctuate under the thermal energy of room temperature, causing data loss, making these grains inadequate for data storage purposes."

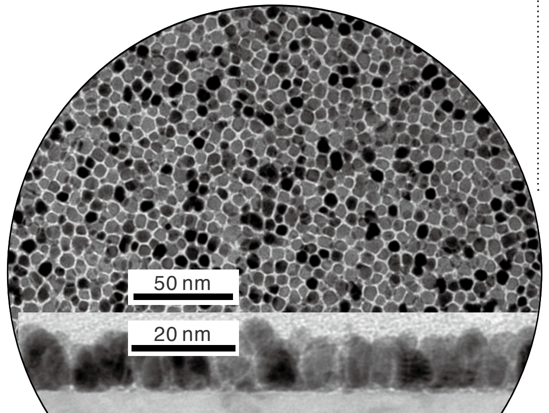
"Magnetically highly anisotropic materials, particularly iron-platinum (FePt) compounds, are drawing attention for their potential use as next-generation magnetic particles," Takahashi said. Because FePt grains exhibit strong magnetic anisotropy and thus are more resistant to thermally driven magnetization fluctuation, they are suited for miniaturization.

However, researchers around the world have struggled to develop data storage media employing FePt grains due to the twin difficulties of synthesizing FePt grains with ordered structures and uniform diameters and of evenly distributing them over an HDD surface. Takahashi's group resolved these issues by filling the gaps between FePt grains with non-magnetic carbon (C), thereby securely separating individual grains and optimizing conditions during the FePt film formation. With these modifications, the group was able to develop a data storage medium coated with 6-nm magnetic grains in 2011. "I heard that our success expedited the development of data storage media with an FePt-C layer by HDD manufacturers and that the products are expected to become commercially available soon," Takahashi said.

The diameters of the grains constituting the FePt-C layer has since been further reduced to 5.2 nm (Figure 1). In addition to the necessity of even further reducing the size of the magnetic grains, their shapes also need to be controlled. Cylindrical magnetic grains—at least 1.5 times greater in height than their diameters—are considered to be the ideal form. Because vertically elongated grains have larger volumes, they are capable of generating sufficiently strong magnetic fields to be detectable by a miniaturized next generation read head. In addition, the crystalline orientations of magnetic grains need to be aligned. "It may be difficult to achieve these results using FePt-C compounds," said Takahashi. With the assistance of the Magnetic Materials Analysis Group, Takahashi has been searching for elements that can be added to FePt-C to attain the desirable properties.

Figure 1. Electron microscope photographs of a magnetic recording medium with an FePt-C layer

(Top) Top view of the magnetic recording medium. Black and gray dots represent FePt particles (5.2 nm in diameter) while white areas indicate carbon (C) surrounding the particles. (Bottom) Side view of the same medium, showing a layer of cylindrical particles. The particle's height to diameter ratio is 2 to 1.



Development of new recording method

"New, compatible data writing and data storage media technology must be developed concurrently," Takahashi said. This is because current write heads are capable of generating magnetic fields of only 1.5 tesla (T), although 4-T magnetic fields are required to induce magnetization reversal in FePt grains. Among the various proposed methods of increasing magnetic field strength, Takahashi has been studying the method of inducing magnetization reversal using circularly polarized light. Irradiation of magnetic grains with circularly polarized light generates magnetic fields strong enough to reverse their magnetization directions. The circular light polarization direction can be switched from clockwise to anticlockwise and vice versa, making magnetization directions controllable (Figure 2). In 2016, Takahashi's group succeeded for the first time in the world in reversing magnetization directions in a data recording medium with a FePt-C media using circularly polarized light.

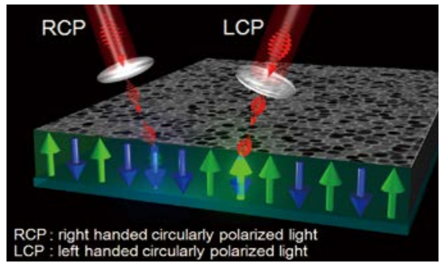


Figure 2. Conceptual diagram showing magnetization reversal being induced by circularly polarized light.

"I would like to observe the dynamics of magnetization reversal process as my next step," said Takahashi. Such observation may enable optimization of circularly polarized light irradiation, thereby increasing the efficiency of magnetization reversal. "No one has ever observed the reversal process in real time as it is extremely difficult. However, such observations are urgently needed in order to develop HDDs with recording densities of 4 Tbit/in². I would like to develop a viable observation method in collaboration with the Magnetic Materials Analysis Group," said Takahashi energetically.

(by Shino Suzuki, PhotonCreate)

Yukiko Takahashi
Group Leader,
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Spintronic Materials

K. Hono et al. MRS Bulletin. 43, 93-99 (2018). DOI: 10.1557/mrs.2018.5
Y. K. Takahashi et al. Phys. Rev. Appl. 6, 054004 (2016). DOI: 10.1103/physrevapplied.6.054004

Chapter 2

Spintronics

The field of "electronics"—which exploits electronic charges—dramatically advanced during the 20th century. More recently, progress was made in understanding the spin properties of electrons. Today, "spintronics"—which takes an engineering approach to exploiting electron spin, in addition to electronic charge—is in the spotlight. Manipulating spin direction enables the control not only of digital information but also heat and electric currents. NIMS has been building a basis for spintronics to facilitate developing devices with novel working principles based on the electron's spin degree of freedom. Based on a solid theoretical foundation, NIMS is also working to enhance the performance of next-generation MRAM (magnetic random access memory) devices capable of preserving data even when they are switched off and exploring new fields in which spintronics is applicable. This article focuses on the latest NIMS activities in spintronics, a field in which expectations are growing.

Research Center for Magnetic and Spintronic Materials

Development of high-capacity MRAM capable of stable operation

Stable, high-density data storage using an insulating "spinel barrier"

Origin of spintronics: discovery of giant magnetoresistance

"In the earlier days, electronic charge and spin were studied separately. However, after the discovery of the giant magnetoresistance (GMR) effect, technologies to control both spin and charge were rapidly put into practical use," said Hiroaki Sukegawa, who has been developing innovative spintronic devices.

First, let's briefly review the history of spintronic devices. The GMR effect was discovered in 1988. The effect concerns a multilayer thin film structure consisting of ferromagnetic layers separated by a metallic layer. The term refers to a significant change in electrical resistance in relation to the relative electron spin directions (or magnetization) between the upper and lower ferromagnetic layers (i.e., the magnetization directions in these layers are either the same [parallel] or opposite [antiparallel]). The GMR effect was applied to HDD (hard disk drive) read heads to enable them to detect weak magnetic fields. It was also applied to memory devices to record parallel and antiparallel spin states as the binary digits 0 and 1.

GMR read heads, which were put into practical application in 1997, contributed to dramatic increases in HDD data storage capacity. The subsequent development of tunnel magnetoresistance (TMR) devices replaced GMR devices, enabling further improvements in HDD performance. In 1995, a research team led by Tohoku University Professor Terunobu Miyazaki (currently a Tohoku University Professor Emeritus, see p. 3) and others succeeded in observing the TMR effect at room temperature by replacing the metallic layer in a GMR device with an insulating layer. TMR devices, which were capable of generating greater magnetoresistance changes than GMR devices, were rapidly put into practical use.

Today, expectations are high for TMR devices to perform data recording in next-generation MRAM. This is because TMR devices can retain written data even when power is switched off and are energy-efficient and durable.

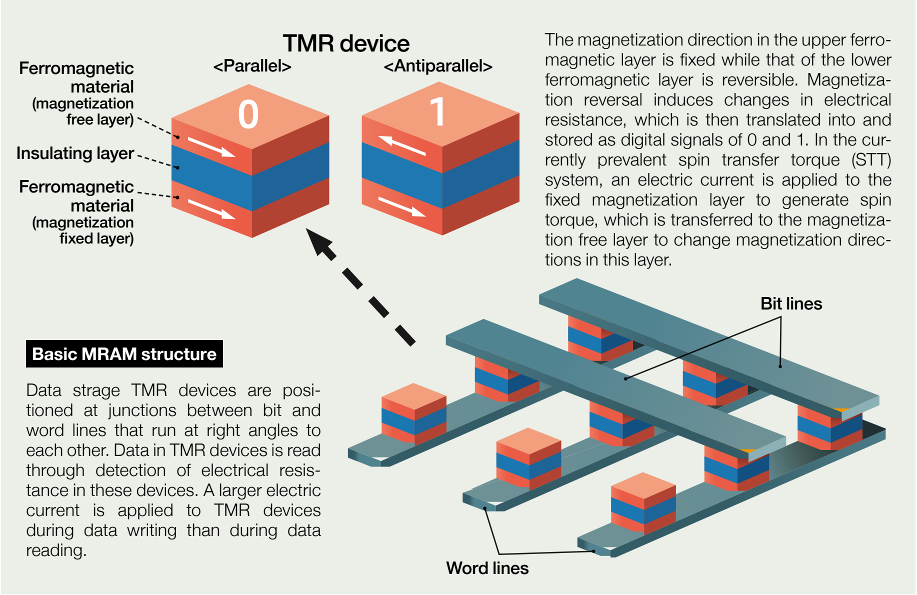
"TMR devices have already been integrated into MRAM in practical use," said Sukegawa. "This MRAM has been used in severe environments in satellites and aircraft, etc., because of its durability. However, TMR devices have not been incorporated into personal computers and mobile phones used by the general public. This is because densification of TMR devices increases their power consumption, making it difficult to develop high-capacity MRAM. We have been searching for new materials to overcome this issue."

"Tunneling barrier" key to improved performance

A TMR device has a triple-layered structure, consisting of two ferromagnetic layers separated by an insulating layer (non-magnetic layer) (see the upper left diagram on p. 12). The insulating layer is only between one and two nanometers thick. Electrons cross this layer at a certain probability. This probability changes in relation to the magnetization states of the ferromagnetic layers, causing electrical resistance to change. This phenomenon is called the TMR effect.

Electrical resistance due to the TMR effect changes at different rates depending on the relative magnetization directions of the upper and lower ferromagnetic layers (parallel or antiparallel). This rate is called a "magnetoresistance ratio."

Large magnetoresistance ratios facilitate conversion of electrical resistance into the



The magnetization direction in the upper ferromagnetic layer is fixed while that of the lower ferromagnetic layer is reversible. Magnetization reversal induces changes in electrical resistance, which is then translated into and stored as digital signals of 0 and 1. In the currently prevalent spin transfer torque (STT) system, an electric current is applied to the fixed magnetization layer to generate spin torque, which is transferred to the magnetization free layer to change magnetization directions in this layer.

Basic MRAM structure

Data strage TMR devices are positioned at junctions between bit and word lines that run at right angles to each other. Data in TMR devices is read through detection of electrical resistance in these devices. A larger electric current is applied to TMR devices during data writing than during data reading.

binary digits 0 and 1, speeding up MRAM operation. They also make MRAM more energy-efficient, enabling the development of higher-capacity MRAM.

“The magnetoresistance ratio is a significant factor influencing the performance of MRAM,” Sukegawa said. “The insulating layer, which is also called a ‘tunneling barrier,’ plays a vital role in increasing magnetoresistance ratios. Past improvements in the performance of TMR devices were achieved by replacing insulator materials.”

The discovery of the TMR effect was actually reported in 1975—earlier than that of the GMR effect. However, because magnetoresistance ratios associated with the TMR effect at room temperature were very low (≤1%), introduction of the TMR effect into practical use attracted little attention. Things changed completely 20 years later when Professor Miyazaki’s group attained a higher magnetoresistance ratio (18%) at room temperature by using aluminum oxide (Al_2O_3) as the insulating layer material. This achievement rapidly raised interest in the TMR effect. In 2004, Dr. Shinji Yuasa and his colleagues of the National Institute of Advanced Industrial Science and Technology (AIST) and others accomplished magnetoresistance ratios of 200% to 500% using magnesium oxide (MgO). Most TMR devices today employ MgO.

Sukegawa noted that MgO has some issues, however.

“MgO is a relatively unstable material due to its deliquescent tendency to absorb moisture from the atmosphere until it dissolves in the absorbed water. In addition, the combined use of MgO and a ferromagnetic material with different lattice constants (the dimensions of unit cells in a crystal lattice) from those of MgO leads to many interfacial defects, greatly reducing the magnetoresistance ratio. For this reason, only a limited number of ferromagnetic materials are compatible with MgO.”

Naturally-occurring “spinel” as a promising insulator

Sukegawa discovered that magnesium aluminum oxide ($MgAl_2O_4$) with a spinel crystal structure may serve as an effective alternative to MgO.

$MgAl_2O_4$ is a naturally-occurring, very stable gemstone mineral. It is compatible with Heusler alloys, a high-potential ferromagnetic material, as their lattice constants match nearly perfectly. This combination of materials is likely to maximize the performance of TMR devices.

In 2009, NIMS Spintronics group succeeded in developing a defect-free TMR device with a single-crystal $MgAl_2O_4$ insulating layer (Figure 1). The group confirmed in 2014 that this TMR device exhibits high magnetoresistance ratios (≳300%) at room temperature.

“When their magnetoresistance ratios are compared, TMR devices employing $MgAl_2O_4$ will need further modifications to exhibit performance superior to that of TMR devices employing MgO,” Sukagawa said. “In addition to higher magnetoresistance ratios, TMR devices with an $MgAl_2O_4$ layer need to satisfy other conditions, such as decreased electrical resistance, crystal stability and compatibility with ferromagnetic materials, in order for them to be used to increase MRAM capacity. Spinel materials have the potential to satisfy these conditions. As we will fabricate various spinel materials in addition to $MgAl_2O_4$, we may discover even more practical materials.”

NIMS Spintronics group and a company collaborator have jointly developed $MgGa_2O_4$ by substituting Al (aluminum) in $MgAl_2O_4$ with Ga (gallium) and integrating an $MgGa_2O_4$ insulating layer into TMR devices. Sukegawa said that electrical resistance associated with $MgGa_2O_4$ was approximately 2% of that associated with MgO and $MgAl_2O_4$, indicating that $MgGa_2O_4$ may be an ideal material for high-performance MRAM devices.

“The true effectiveness of materials can be assessed only based on the performance of devices in which they are used,” said Sukegawa. “I hope to continue contributing to the development of innovative spintronic devices not only by engaging in materials R&D but also by striving to enhance the performance of target devices.”

(by Kumi Yamada)

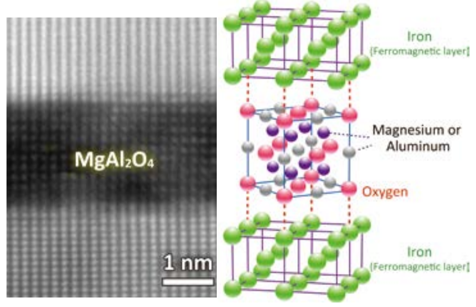


Figure 1. Cross-sectional electron microscope image of the iron / spinel / iron layers

Sukegawa fabricated TMR devices using a sputtering method already applied in a wide range of industries. Target material films were deposited on the surface of a single-crystal MgO substrate, which led to the formation of an insulating film. He then allowed the insulating film to oxidize to a precise extent using a plasma oxidation process. “When I observed the resulting insulating layer under an electron microscope, I found that the film had a high-quality single-crystal structure, rather than an amorphous structure, and virtually no defects were found at interfaces between the insulating layer and the upper/lower ferromagnetic layers. I was pleasantly surprised by these results,” Sukegawa said. “This success was attributed to the use of a single-crystal MgO substrate instead of a glass substrate, which enabled satisfactory $MgAl_2O_4$ crystallization. My technique effectively produced TMR devices of superb quality.”

Hiroaki Sukegawa

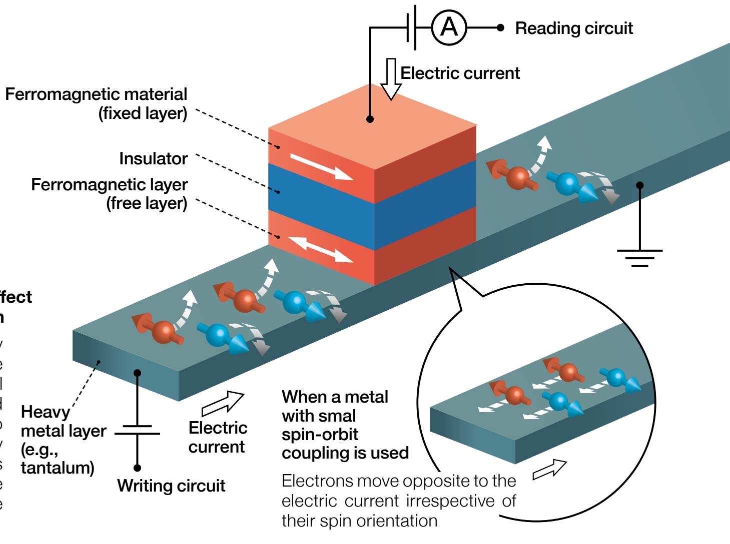
Principal Researcher,
Spintronics Group,
Research Center for Magnetic and Spintronic Materials

R. Shan et al., Physical Review Letters 102, 246601 (2009). DOI: 10.1103/PhysRevLett.102.246601
M. Belmoubarik et al., Applied Physics Letters 108, 132404 (2016). DOI: 10.1063/1.4945049

Research Center for Magnetic and Spintronic Materials

Energy-efficient data writing with spin polarized electrons

Development of high-capacity, energy-efficient MRAM that exploits the “spin Hall effect” of heavy metals



TMR device that exploits the spin Hall effect to control the direction of magnetization

A TMR device is placed on top of a heavy metal layer. (This structure allows the free layer to be in contact with the heavy metal layer.) When an electric current is applied to the heavy metal layer, the direction to which the electrons move is defined by their spin direction. Transferring electrons with the same spin direction into the free layer enables energy-efficient control of the magnetization direction of the free layer.

Writing data with lower current via materials with large spin orbit coupling

MRAM (magnetic random access memory, see p. 12) technology is based on writing and reading information stored in magnetic bits. A number of information writing schemes have been identified. Among these, “spin transfer torque writing”—which takes advantage of the effect known as the “spin transfer torque”—is already in practical use and is the focus of further development. Spin transfer torque (STT) allows direct control of the electron spins’ (or the magnetization) direction of a ferromagnetic layer when an electric current is applied to the layer. MRAM in which data is written in this manner is specifically called the STT-MRAM.

The TMR (tunneling magnetoresistance) device used in STT-MRAM contains two types of ferromagnetic layers: a “fixed” and a “free” magnetic layers. The magnetization direction of the free layer, pointing either “up” or “down”, represents the digital bit, “1” or “0”, respectively, of the device. The magnetization direction of the fixed layer provides a reference to the directions which correspond to “up” and “down”. Application of an electric current across the TMR device causes electrons in the fixed layer to align its spin direction along the magnetization direction. The “spin polarized” electrons emerging from the fixed layer move into the free layer and exerts spin transfer torque on the free layer magnetization. When a sufficiently large electric current is supplied, spin transfer torque can cause the magnetization direction of the free layer to reverse. Such process can be confirmed by measuring the electrical resistance of the TMR device, which is high, corresponding to digital bit 1, and low (digital bit 0) when the relative orientations of the fixed and free magnetic layers are anti-parallel and parallel to each other, respectively.

To further develop the STT-MRAM technology, it is understood that the current density required to control the free layer magnetization direction via the STT needs to be further reduced. In particular, to meet today’s growing demand for high-capacity MRAM, it is vital to develop technologies capable of controlling the magnetization direction at significantly lower current densities. Masamitsu Hayashi has been attempting to achieve this by exploiting the so-called “spin Hall effect.”

When an electric current passes through a metallic material, all of the electrons within it normally move in the opposite direction of the electric current, irrespective of their spin direction. By contrast, when heavy metals with large spin-orbit coupling*—such as tantalum (Ta) and platinum (Pt)—are subjected to an electric current, the direction of electron motion is influenced by the electron spin direction due to the so-called spin Hall effect. The spin Hall effect enables electrons with the same spin direction to flow (the spin current) in one direction whereas the electrons with the opposite spin move in the opposite direction (Figure). Such flow of electrons is referred to as spin current. By exploiting the spin current generated from the spin Hall effect in heavy metals, one can control the magnetization of a nearby magnetic layer. This approach provides a new architecture for information writing in the STT-MRAM technologies.

Hayashi is currently studying a structure in which a TMR device is stacked onto a heavy metal layer. The magnetization direction within the ferromagnetic material (bottom free layer) can be reversed efficiently by transferring spin currents generated within the heavy metal layer into the free layer. The switching of the magnetization direction can be regulated by reversing the direction of the electric current flow within the heavy metal layer.

“This approach of using the spin Hall effect of the heavy metal layer has another advantage in addition to reducing the power consumption,” says Hayashi. “In conventional STT-MRAM, the circuit used for reading and writing information is the same, which in some occasions results in inadvertently writing a bit during the reading process. This will increase the error rate. By contrast, with the writing scheme exploiting the spin Hall effect of a heavy metal layer, the circuit used for reading and writing information is different: current flows across the TMR device during the reading process whereas current passes through the heavy metal layer for the writing process. This arrangement can reduce the likelihood of read/write errors.

“I am not at the stage of elaborating on how much power consumption can be reduced with the spin Hall effect.” Hayashi says. “On the course of my study, I plan to clarify the viability of this approach. With many new materials being developed today, including the topological insulators and Weyl semimetals, it will be interesting to explore their possibilities for the MRAM technologies.” Hayashi hopes to complete the development of a high-capacity MRAM in the near future.

(by Kumi Yamada)

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* Spin-orbit coupling: interaction between the electron’s spin angular momentum and orbital angular momentum.

Masamitsu Hayashi

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J. Kim et al., Nature Mater. 12, 240 (2013) DOI: 10.1038/NMAT3522
J. Torrejon et al., SPIN 06, 1640002 (2016) DOI: 10.1142/S2010324716400026

Research Center for Magnetic and Spintronic Materials

Using spin to manipulate heat and electricity

Successful visualization: temperature change in magnetic materials induced by interaction between magnetism and charge current

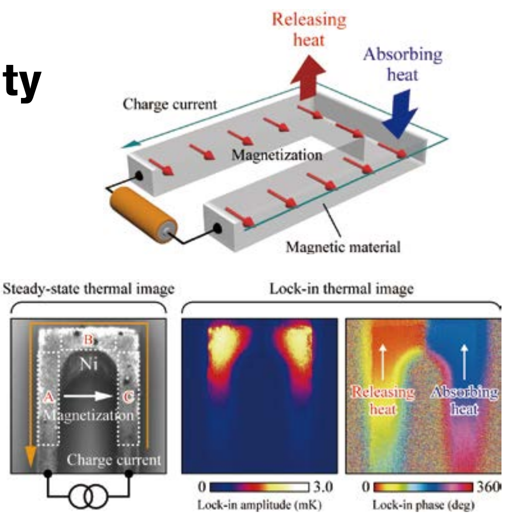

Figure 2. Observation of anisotropic magneto-Peltier effect.

What is the "anisotropic magneto-Peltier effect" that has been observed for the first time in the world?

The flow of electricity (i.e., charge current), thermal flow (i.e., heat current) and magnetic flow (i.e., spin current) within a material are known to interact and transform into one another. Precise control of these interactions may lead to the development of more energy-efficient devices. Ken-ichi Uchida has been leading basic research on spin currents by being the first in the world to observe many spin current phenomena.

Of the three types of currents mentioned above, the interaction between charge and heat currents was observed as early as the 1800s. The conversion of a heat current into a charge current is called the "Seebeck effect," while the conversion of a charge current into a heat current is called the "Peltier effect." Unlike these long-established effects, attempts to observe and verify interactions between spin currents and charge/heat currents had been unsuccessful until recently. In 2008, Eiji Saitoh (then an assistant professor at Keio University and currently a professor at The University of Tokyo) and Ken-ichi Uchida (then a senior student at Keio University and currently a NIMS Group Leader) succeeded for the first time in observing the "spin Seebeck effect"—the conversion of a heat current into a spin current in metals with magnetic properties. Since then, Uchida and his colleagues have continued to make novel discoveries in this field, including confirmation of the existence of the spin Seebeck effect in electrically insulating materials.

In May 2018, Uchida published a paper detailing the world's first observation of the anisotropic magneto-Peltier effect—a phenomenon in which simple redirection of a charge current in a ferromagnetic material, such as nickel (Ni), causes specific parts of the material to warm and cool.

The Peltier effect is a phenomenon in which the application of a charge current to metals or semiconductors generates a heat current within them which flows in the direction parallel to the charge current. This effect can be used to control heat release and absorption by changing the direction of the charge current. The release and absorption of heat attributed to the Peltier effect had been confirmed to occur only at the junction between two different materials. In ferromagnetic materials, in which electron spins are aligned in parallel, it had been predicted that the efficiency of the conversion from a charge current to a heat current would vary depending on whether the direction of the magnetization* is parallel or perpendicular to the direction of the charge current (Figure 1). "By using this property, the heat release and absorption can be generated even in a single material simply by forming curved/bent structure or by manipulating the direction of the magnetization non-uniformly," Uchida said. "To demonstrate this, we processed a ferromagnetic Ni slab into a square-cornered U shape, magnetized it uniformly, and measured the temperature distribution on the surface of the material while applying a charge current to it. We performed these measurements using lock-in thermography** (the system shown on the cover page), which we have used for spintronic research."

The square-cornered U shape of the Ni material allowed Uchida to make temperature measurements with changing the angles between the magnetization and charge current directions. As expected, temperatures in the vicinity of the corners differed from those of the rest of the material (Figure 2). Uchida also confirmed that no temperature change occurs when the Ni material is not magnetized, ensuring that the observed temperature change is attributed to the anisotropic magneto-Peltier effect.

Uchida shared his future research plans. "As one example, the anisotropic magneto-Peltier effect could be applied to the development of a device which requires that neighboring components have different temperatures. A single ferromagnetic material could be processed properly and incorporated into a device and the temperature modulation can be driven simply by applying a charge current to it. Future advances in spintronics require both the building of a fundamental physics and exploration of its potential applicability. Many challenges lie ahead."

(by Kumi Yamada)

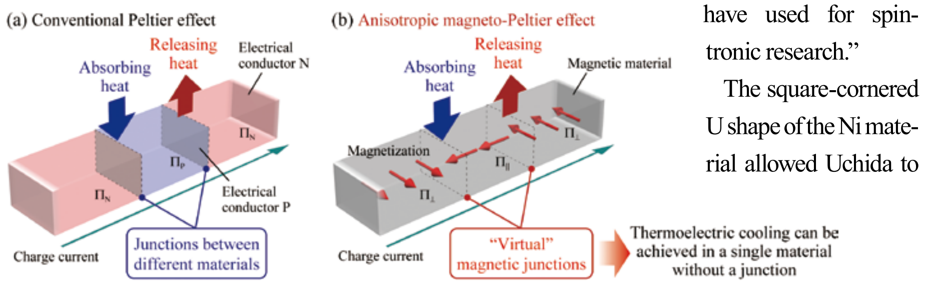

Figure 1. Diagrams illustrating the concepts of (a) conventional Peltier effect and (b) anisotropic magneto-Peltier effect.

K. Uchida et al., Nature 558, 95-99 (2018) DOI: 10.1038/s41586-018-0143-x

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* Magnetization: a phenomenon in which a material exhibits magnetism when subjected to a magnetic field. The term also denotes a physical quantity, representing the strength and orientation of magnetism in a magnetic material (i.e., magnetic moment per unit volume).

** Lock-in thermography: a technique used to measure temperature distributions on the surface of a material by applying a periodic signal (a charge current in this specific study) to the material and detecting thermal radiation from the surface of the material using an infrared camera. This technique enables highly sensitive imaging of surface temperature distributions by selectively extracting radiation that oscillates at the same frequency as the input signal.

Ken-ichi Uchida

Group Leader,
Spin Caloritronics Group,
Research Center for Magnetic and Spintronic Materials

Guiding the development of magnetic and spintronic materials

—Analytical techniques and theoretical calculations that give direction to materials research—

Analysis specialist

For Sepehri-Amin and his colleagues, the focus of research is improving existing functional magnetic materials and developing new ones.

That includes permanent magnets, Sepehri-Amin's speciality. He conducts analysis of different types of magnetic materials, combining multi-scale advanced microstructure characterization from micro and nano-scale and even resolving atom by atoms using 3D atom probe tomography to understand the material's microstructure and then correlate these features with the magnetic properties.

Currently, Sepehri-Amin's main research topic is the development of high performance permanent magnets without reliance on scarce elements such as dysprosium or terbium.

"In order to make Nd-Fe-B based permanent magnets more resistive against magnetization reversals, in other words enhancing their coercivity, heavy rare earth elements such as Dy or Tb are added to increase the room temperature coercivity of the magnet" he said. "However, anisotropy field (theoretical limit for the coercivity) of $Nd_2Fe_{14}B$ phase without scarce elements is large enough to have a high coercivity at room temperature. So we want to modify the microstructure, remove the defects that are easy points for the magnetization reversals, and for that, we employ multiscale microstructure characterizations combined with micromagnetic simulations and materials processing."

The team uses a scanning electron microscope, aberration corrected scanning transmission electron microscope, and 3D atom probe to figure out what's happening in the material's microstructure. They combine these with finite element micromagnetic simulations and design the material's microstructure to improve the coercivity and thermal stability of the permanent magnets.

They have found that the existence of large amounts of iron at grain boundaries is responsible for the low coercivity of Nd-Fe-B magnets. This led to a technique to diffuse low-melting point (non-magnetic) Nd-Cu eutectic alloys through grain boundaries in Nd-Fe-B magnets. The result was lower iron concentration at the grain boundaries, which enhanced the coercivity.

Microstructure and materials design using micromagnetic simulations and advanced microstructure characterizations applies to various types of functional magnetic materials, such as for data storage that is incorporated in development of the next generation of magnetic recording in hard disk drives with increased areal density. The group is collaborating with Magnetic Materials Group and Magnetic Recording Materials Group, and also directly with researchers at companies that develop hard disc drives.

"One application we're working on is realization of spin-torque oscillator for microwave-assisted magnetic recording, the next generation of magnetic recording. In addition, we are working on correlation of microstructure of FePt granular media with its magnetic properties and recording performance for heat assisted magnetic recording. Both technologies are the next generation of magnetic recording that will lead to the development of hard disk drives with increased energy density" Sepehri-Amin said.

"For the future, there are new materials to be developed, such as finding a permanent magnet with a higher performance than the existing Nd-Fe-B based permanent magnets. That is not an easy task, but it is the dream of people working in this field."

(interview and text by R.Cameron)

Hossein Sepehri-Amin

Senior Researcher,
Magnetic Materials Analysis Group,
Research Center for Magnetic and Spintronic Materials

Prediction specialist

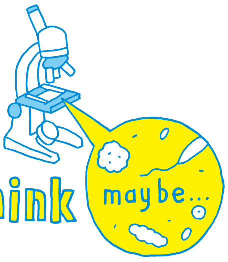
"My role is to facilitate the discovery of novel magnetic and spintronic materials," Miura said. He has a great deal of expertise in first-principles calculations. "The first-principles technique is a powerful tool for the analysis of material properties. As an alternative to conducting experiments, the use of this quantum mechanics-based technique enables accurate prediction of material properties by precisely describing interactions involving electrons in a material. The application of this technique is particularly crucial as it is the only method available to describe the magnetic and spin properties of materials," Miura said.

Miura has been using various electron theories to find ways of greatly stabilizing the magnetic properties of materials—such as the magnetoresistance effect and magnetic anisotropy—at near room temperature at which these materials are expected to be used. He recently discovered that the temperature-related variability of the magnetoresistance effect may be reduced by strengthening "exchange stiffness of spin" at the junction between an insulator and a magnetic thin film. "My goal is to design practical magnetic/spintronic materials using a theoretical approach, including the theory of finite temperature magnetism. At the same time, I would like to work collaboratively with experimental researchers."

Yoshio Miura

Independent Scientist
Research Center for Magnetic and Spintronic Materials

Science is even more amazing than you think



The lady and the sharks

Text by Akio Etori

Illustration by Joe Okada (vision track)

More than 50 years ago, I made my first overseas trip to the United States. I visited many scientific facilities, including space development facilities and the New York World's Fair, to collect information for a TV program.

A small marine research facility in Florida left me with a particularly strong impression.

When my cameraman partner and I arrived at the airport in Tampa, a charming female researcher named Eugenie Clark came to pick us up. She drove a Cadillac convertible and dressed casually in jeans and sandals. We were impressed by the image of her driving there; for us, it symbolized American prosperity at that time.

Dr. Clark was the founding director of the Cape Haze Marine Laboratory, where her main research focus was the reproductive mechanisms of sharks. The enthusiasm with which she welcomed us may have been in part because she was a quarter Japanese by blood.

In her research, Dr. Clark captured sharks every day using tools that resembled long-line fishing gear and measured and dissected them. She reared small sharks for observational study. She eventually started training them and succeeded in teaching sharks certain signs.

The trained sharks later brought Dr. Clark an exciting opportunity—she was invited by the then-Crown Prince of Japan (now Emperor) who, like the late Japanese Emperor Hirohito, was a noted ichthyologist. Dr. Clark planned to show the Crown Prince a trained shark as a gift and managed to transport it to Japan by airplane. The shark arrived safely and performed well, to the amazement of the Crown Prince.

Dr. Clark's achievements include the discovery of paired sexual organs in both male and female sharks and the observation of "sleeping" sharks. She also published a book, "The Lady and the Sharks," which describes her life in Florida.

After meeting with her many times in the US and Japan, I translated her book into Japanese, which was published in 1972 under the Japanese title, "Umi to taiyo to same" (The Ocean, the Sun and the Sharks).

I developed an abiding interest in sharks through my interactions with Dr. Clark. A new book recently came to my attention, published this May, entitled "Hobo inochigake same zukan" (Shark Guide: Based on Real-life Shark Experiences) (Kodansha Ltd.). Its author, Ms. Asako Numaguchi, is known as a "shark journalist." The book contains current, comprehensive knowledge and information on sharks, including many discoveries made by Dr. Clark.

Although space considerations prevent a comprehensive synopsis, the book mentions that many shark species are now on the endangered species list due to the deteriorating global environment, which was not an apparent issue when Dr. Clark was actively conducting research.

Of the 509 known shark species, 74 are on the endangered species list,* including relatively well known species such as the great white shark, whale shark and hammerhead shark. Ms. Numaguchi, an enthusiastic shark lover, hopes that the public will develop "sharkibility" (a term coined by Numaguchi, meaning knowledge of and passion for sharks).

The conservation of biodiversity is an urgent global issue important to us all. Environmental degradation is having a severe impact on various groups of organisms, including mammals, reptiles, amphibians and fishes. I therefore hope that "sharkibility" prevails among the public as part of a broad, profound interest in and empathy for all living organisms. I believe that Dr. Clark would agree with me.

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* Source: IUCN Red List of Threatened Species 2013

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

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