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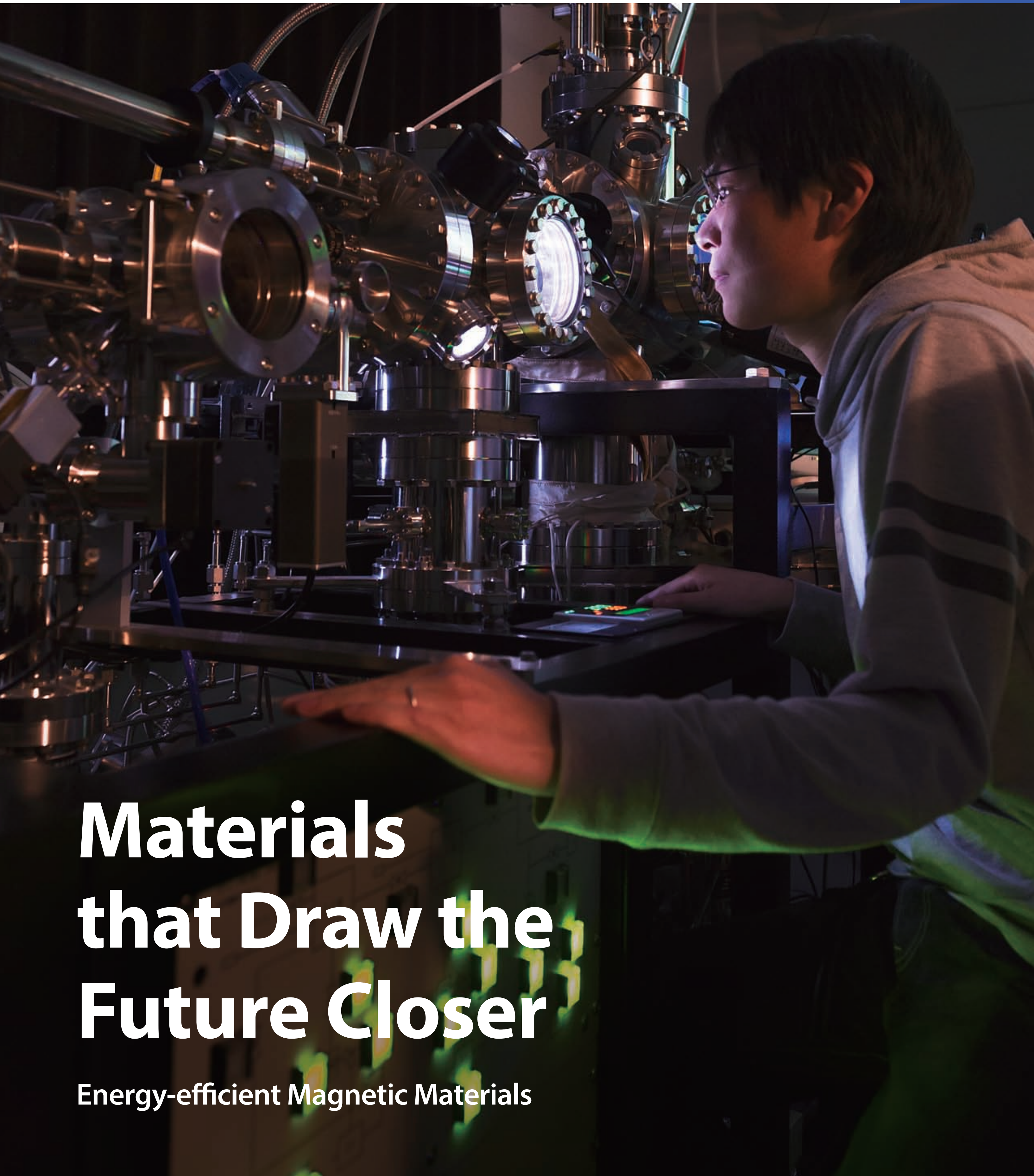

Materials that Draw the Future Closer

Energy-efficient Magnetic Materials

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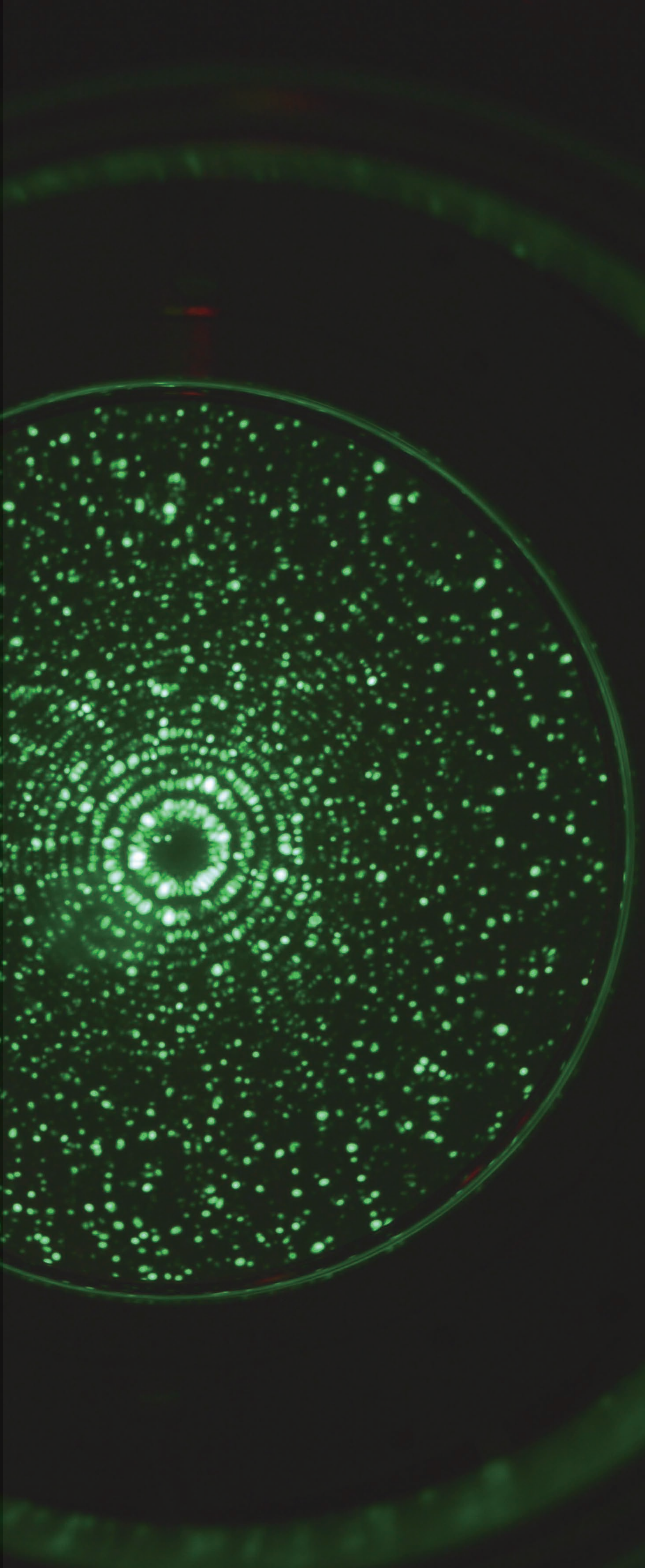
Many of us have a memory of playing with magnets in our childhood.
They stick together and repel each other.
What seemed to be plain rocks inspired our wonder and curiosity.
Today, those magnets play an indispensable part in our daily lives.

For example, hard disks are used as storage devices for storing various data supporting the fundamentals of modern life.
In these hard disks, data are written on nanosized magnets.
How much we can miniaturize the nanoparticles of those magnets in a stable manner is a huge challenge at present.
Since the amount of data processed by servers has increased dramatically in recent years due to the spreading use of smartphones and other reasons, prompt action is sought.

Magnets are also used in hybrid vehicle motors and wind power generators.
Because the output performance of these applications is greatly affected by the magnetic force of the magnets, there are calls for magnets that have a higher magnetic force while considering resource issues, such as rare earth issues.

Also, there is a demand for searching for the possibility of directly generating power from a heat source by using a magnet, and for conducting research to miniaturize and improve the magnets used as components of a new memory, MRAM.
The research tasks concerning magnet application are thus expanding widely.

The materials that inspired our wonder and curiosity in our childhood are now shaping the future of our society.



FIM image of neodymium magnet

Ultrahigh-Density Magnetic Recording Materials

Magnetic Materials Group,
Magnetic Materials Unit,
Environment and Energy Materials Division
Yukiko Takahashi

Spintronics Group,
Magnetic Materials Unit,
Environment and Energy Materials Division
Shinya Kasai

Magnetic Materials Group,
Magnetic Materials Unit,
Environment and Energy Materials Division
Takao Furubayashi

Unit Director,
Magnetic Materials Unit,
Environment and Energy Materials Division
Kazuhiro Hono

Magnetic recording that supports a digital information society

Due to the spread of the cloud computing and digital home appliances, the amount of data used around the world has shown an explosive increase. The total amount of data, which is currently said to be about 3 zettabytes (10^{21} bytes) is expected to reach 40 zettabytes by 2020.

The storing such enormous data is led by hard disk drives (HDD). Although flash memory has expanded its share as notebook PC storage recently, HDDs are expected to remain the key player in future data storage due to their low bit unit price and large capacity.

While the growth of energy consumption at data centers to deal with such enormous data has become a social issue, an increase in the recording density of HDDs is also expected to have a significant energy-saving effect. The current recording density of HDDs is about 800 Gbit/in^2, but Japanese and U.S. industry-academia consortiums (the Storage Research Consortium (SRC) and the Advanced Storage Technology Consortium (ASTC)) are conducting research and development aimed at achieving 4 Tbit/in^2.

The NIMS Magnetic Materials Unit is contributing to the materials research necessary for dramatically increasing the recording density of HDDs, in cooperation with Japanese and U.S. HDD manufacturers.

Mechanism of HDD

As shown in the photograph of Fig. 1(a), an HDD is composed of a disk-shaped medium for recording information, heads for reading and writing information, and an actuator which moves the heads to the read/write position. A neodymium magnet is used for the actuator.

Figure 1(b) shows a schematic of the medium and the heads. The write head is a small electromagnet. When electric current is applied to the coil, a magnetic field is generated at the tip of the head. The magnetic field magnetizes the magnetic nanoparticles densely filled in the medium, and records the digital information "0" or "1" according to the magnetization direction (S-N). When reading, the head detects the magnetic field generated by the nanomagnets.

Figure 1(d) shows a transmission electron microscope (TEM) image of a currently used recording medium. CoCrPt magnetic particles of about 8 nm are evenly distributed within a SiO_2 nonmagnetic matrix. The read head uses a tunnel magnetoresistance device consisting of two ferromagnetic layers with an ultrathin insulator layer between them as shown in Fig. 1(c). The device resistance changes significantly as the relative magnetization direction of the two ferromagnetic layers of the read head changes according to the magnetic field emanating from the medium. Therefore, in order to further increase the recording density of HDDs, technological innovation of both the medium and the read head will be essential.

Heat-assisted magnetic recording media

In order to achieve a recording density of 4 Tbit/in^2 for HDD, the size of the magnetic particles of the medium must be reduced to about 5 nm. Since the crystal magnetic anisotropy (K_u) of the currently used CoCrPt alloy is small, if the particle size is reduced to a several nanometer scale, the magnetic anisotropy energy of the particles (K_uV ; V is the particle volume) will be about the same level as the thermal energy at room temperature (k_BT; k_B is the Boltzmann constant and T is the absolute temperature), so magnetization of the particles will fluctuate by heat.

In order to achieve stable magnetization even for nanoparticles, a necessary nanoparticle structure (Fig. 1(d)) needs to be realized in the medium by using ferromagnetic materials with large K_u.

Since a FePt alloy with an $L1_0$ structure has more than ten times the K_u of a CoCrPt alloy, its magnetization will be stable even when it is in a nanoparticle form. However, due to the high K_u, the magnetic field required for writing becomes larger than that can be generated at the head when in nanoparticle form. As a result, writing will not be possible at room temperature.

Therefore, a method called heat-assisted magnetic recording (HAMR) is edging close to practical application as a next-generation recording technology. HAMR is a method whereby a nanomagnet is heated by laser to the Curie point, and data is written by using the magnetic field of the head at the instant when the magnetization switching field is reduced.

HAMR requires a medium in which FePt nanoparticles with an $L1_0$ structure are uniformly dispersed. In 2010, we realized an $L1_0$-FePt granular thin film with an average particle diameter of 6 nm and size dispersion of about 20% by simultaneously depositing a FePt alloy and carbon. Jointly with the San Jose Research Center of HGST, a U.S. company, we showed that this medium is capable of achieving a recording density of 550Gbit/in^2, which was the highest level for HAMR at that time.

This finding prompted rapid acceleration of media development by HDD manufacturers, and at present, HAMR with a recording density of 1.5 Tbit/in^2 has been reported by manufacturers.

Much more improvement is required for practical application, such as further reducing the size dispersion of the particles, and growing the particles into a columnar shape. As part of such effort, by proposing new nonmagnetic materials and improving the film deposition process, we succeeded in creating a columnar FePt-based medium with an axial ratio of 2 as shown in Fig. 2.

Read head: Current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) device

A tunnel magnetoresistance (TMR) device which has a thin MgO insulator layer between two CoFeB ferromagnetic electrodes is currently used as the read head for HDDs.

A TMR device, which can obtain a high magnetoresistance ratio, excels as a magnetic sensor, but because it uses an insulator as an interlayer, it has high device resistance, and is unsuitable for fast-response low-resistance devices. Meanwhile, the device resistance can be easily lowered by using a current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) device, which consists entirely of metal layers. However, since conventional CPP-GMR devices have been unable to produce a sufficiently high level of magnetoresistance output, they have not been put to practical use.

The output of the CPP-GMR greatly depends on the spin polarization of the ferromagnetic layers constituting the device. We systematically searched for ferromagnetic materials that exhibit high spin polarization through measuring the spin polarization by point contact Andreev reflection, and developed new materials with high spin polarization, such as Co_2Fe ($Ga_{0.5}Ge_{0.5}$) (CFGG). Moreover, in order to demonstrate the compatibility of these materials for devices, we created CPP-GMR devices with the new materials, and showed that high magnetoresistance output can be achieved.

Figure 3 shows TEM images and magnetoresistance curves of a CPP-GMR device using CFGG. It was confirmed that the upper and lower CFGG layers are ordered to the $L2_1$ structure which brings about high spin polarization. As a result, it achieves the world's highest level of magnetoresistance output for CPP-GMR. Research in the past had been conducted on single-crystal devices in order to show the potentials of the materials, but recently, with industrial application in view, we have been attempting to raise the performance of polycrystal devices deposited on Si substrates.

Read head: Lateral spin-valve (LSV) device

Since the resolution of a read head depends on the device size, the device thickness needs to be reduced to about 15 nm in order to achieve application to magnetic recording exceeding 4 Tbit/in^2.

The TMR devices currently used and the CPP-GMR devices currently under development fix magnetization of one of the ferromagnetic electrodes, so an antiferromagnetic layer of about 10 nm will be required, making it difficult to make the devices ultrathin. As a promising means to solve this problem, the potential of lateral spin-valve (LSV) devices that arrange CPP-GMR devices in-plane is being studied.

As shown in Fig. 4(a), an LSV device injects a spin polarized current from the ferromagnetic layer (FM1) to the nonmagnetic layer (NM), and detects the conducted spin at the other ferromagnetic (FM2)/nonmagnetic interface. Fig. 4(b) shows a schematic of the read head with an LSV device. Since the read section consists of two layers, a ferromagnetic layer and a nonmagnetic layer, it is possible to make the device ultra-thin. Although there have only been reports of LSV devices made from materials that have been known for a relatively long time, such as permalloy or Co, we succeeded in obtaining output 17 times larger than before by using CFGG, which is a material with high spin polarization (Fig. 4(c) and (d)).

At present, we are experimentally verifying whether the output necessary for application to the read head can be obtained with LSV devices using such new materials with high spin polarization.

Future of HDD: Toward higher recording density

In order for HDDs to remain the key player in future data storage, their recording density needs to keep growing with the introduction of new materials and new recording methods. To realize a recording density of 4 Tbit/in^2, it is necessary to not only develop the HAMR media and magnetic centers for the read head as mentioned earlier, but also study the potential of new technologies.

To this end, we are, for example, also exploring the potential of new technologies such as the following:
(i) recording heads and media for realizing microwave-assisted magnetic recording (MAMR) which induces precession of magnetization by imposing a high-frequency magnetic field and reduces the magnetization switching field;
(ii) media for bit pattern magnetic recording (bit pattern media: BPM) where one particle represents 1 bit of information; and
(iii) magnetic recording using a circularly polarized laser (all-optical helicity-dependent switching: AOHDS).

The amount of data used in our society will definitely expand further in the future due to diversification of devices and the associated use of cloud computing. We will push forward research with an aim to further enlarge the capacity of HDDs, which are an optimal storage device for storing and using massive data.

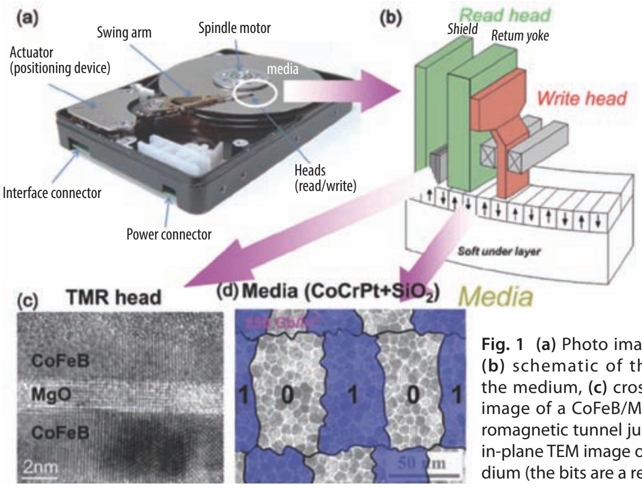


Fig. 1 **(a)** Photo image of an HDD, **(b)** schematic of the heads and the medium, **(c)** cross-section TEM image of a CoFeB/MgO/CoFeB ferromagnetic tunnel junction, and **(d)** in-plane TEM image of a CoCrPt medium (the bits are a representation).

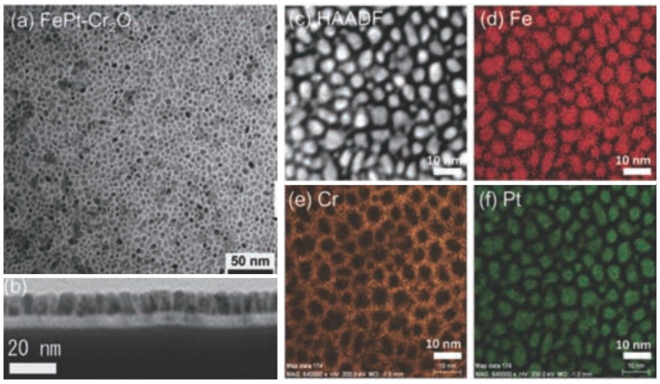


Fig. 2 The following images of a FePt-Cr_2O_3 medium: **(a)** in-plane TEM image, **(b)** cross-section TEM image, **(c)** high-angle annular dark-field (HAADF) image, **(d)** Fe map, **(e)** Cr map, and **(f)** Pt map.

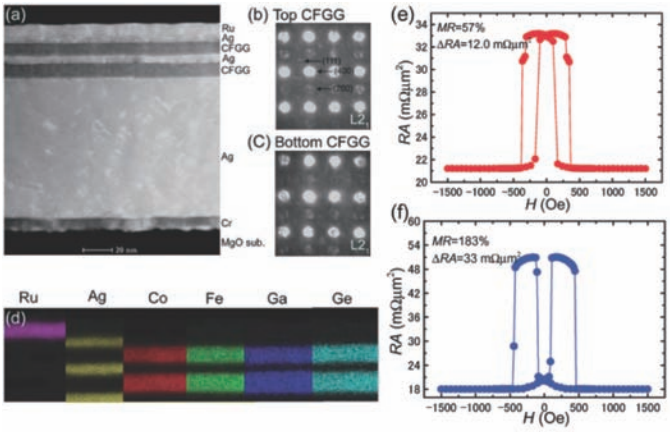


Fig. 3 The following images of CFGG/Ag/CFGG-CPP-GMR: **(a)** cross-section HAADF image, **(b)** and **(c)** nano-beam electron diffraction images of the upper and lower CFGG layers, **(d)** elemental maps of Ru, Ag, Co, Fe, Ga, and Ge, and **(e)** magnetoresistance curve at room temperature and **(f)** that at 10K.

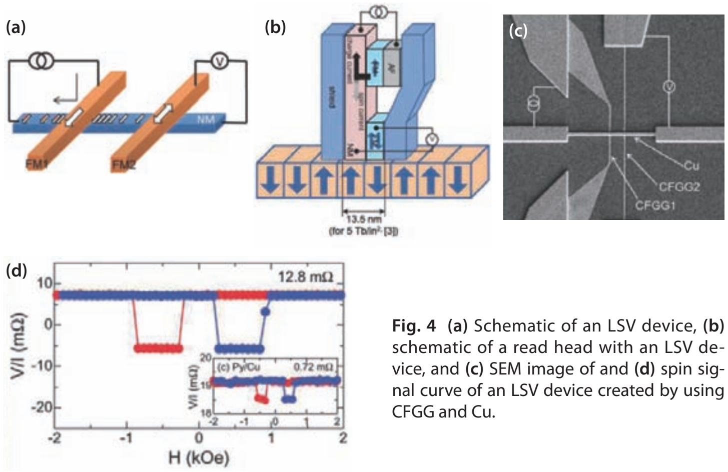


Fig. 4 **(a)** Schematic of an LSV device, **(b)** schematic of a read head with an LSV device, and **(c)** SEM image of and **(d)** spin signal curve of an LSV device created by using CFGG and Cu.

Profile

Yukiko Takahashi Ph.D. (Engineering). Completed the doctoral course in the School of Engineering, Tohoku University, and joined NIMS as a Postdoctoral Researcher in 2001. Appointed as a NIMS Principal Researcher in 2010. **/ Shinya Kasai** Ph.D. (Science). Completed the doctoral course in the Graduate School of Science and Technology, Keio University in 2004. Became an assistant at the Institute for Chemical Research, Kyoto University in the same year. Joined NIMS as a Principal Researcher in 2009. **/ Takao Furubayashi** Ph.D. (Science). Completed the doctoral course in the School of Science, the University of Tokyo in 1984. Joined the National Research Institute for Metals (NRIM; present NIMS) in the same year. **/ Kazuhiro Hono** Ph.D. Completed the doctoral course in the Graduate School of Pennsylvania State University in 1988. After serving as a postdoctoral researcher at Carnegie Mellon University, an assistant at the Institute for Materials Research, Tohoku University, in 1990, and a Principal Researcher at the NRIM in 1995, assumed the present position in 2004.

Tunnel magnetoresistance device Materials for STT-MRAM

Group Leader, Spintronics Group, Magnetic Materials Unit,
Environment and Energy Materials Division
Seiji Mitani

Spintronics Group, Magnetic Materials Unit,
Environment and Energy Materials Division
Hiroaki Sukegawa

What is STT-MRAM based on current writing?

Magnetic random access memory (MRAM) is a kind of memory device. Its major characteristic is its non-volatility, that is, it does not lose stored information even when its power is turned off. Furthermore, as it is in principle possible to reduce its standby power consumption to zero, it is expected to contribute to saving energy for information communication devices.

Against the backdrop of the global energy issues and the call for reduced power consumption in mobile devices, MRAM will take on more and more importance in the future. Due to its high resistance to cosmic radiation, it is also applied to flight recorders mounted in passenger aircraft.

In order to solve the challenges involved in semiconductor memory devices known as issues relating to the scaling limit and standby power consumption and to make constant contribution to increasing performance and reducing power consumption in information devices, it is imperative to miniaturize MRAM memory cells, as in the case of semiconductor devices.

Ferromagnetic materials can make a memory element of a few nanometers in size, which is far smaller than a capacitor used for semiconductor DRAM. However, it is difficult to write information to a micro-sized element, or more specifically, change the direction of magnetization of magnetic materials.

Figure 1 shows a schematic of MRAM to which information is written with the use of a magnetic field generated by an electric current, and that of MRAM made by using a phenomenon called spin-transfer torque (STT). Each schematic represents the structure of one memory cell. In an actual memory device, such cells are arrayed to increase capacity. In each of the MRAM cells, a magnetic tunnel junction (MTJ), which has a laminated ferromagnetic electrode/tunnel barrier/ferromagnetic electrode structure, is placed above the cell selection transistor.

In the case of MRAM based on magnetic field writing, as the device becomes smaller, the current that can be passed through the fine wire would become insufficient to write information to the memory. On the other hand, in the case of STT-MRAM, one ferromagnetic electrode (magnetization fixed layer) in the MTJ spin-polarizes the current, the spin angular momentum of the current is transferred to the magnetization of the other ferromagnetic electrode (recording layer), and the torque generated by this transfer causes magnetization reversal (record writing).

This is an interesting phenomenon in that, when the direction of the current flow is reversed, the direction of the magnetization of the recording layer is also reversed. At the same time, the current density is an important physical quantity, which means that a smaller device can cause magnetization reversal more easily. "Magnetization reversal induced by STT" is a new field in which research and development has become active recently and many issues that get into the very heart of magnetism and spin remain unsolved.

Ferromagnetic tunnel junction for STT-MRAM

Various properties are required of an MTJ that is to be used for STT-MRAM. The magnetoresistance effect, which is the most fundamental property, is defined by the ratio of tunnel resistance between the MTJ's parallel and antiparallel magnetization states (MR ratio), and it must be over 100% in order to achieve a practical readout characteristic. Furthermore, the critical current density (Jc) for STT writing must be smaller along with the miniaturization of the transistor.

In order to secure non-volatility of recorded information for a long time, it is necessary for the ferromagnetic electrode in the MTJ to have large magnetic anisotropy, as in the case of the recording medium in a hard disk drive. Research in magnetization dynamics has revealed that perpendicular magnetic films are effective for achieving this together with the reduction of Jc.

What is interesting is the importance of perpendicular magnetic anisotropy to both hard disks and MTJs. With regard to MTJs for STT-MRAM, toward achieving a high MR ratio and low Jc, it is further necessary to ensure that tunnel electrons have large spin polarization and a small magnetic damping constant. It is no exaggeration to say that the development of perpendicular magnetic anisotropy materials for MTJ is the deciding factor for the future of STT-MRAM. In order to complete high-performance perpendicularly magnetized films as MTJ devices, tunnel barrier materials need to be compatible with such films.

Thin magnetic films that demonstrate perpendicular magnetization

When an oxide layer such as one made of magnesium oxide is laminated on a thin film of ferromagnetic materials of 1 nm in thickness, strong perpendicular magnetic anisotropy is induced between the film and the oxide layer. With the use of perpendicularly magnetized MTJ devices produced using this phenomenon, research has been carried out actively toward achieving the application of MRAM.

We have worked on research aimed at elucidating how such perpendicular anisotropy occurs and how to induce greater perpendicular magnetic anisotropy, including the search for optimal materials.

We first paid attention to Co_2FeAl, which is known as a material that can achieve both a small damping constant and high spin polarization. We produced an ultrathin Co_2FeAl film of 0.8 nm in thickness on Cr, and found that by covering this film with MgO, we can make a perpendicularly magnetized film in which the energetically stable magnetization direction is perpendicular to the thin film surface. [1]

The magnetization curve shown in Fig. 2 represents the characteristic of Co_2FeAl ultrathin film that it is easily magnetized in the direction perpendicular to the film and not easily magnetized in the film surface direction. Theoretically, the existence of Fe is considered important in inducing such anisotropy at the interface. The finding that strong anisotropy can be induced on an ordered alloy material such as Co_2FeAl, which contains a large amount of Co and has a relatively complex structure, is interesting in the process of elucidating the physical origin of perpendicular anisotropy.

We also conducted research with the goal of finding the theoretical limit of interface-induced anisotropy in a structure that uses Fe as an ultrathin film layer. Figure 3 shows the magnetic anisotropy characteristic induced between the Fe layer of 0.7 nm in thickness and the MgO layer. [2] This structure, although it is simple, induced an extremely strong magnetic anisotropy to the extent that it can be applicable to a device that is as minute as 18 nm. As shown in electron microscopy images, we succeeded in demonstrating such a large magnetic anisotropy because we were able to produce a thin, flat mono-crystal of Fe consisting only of five atomic layers (upper part of Fig. 3). This ferromagnetic ultrathin film is expected to be applied to create large-capacity MRAM in the future.

New tunnel barrier materials: barriers with a spinel structure

At present, MgO is mainly used as a tunnel barrier material for MTJ devices. It is known that in the case of MTJ using an MgO barrier, a mechanism referred to as "coherent tunnel effect," which occurs when crystals are oriented to a certain direction, causes an increase in the effective spin polarization and results in a huge TMR ratio, as large as several hundred percent, at room temperature.

On the other hand, there has been no successful case where materials other than MgO could cause this effect and bring about that scale of TMR ratio at room temperature, and thus there was no option that could be used as a barrier material except for MgO.

Meanwhile, we recently succeeded in producing a high-quality monocrystalline $MgAl_2O_4$ with a spinel structure and found that it can serve as a barrier layer (Fig. 4). We also achieved a high room-temperature TMR ratio, over 300%, which made it clear that a spinel barrier is the first barrier material besides MgO that can bring about the coherent tunnel effect. [3]

Spinel is a stable material that is known as a kind of jewelry, and it does not have deliquescence as is found with MgO. We found that the size of the crystal lattice of spinel can be altered successfully by over several percentage by changing the methods and compositions for producing a spinel barrier, and therefore it is possible to create MTJ devices of extremely high quality which do not contain defects at the interface with the ferromagnetic materials.

The use of this novel barrier material developed by NIMS will make it possible to achieve a far greater TMR ratio and create a device in combination with perpendicular magnetic materials that have a complex crystalline structure, thereby opening the door to the creation of an innovative magnetic device in addition to STT-MRAM.

[1] Z. C. Wen, H. Sukegawa, S. Mitani, and K. Inomata, Appl. Phys. Lett. 98, 242507 (2011).
[2] J. W. Koo, S. Mitani, T. T. Sasaki, H. Sukegawa, Z. C. Wen, T. Ohkubo, T. Niizeki, K. Inomata and K. Hono, Appl. Phys. Lett. 103, 192401 (2013).
[3] H. Sukegawa, Y. Miura, S. Muramoto, S. Mitani, T. Niizeki, T. Ohkubo, K. Abe, M. Shirai, K. Inomata, and K. Hono, Phys. Rev. B 86, 184401 (2012).

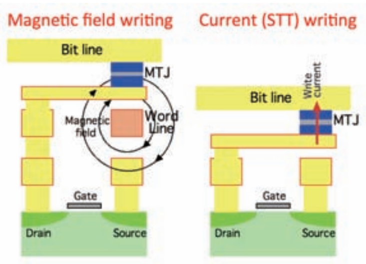


Fig. 1 Schematics of the structures of an MRAM cell based on magnetic field writing (left) and of an MRAM cell based on spin transfer torque (STT) writing

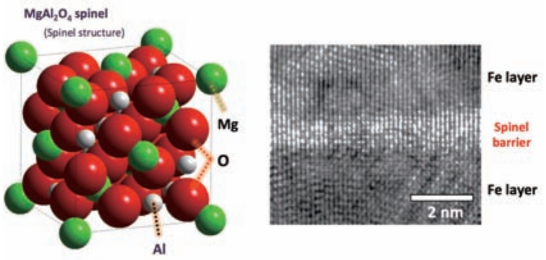


Fig. 4 Crystalline structure of $MgAl_2O_4$ (left). Cross-sectional electron microscopy image (TEM image) of a mono-crystal MTJ element composed of Fe/$MgAl_2O_4$ /Fe (right).

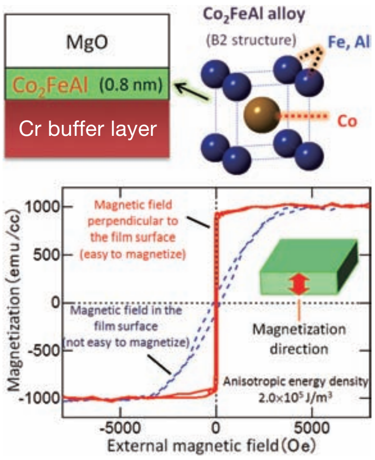


Fig. 2 Structure of a Co_2FeAl ultrathin film (upper left), crystalline structure of a Co_2FeAl alloy (upper right), and magnetization curve of a Co_2FeAl ultrathin film (lower graph). We obtained a perpendicularly magnetized film which was easily magnetized by a magnetic field perpendicular to the film surface.

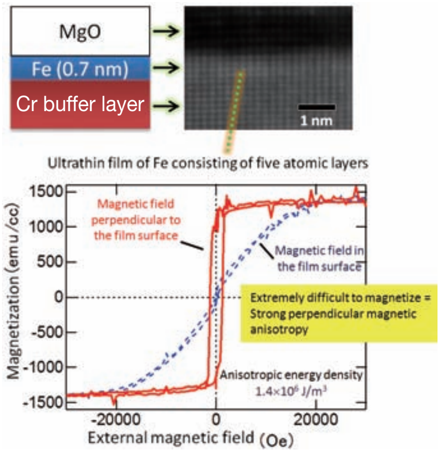


Fig. 3 (Upper) Schematic of the structure of an ultrathin film of Fe, and cross-sectional electron microscopy image (HAADF-STEM image) of a sample, showing mono-crystal growth of Fe consisting of five atomic layers. (Down) Magnetization curve of an ultrathin film of Fe, showing a considerably strong perpendicular magnetic anisotropy.

Profile

Seiji Mitani Ph. D (Engineering). Completed the doctoral course at the graduate school of Nagoya University and became a research associate at Tohoku University in 1993. Became an associate professor at Tohoku University in 2001 and joined NIMS in 2008. Has held the current position since 2009. Specialized in magnetic thin film materials, spintronics. / **Hiroaki Sukegawa** Ph. D (Engineering). Completed the doctoral course at the Graduate School of Engineering of Tohoku University in 2007, and has held the current position since that year. Specialized in magnetic thin films, spintronic devices.

New Paradigms for Spintronics Devices: The Spin Orbit Effects

Spintronics Group, Magnetic Materials Unit,
Environment and Energy Materials Division
Masamitsu Hayashi

Development of magnetization control technologies and their application to devices

In recent years, technology to control the magnetization direction of a ferromagnet with electric current has made significant progress. Recently, magnetic random access memory (MRAM) using this technology has been put to practical use. MRAM has the advantage of being faster and more energy-saving than semiconductor memories and has the potential to become a universal memory. However, technical issues remain for developing storage class memories to compete with hard disk drives and flash memories.

In order to increase the capacity of MRAM, the device size needs to be reduced. Key to achieving wider application of MRAM in the future will be to develop technology for controlling the magnetization direction of a nanosized ferromagnet with as low current as possible.

The current necessary for controlling magnetization of a ferromagnet depends primarily on two groups of physical parameters. The first group is the material parameters such as saturation magnetization, magnetic damping and spin polarization of the ferromagnet, and the second group is the shape and size of the device. By selecting materials with low magnetization/magnetic damping constants and high spin polarization, one can lower the current needed for controlling magnetization to a certain extent. One can also reduce the operating current by scaling the device size, but this has limits due to the difficulty in patterning devices below tens of nanometers at present.

Generation of a "spin current" with spin-orbit interaction

Materials with large spin orbit coupling is attracting great interest recently since it has the potential to reduce the current needed to manipulate magnetic moments.

In heavy metal elements with large spin-orbit interaction, such as Ta and Pt, a phenomenon called the Spin Hall effect is observed.

Normally, when an electric current is applied to metal, all electrons move in a direction opposite to the current flow, irrespective of their spin direction (Fig. 1 left). However, in materials with large spin-orbit interaction, the direction to which electrons move depends on their spin direction. For example, when we apply an electric current to Pt, whose Spin Hall effect is relatively large, spin-up (green) electrons move to the left, and spin-down (purple) electrons move to the right (Fig. 1 right). An important point to note here is that electrons whose spin direction is horizontal to the film surface move either up or down. In the case of Fig. 1, only electrons with spin pointing to the right (blue electrons) enter the film above the Ta or Pt layer.

This 100% spin polarized electron flow is called the "spin current." Expectations are growing for using spin current generated by the Spin Hall effect to control the direction of magnetic moments of a ferromagnetic layer, placed next to the heavy metal layer, with low operating current.

Magnetization switching technology using the Spin Hall effect

Figure 2 schematically illustrates an example of application using the Spin Hall effect to manipulate magnetic moments.[1] When an electric current is applied to the heavy metal layer, a group of electrons with an aligned spin direction, i.e. a spin current, flows into the ferromagnetic layer that is in contact with the heavy metal layer. Such spins will then exert torque on the magnetic moments of the ferromagnetic layer, and if the torque is strong enough, results in switching the direction of magnetization.

In contrast to the case of a current-perpendicular-to-plane device such as TMR or CPP-GMR (a type of device where the driving current flows perpendicular to the plane of the device), the current value required for magnetization switching in this device structure depends on the film thickness of the heavy metal layer, and magnetization switching can be triggered with low current, independent of the minimum processing size.

Recent studies have found that sufficient spin current can be generated for controlling magnetization even if the heavy metal (Ta) layer is only 1 nm thick.[2]

To develop devices using the Spin Hall effect, it is important to search for materials with even larger Spin Hall effect and/or to establish technologies for efficiently generating a spin current at the interface between the heavy metal layer and the ferromagnetic layer. We expect this research leads to the development of power-saving magnetic memory storage devices.

1) M. Yamanouchi et al., Appl. Phys. Lett. 102, 212408 (2013).
2) J. Kim et al., Nat. Mater. 12, 240 (2013).

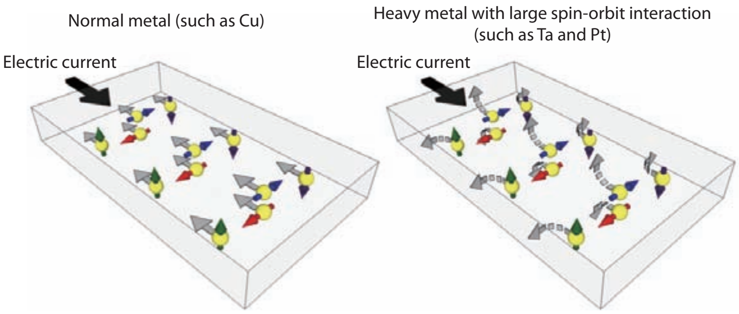


Fig. 1 Schematic illustrations of the motion of electrons when an electric current is applied to metal. Left: In a relatively light metal, such as Cu, electrons move in the same direction irrespective of their spin direction. Right: When an electric current is applied to a heavy metal with large spin-orbit interaction, such as Ta and Pt, the direction to which electrons move depends on their spin direction due to the Spin Hall effect.

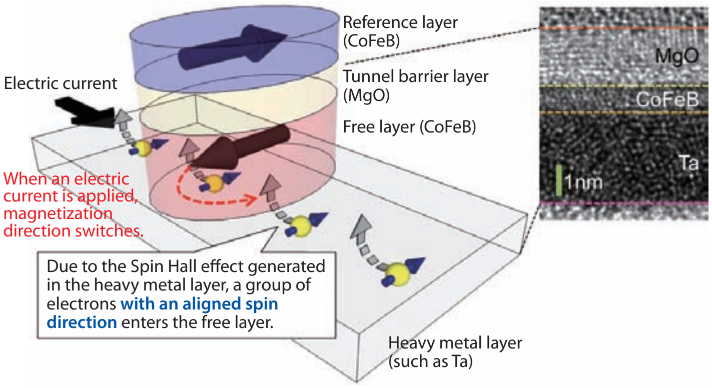


Fig. 2 Schematic of an MTJ device in which Spin Hall effect induced magnetization switching takes place. An MTJ device having three layers—ferromagnetic (free layer)/nonmagnetic (tunnel barrier layer)/ferromagnetic (reference layer)—is positioned above the heavy metal layer (such as Ta), and an electric current is applied to the heavy metal layer to control the magnetization of the free layer. Right: Cross-section TEM image of the heavy metal layer, free layer and tunnel barrier layer.

Profile

Masamitsu Hayashi Ph.D. Completed M.S. at Tohoku University and received Ph. D. from Stanford University. After serving as a postdoctoral researcher at the IBM Almaden Research Center, joined NIMS as a Principal Researcher in 2008.

New Ecological Power Generation Technology through the Use of Anomalous Nernst Effect in Magnetic Materials

Magnetic Materials Group, Magnetic Materials Unit,
Environment and Energy Materials Division
Yuya Sakuraba

A new thermoelectric generation method

When a thermal flow is applied to electric conductive materials such as metals and semiconductors, this induces a flow of charge carriers such as electrons and holes coaxially with the thermal flow. This phenomenon is called the Seebeck effect.

As the Seebeck effect causes direct conversion from thermal energy to electric energy, it has attracted great attention for a long time for its potential to be used in ecological thermoelectric generation, which uses waste heat discharged from primary power generation or environmental heat such as solar heat and geothermal heat.

However, the Seebeck effect also has a problem in that, since the thermal flow and the electric flow occur coaxially, it is unavoidable that the power generation module has a complex structure wherein n-type and p-type semiconductors are aligned alternately and their tops and bottoms are connected in series, as described in Fig. 2(a), in order to raise the voltage.

To solve this problem, we have proposed an idea of applying the anomalous Nernst effect, which occurs in magnetic materials, to thermoelectric power generation, and have engaged in research to increase the power generation efficiency using this effect in recent years.

The anomalous Nernst effect is a phenomenon in which, when thermal gradient ∇T is applied to a magnetic material magnetized in a certain direction M, an electric voltage occurs in the direction of their cross product (the direction that is orthogonal to both M and ∇T) (Fig. 1(b)). Although, at the present stage, the thermoelectric power caused by the anomalous Nernst effect is not more than 10% of that caused by the Seebeck effect, the anomalous Nernst effect is expected to achieve new applications that cannot be achieved by the conventional thermoelectric generation technology, by making use of its characteristic that the thermal flow and the electric voltage cross at right angles.

Application through the use of large-area heat sources and three-dimensional heat sources

The anomalous Nernst effect generates the electric voltage to the perpendicular direction of the thermal flow. Therefore, with the use of a very simple structure created by arranging a wire made of magnetic materials across the surface of the heat source and connecting both ends of the wire in series, as described in Fig. 2(b), it is possible to increase the electric voltage in proportion to the length of the wire. This can be achieved without using two magnetic materials that generate the electric voltage in opposite directions, but just by making the same magnetic material having different levels of coercivity and thereby making their directions of magnetization opposite to each other alternately. This characteristic has not been seen in the conventional thermoelectric generation technology.

Furthermore, by making use of the characteristic that the electric voltage occurs to the parallel direction to the surface of the heat source, it will be easy to use a heat source with a three-dimensional and distorted-shaped structure. For example, when a magnetic wire is coiled around a cylinder-shaped heat source, as described in Fig. 2(c), and its direction of magnetization is aligned along the longitudinal direction of the cylinder, the electric voltage always occurs tangential to the cylinder, and voltage output in proportion to the length of the wire can be obtained.

In short, while the conventional Seebeck effect is a one-dimensional phenomenon, the anomalous Nernst effect has a three-dimensional nature in terms of the thermal flow, magnetization and electric voltage, and the use of this characteristic will open the door to new applications with a broader spacial degree of freedom.

The improvement of thermoelectric power and generation efficiency remains as a challenge that must be overcome in the future. However, the recent research in spintronics has revealed that the control of the spin scattering mechanism in magnetic materials is expected to considerably improve thermoelectric power. We will continue tackling materials development from a nano-level perspective.

[1] Sakuraba et al., Appl. Phys. Express 6, 033003 (2012).

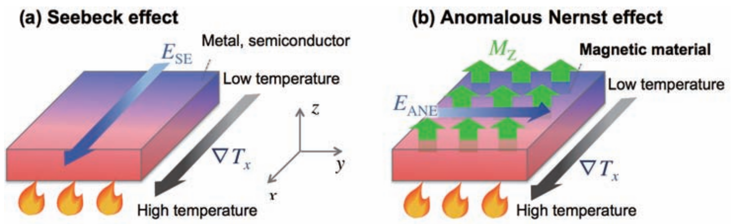


Fig. 1 **(a)** Seebeck effect; **(b)** anomalous Nernst effect, a phenomenon in which an electric voltage occurs in the direction of the cross product of magnetization M and thermal gradient ∇T.

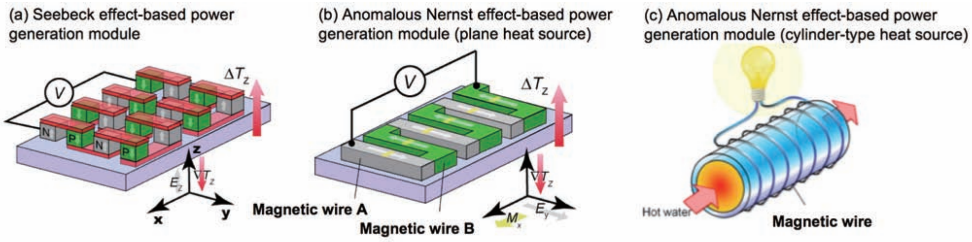


Fig. 2 Diagrammatic illustrations of **(a)** Seebeck effect-based power generation module, and **(b)(c)** anomalous Nernst effect-based power generation modules.

Profile

Yuya Sakuraba Ph.D (Engineering). Completed the doctoral course at the Department of Applied Physics, School of Engineering, Tohoku University in 2006, and became an assistant professor at the Institute for Materials Research, Tohoku University (Magnetic Materials) in 2007. Senior Researcher of the National Institute for Materials Science since 2013.

Designing Optimal Microstructure for Nd-Fe-B Permanent Magnets

Nanostructure Analysis Group,
Magnetic Materials Unit,
Environment and Energy Materials Division
Taisuke Sasaki

Group Leader, Nanostructure Analysis Group,
Magnetic Materials Unit,
Environment and Energy Materials Division
Tadakatsu Ohkubo

Nd-Fe-B permanent magnets are currently used in traction motors for hybrid vehicles etc. There are strong demands for the development of higher performance Nd-Fe-B magnets at low cost. Since the performance of the magnet strongly depends on its microstructure, the best way to develop the high performance magnet is to fully understand the relationship between the microstructures and magnetic properties via the use of state of the art characterization instruments such as electron microscopes (e.g., atomic resolution transmission electron microscope, high resolution scanning electron microscope), 3D atom probe, and micromagnetic simulation. Based on the knowledge gained from the characterization, we propose guidelines for designing a microstructure that can educe the inherent characteristics in Nd-Fe-B magnets.

Microstructure of neodymium magnets

As shown in Fig. 1, the commercially available Nd-Fe-B permanent magnet consists of $Nd_2Fe_{14}B$ magnetic phase with the size of ~ 5 µm, Nd-rich phases located at the grain boundary triple junctions of the $Nd_2Fe_{14}B$ phase, and thin Nd-rich grain boundary phases with only a few nanometers in thickness formed along the grain boundaries. To improve the magnetic property, particularly the coercivity, the most important is to de-couple the magnetic coupling between the neighboring $Nd_2Fe_{14}B$ grains, which could cause the ease spread of the reversal domains throughout the magnet upon applying reversal magnetic field. The Nd-rich thin grain boundary phases can be a barrier for the domain wall motion, and has a decisive impact on the prevention of the magnetization reversal. To control the formation of the Nd-rich thin grain boundary phases, the dispersion of the metallic Nd-rich phases located at the grain boundary triple junctions would be critical, since the Nd in the thin grain boundary phases is supplied from the metallic Nd-rich phase during final heat treatment.

Towards the complete understanding of microstructure by nano-/micro-structure characterization

In fact, there are various types of Nd-rich phases, e.g., oxides such as NdO_x and Nd_2O_3, and borides like $NdFe_4B_4$ and the metallic Nd. While conventional imaging technique, backscattered electron imaging in scanning electron microscope (BSE-SEM) allows us to observe the Nd-rich phases with brightly imaging contrast, all of the Nd-rich phases are imaged with similar contrasts making it difficult to identify each phase unambiguously (See BSE in the upper part of Fig. 2). However, the imaging contrast seen in the secondary electron image acquired using an in-lens type detector is different from phase to phase (See IL-SE on the upper part of Fig. 2).

The imaging contrast in the SEM image does not provide any information on the phase. To correlate the imaging contrast in SEM and the phase, we look into the same region of interest by SEM and transmission electron microscope (TEM), which can analyze the elemental distribution and structure (as shown in the lower part of Fig. 2). Once they are correlated, we can unambiguously identify all the Nd-rich phases, and the distribution of each phase can be understood from the SEM images. [1)]

Achieving high coercivity in Dy-free Nd-Fe-B magnets by nano- and atomic- structure control

To gain more about the structure and chemistry of the thin Nd-rich grain boundary phases (Fig. 3), atomic resolution TEM, and 3D atom probe (3DAP) are used to provide critical information on the structure in nano- and atomic-scale. This state-of-the-art analysis unveils the interesting characteristics of the Nd-rich thin grain boundary phase. The Nd-rich grain boundary phases have been believed to be a non-magnetic phase, however, recent observations suggest that it is a ferromagnetic phase. The ferromagnetism of the grain boundary phases are being proved by various approaches. Based on the information on the characteristics of the grain boundary phases, and other microstructure features (Fig. 3), we look into the details on the microstructure-magnetic property relationship by micromagnetic simulation, and design the optimal microstructure. We are also trying to develop a process for fabricating the optimal structure at a laboratory level.

1) T.T. Sasaki, T. Ohkubo, K. Hono, Y. Une, M. Sagawa, Ultramicroscopy, 132 (2013) 222.

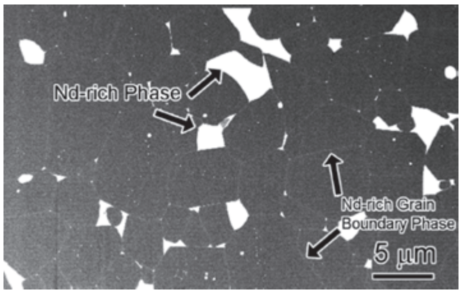


Fig. 1 SEM image of the microstructure of a Nd-Fe-B magnet.

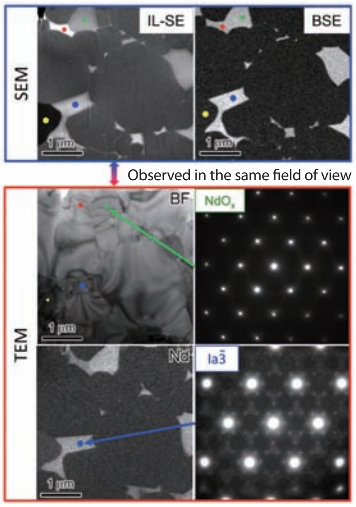


Fig. 2 Example of the correlative SEM/TEM characterization for unambiguous phase identification of various Nd-rich phases in a Nd-Fe-B magnet.

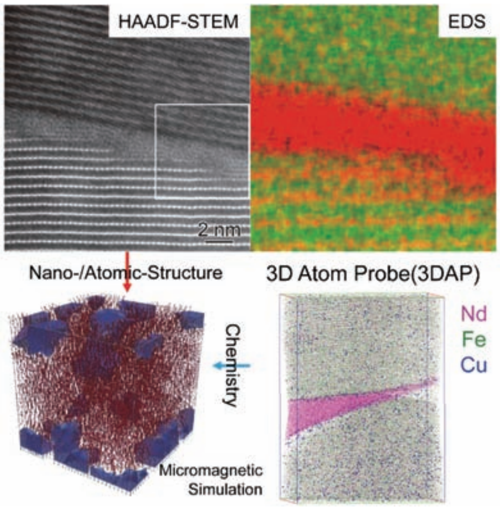


Fig. 3 Observations of the Nd rich grain boundary phase by the atomic resolution HAADF-STEM-EDS and 3DAP, and micromagnetic simulation.

Profile

Taisuke Sasaki Ph. D (Engineering). Researcher. Completed the doctoral course at the graduate school of the University of Tsukuba in 2008. Has held the current position since 2011 after serving as a post-doctoral researcher at the University of Alabama, U.S.A. **/ Tadakatsu Ohkubo** Ph. D (Engineering). Group Leader. Graduated from Creative Design & Engineering of Nagaoka University of Technology in 1989. Joined NIMS in 2002, and after serving as the Senior Researcher, has held the current position since 2006.

Dysprosium-free Neodymium Magnets for Automotive Applications

Unit Leader,
Magnetic Materials Unit,
Environment and Energy Materials Division
Kazuhiro Hono

NIMS Postdoctoral Researcher,
Elements Strategy Initiative Center for Magnetic Materials
Takahiro Akiya

NIMS Postdoctoral Researcher,
ICYS-SENGEN
H. Sepehri-Amin

Group Leader, Nanostructure Analysis Group,
Magnetic Materials Unit,
Environment and Energy Materials Division
Tadakatsu Okubo

Ultrafine-grained neodymium magnets

The quantity of neodymium magnets used in traction motors for hybrid vehicles has been rapidly increasing recently. Since the temperature of this magnet rises to nearly 200°C during use, about 8% dysprosium must be alloyed in the neodymium magnets to make them heat-resistant. Dysprosium is categorized as a rare metal that has high geopolitical risk in stable supplies for industrial use. Thus, finding a way to improve the heat resistance or coercivity of neodymium magnets without using Dy has been strongly desired.

High-performance commercial neodymium magnets are manufactured by the sintering process. The coercivity of the sintered magnets is empirically known to increase with decreasing grain size. In a laboratory scale, a high coercivity of 2 tesla (T) was reported for a grain size of 1 μm. However, further reduction of the grain size below 1 μm is technologically challenging because of the explosive nature of fine powders of rare earth alloys.

Ultrafine-grained magnets can be manufactured by hot-pressing and hot-deforming rapidly-solidified neodymium alloy powders. These hot-deformed magnets have platelet-shaped grains of approximately 300 nm in width and 50 nm in height. The hard magnetic properties of such hot-deformed magnets are comparable to those of sintered magnets with a coercivity of about 1.2 T. However, considering the ultrafine grain size, the coercivity is too low. One possible reason for the disappointedly low coercivity for their fine grain size is the exchange coupling of the ultrafine crystal grains through a ferromagnetic intergranular phase.

Coercivity enhancement by magnetic isolation of ultrafine grains

As a method to magnetically decouple grains, we developed the "eutectic diffusion process" by which a nonferromagentic intergranular phase is formed by infiltrating low melting temperature Nd-Cu alloy. Although this process dramatically increases the coercivity of hot-deformed magnets, remanent magnetization is substantially decreased due to the increase in the volume fraction of the nonferromagnetic phase. When we applied the eutectic diffusion process to bulk samples, we found that a notable sample expansion occurs only in the perpendicular direction to the flat surface of the platelets. Thus, we have applied a constraint to the volume expansion along the c-axis during the eutectic diffusion process to achieve minimization of the remanence loss.

When the eutectic diffusion process was applied, the coercivity, which is an index of heat resistance, increased to 1.97 T, while the residual magnetization decreased to 1.27 T. This was due to the increase of the non-magnetic $Nd_{70}Cu_{30}$ intergranular phase by the infiltration of Nd-Cu alloy. This also induces the expansion of the thickness of the magnet by 9%. To solve this problem, we constrained the volume expansion during the eutectic diffusion process and controlled the fraction of the non-magnetic intergranular layer. As a result, we were able to maintain a residual magnetization of 1.36 T, while increasing the coercivity to 1.92 T.

Figure 2 shows the microstructures before and after the Nd-Cu diffusion treatment and their schematics. Before the diffusion treatment (a), the areal fraction of the grain boundary phase is small, suggesting that the grains are magnetically coupled. After the diffusion treatment (b), the thickness of the grain boundary layer substantially increased. As a result, the residual magnetization decreased by 8.6%. On the other hand, when the diffusion treatment was conducted under an expansion constraint, the quantity of the Nd-Cu layer diffused within the magnet was restrained at a moderate level. The orientation of the magnetic grains was also maintained, and this in part contributed to minimizing the decrease in the magnetization.

Hard magnetic properties comparable to dysprosium-containing neodymium magnets

As shown in Fig. 3, the room temperature coercivity of the hot-deformed magnet that was diffusion processed with an expansion constraint is slightly smaller than that of a commercial 4% dysprosium-containing neodymium sintered magnet, but its temperature dependence is lower than that of the 4% dysprosium-containing sintered magnet. This is an outstanding effect of the fine grain size. The maximum energy product of the magnet that was diffusion processed under the expansion constraint is 190 kJ/m^3 at 200°C, a level required for electric vehicles and wind power generators. Although its coercivity is still insufficient, this magnet has proved to have a maximum energy product larger than those of the dysprosium containing sintered magnets.

In summary, we have developed a eutectic diffusion process with an expansion constraint as a method to achieve high-coercivity and high-energy-density in Dy-free Nd-Fe-B magnets, i.e., coercivity of 2 T, remanent magnetization of 1.36 T and the energy density of 358 kJ/m^3 at room temperature. Because of the low-temperature coefficient of coercivity for the ultrafine grain size, coercivity of 0.5 T with a $(BH)_{max}$ of 191 kJ/m^3 was achieved at 200°C. This Dy-free magnet outperforms the 4%Dy-containing (Nd,Dy)-Fe-B sintered magnet.

T. Akiya, J. Liu, H. Sepehri-Amin, T. Ohkubo, K. Hioki, A. Hattori, K. Hono, High-coercivity hot-deformed Nd-Fe-B permanent magnets processed by Nd-Cu eutectic diffusion under expansion constraint, Scripta Mater. 2014; http://dx.doi.org/10.1016/j.scriptamat.2014.03.002

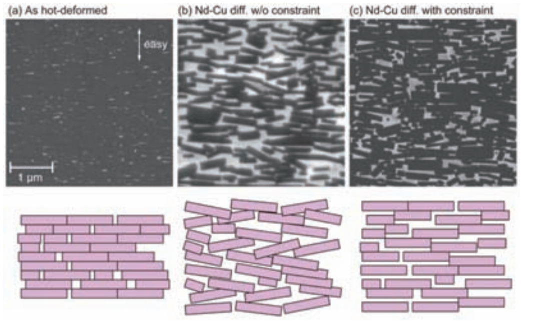


Fig. 2 Comparison of microstructures before and after the Nd-Cu diffusion treatment. The direction of magnetization is perpendicular to the flat surfaces of the platelet-shaped grains. The grey area represents magnetic grains and the white area represents non-magnetic grain boundary layers. **(a)** before the diffusion treatment, **(b)** after the ordinary diffusion treatment, and **(c)** after the diffusion treatment with an expansion constraint.

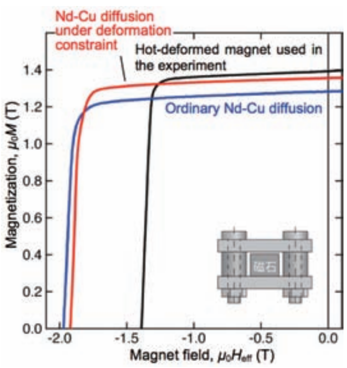


Fig. 1 Demagnetization curves of the samples before and after the Nd-Cu diffusion treatment.

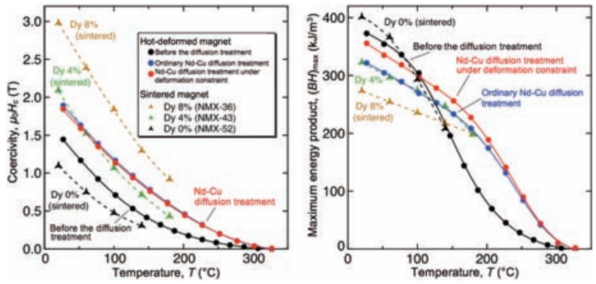


Fig. 3 Temperature changes in the coercivity and maximum energy product with regard to the hot-deformed magnet produced in this research and the sintered magnet commercially available.

Profile

Kazuhiro Hono For his profile, see page 4. **/ Takahiro Akiya** Ph. D (Engineering). Completed the doctoral course at the Graduate School of Engineering of Tohoku University (Applied Physics). Holds the current position of Postdoctoral Researcher at NIMS since 2012 after serving as an assistant professor at the New Industry Creation Hatchery Center of Tohoku University. **/ Hossein Sepehri-Amin** Completed Ph. D. degree at the University of Tsukuba on March 2011. He has been working as ICYS-fellow in international centre for young scientists, NIMS since September 2011 to present. **/ Tadakatsu Okubo** For his profile, see page 9.

Permanent Magnet Research Network at the Elements Strategy Initiative Center for Magnetic Materials

Director, Elements Strategy Initiative Center for Magnetic Materials (ESICMM)
Satoshi Hirosawa

Purpose of establishment of the Elements Strategy Initiative Center for Magnetic Materials

The Elements Strategy Initiative Center for Magnetic Materials (hereinafter referred to as "ESICMM") was established within NIMS in August 2012, as the element strategy initiative center under the Research Center Project sponsored by the Ministry of Education, Culture, Sports, Science and Technology, which is dedicated to promoting research on the challenges of permanent magnets.

ESICMM has declared its goals as (1) maximizing the properties of magnetic materials currently in use, without using rare elements, and (2) searching for novel substances and thereby finding new magnetic materials using only elements that exist in abundance everywhere.

At ESICMM, established for the purpose of solving these challenges through thorough investigation into materials science in magnetics, research activities are being led by 18 principal investigators who belong to the eight research institutions shown in Fig. 1 as theme leaders. The list of researchers and their research details can be seen on the NIMS website (http://www.nims.go.jp/ESICMM/).

About 150 researchers work at ESICMM, and 31 of them are NIMS researchers (as of January 2014). These researchers belong to one of three groups, (1) the Computer Physics Group, (2) the Structural and Property Characterization Group, or (3) the Materials Processing Group. The aim of ESICMM in whole is to form a network of researchers beyond the boundaries of the respective research groups, make large-scale research facilities such as SPring-8, J-PARC and the K computer, available to them, and thereby promote joint research and create breakthroughs from a new perspective which has been lacking in conventional magnet research.

New challenges in magnetic materials research

When the strength of a magnetic field, which is applied in a direction opposite to magnetization, exceeds the threshold called coercivity, the magnetization of the magnet is inverted irreversibly (magnetization reversal), and the magnet is no longer able to generate a magnetic field as a permanent magnet. In order to prevent this phenomenon from occurring in motors or generators while in use, permanent magnets must have high coercivity.

However, the coercivity of a neodymium magnet decreases when its temperature rises. Therefore, in order to use neodymium magnets at the temperatures that occur in hybrid vehicles, it is necessary to increase their coercivity to a much higher level.

Rare earth elements such as dysprosium (Dy) and Terbium (Tb) are used despite their associated resource problems because it is possible to increase the coercivity of magnets by replacing part of Nd with these elements.

High-performance neodymium magnets with high coercivity are used in drive motors and energy recovery generators mounted on hybrid vehicles and electric vehicles, and as a result, the amount of use of neodymium magnets has been increasing explosively. The demand for neodymium magnets is expected to further increase in the future along with the demand for their use in off-shore wind power generation, causing a concern over the procurement of rare earth elements to be used to make these magnets, such as Nd, Dy and Tb. If we continue to use Dy and Tb at the current pace, we will deplete these elements before too long.

Elements strategy in permanent magnet research

A strategic approach relating to the use of elements in the course of research and development of magnets is to thoroughly investigate into the coercivity control mechanism and the causes of the material structure, and find a method to increase coercivity without using rare earth elements.

Magnetization reversal occurs when the magnetic field applied to the magnet exceeds its coercivity, causing the creation and spread of a magnetic domain in an opposite direction (reverse magnetic domain) to the unidirectional magnetic domain saturated in the magnet. The boundary between the magnetic domain and the reverse magnetic domain is called a magnetic domain wall, inside which the magnetization vector is distorted over a small range of a few nanometers (Fig. 2).

Magnetic domains and magnetic domain walls are purely magnetic structures and they can exist independently of the material structures. However, if the material structure has the same size as the magnetic domain wall, a magnetic structure like a magnetic domain wall may be easily created or the magnetic domain wall strongly interacts with the material structure and may be pinned there.

In rare earth magnets such as neodymium magnets, the magnetic domain wall is extremely thin, about 4 nm in thickness, which is the relative size at which the atoms that make up the materials would be recognized as discrete objects. Therefore, if a distortion of a nanometer in size in the atomic arrangement exists in the magnet, this greatly affects and changes the coercivity.

For example, a neodymium magnet is made of a large number of $Nd_2Fe_{14}B$ crystals. The boundary between the crystals (crystal grain boundary) has a structure of a few nanometers in width.

In order to understand the factors that cause such a change in coercivity, it is necessary to conduct material analysis and kinetic analysis of magnetization within a minute range of a sub-nanometer scale. Theoretical development for understanding the relationship between the minute structure and coercivity is also a challenge to overcome.

Network of researchers

ESICMM provides a framework so that researchers can freely travel between the analysis and evaluation platform and the theoretical research platform (Fig. 3) and carry out research activities collaboratively. NIMS researchers serve as the key members among them.

Many research teams participate in the research activities at ESICMM such as: a team of experts in multiscale structure analysis from the atomic scale to the nano-micrometer scale; a magnetic structure analysis team using synchrotron radiation X-ray facilities (SPring-8 and Photon Factory) and a high-intensity neutron source (J-PARC); a team of theorists predicting the magnetic properties of magnetic compounds that have complex crystalline structures (e.g. $Nd_2Fe_{14}B$) and the magnetic nature of the boundary interface, through a large-scale theoretical calculation using the K computer; a theoretical analysis team calculating the kinetic features of the magnetic domain wall motions in magnetic materials, which is a multi-crystalline aggregate, based on the results of theoretical calculations; and a team observing the process of formation of magnetic domains and analyzing the process of their time development.

Initially, the researcher groups in different fields of expertise engaged in research independently, using different terminologies and unit systems for physical values. However, as they are working toward common goals at ESICMM, considerably vigorous collaboration through the fusion of various fields is being created. It is expected that the industry community will make great use of ESICMM as a temple of basic research in magnets.

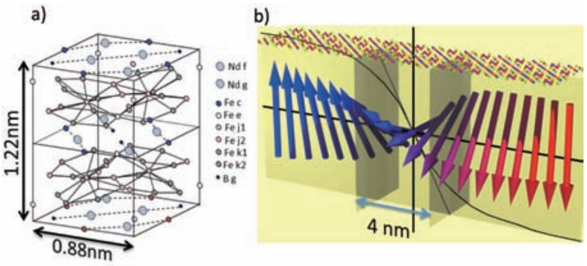


Fig. 2 Comparison in size between the crystalline structure and the magnetic domain wall structure of $Nd_2Fe_{14}B$ compound. The arrows represent magnetization vectors, and the circles represent the locations of Fe (●), Nd (●) and B (●) on the bottom surface of the crystalline structure drawing. The vertical straight line represents the direction of the easy axis of magnetization of crystals [001], the horizontal straight line represents the direction normal to the magnetic domain wall, the shaded planes represent surfaces the magnetic domain wall, and the curve represents the rotation angle of the magnetization vectors. The tangent to the curve shows a rough indication of the width of the magnetic domain wall with which the surfaces of the wall are defined.

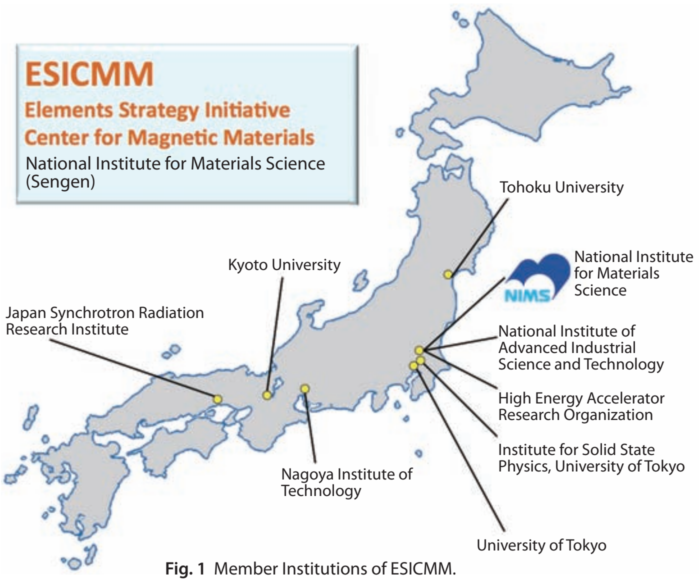


Fig. 1 Member Institutions of ESICMM.

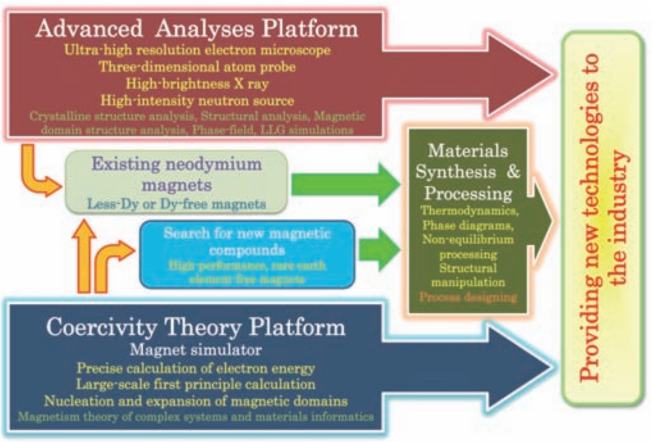


Fig. 3 Research themes of the research groups at ESICMM and the role of the research platforms.

Profile

Satoshi Hirosawa Ph. D (engineering). Completed the doctoral course at the graduate school of Kyoto University in 1981. After serving as a post-doctoral researcher at the University of Pittsburgh and then Carnegie Mellon University, worked for Sumitomo Special Metal Co., Ltd. between 1984 and 2004, NEOMAX CO., Ltd. between 2004 and 2007, and then Hitachi Metals, Ltd. between 2007 and 2012. Became a NIMS Special Researcher thereafter. Specialized in research and development of rare earth magnets.

NIMS NEWS

1 NIMS Signs a Comprehensive Collaborative Agreement with Temple Materials Institute in US

On January 27th, NIMS President Prof. Sukekatsu Ushioda signed a Comprehensive Collaborative Agreement (CCA; a sister institute agreement) with Temple Materials Institute of Temple University in US together with its Director, Prof. Michael L. Klein. Temple University (TU) is one of the state universities in Pennsylvania, established in 1884, and quite familiar to the Japanese due to its Tokyo Campus. Temple Materials Institute (TMI) was established in 2009 with the founding director Prof. Klein, recruited from University of Pennsylvania. Since then, TMI has vigorously recruited more than 40 prominent professors, strongly promoting the materials research at TU, and now it is one of the world-renowned research institutes dedicated to materials science. In particular, TMI scientists have shown tremendous achievements in theoretical and computational materials sciences. Together with the International Cooperative Graduate School Agreement now being negotiated, this CCA will certainly enhance the collaboration between two institutions.

President Ushioda and Director Klein after the signing ceremony.

2 ENERGY TECHNOLOGY RESEARCH - ENERGY POLICIES Workshop was held at the Gstaad in Switzerland

On March 9-12, in the frame of 150th anniversary of diplomatic relation between Switzerland and Japan, ENERGY TECHNOLOGY RESEARCH - ENERGY POLICIES was held at the Gstaad in Switzerland, sponsored by Japan Science and Technology Agency (JST), Swiss Federal Office of Energy and NIMS.

More than 20 prominent scientists and 20 promising young scientists in the field of energy research from both countries reported their latest research results. And poster session was also presented by young researchers. They exchanged very vigorous questions and discussions on this theme during 4 days. On the first day, the workshop had the honor of a visit by Ambassador Mr. Maeda from Japan Embassy. He delivered an opening address and expressed his strong expectations for the research cooperation between the two countries. This workshop would be an excellent opportunity to accelerate the collaboration on energy research between the two countries.

Participants of the workshop.

Hello from NIMS

Dear NIMS NOW readers,

This is Himansu wish to welcome all the readers of NIMS NOW International who are going through my column. I feel privileged to get this chance to share few words from my own experiences during my research career at NIMS. In my knowledge, NIMS is the big motivator for me to choose Japan for my graduate study. I still remember when I joined here and met a post doctoral researcher in campus, graduated from a well recognized university from US, and asked him, how he rate NIMS in his experience compared to the schools in US. His reply for me was, it is very hard to find this amount of material research facilities under a single roof, even in top 10 universities of US. After this experience, three years has been passed and my own experience came into the picture. I can just say NIMS is an amazing place for the students who wish to perform his/her graduate studies here. Staying in Tsukuba, an international science city with its calm green environment, as well as conducting research in NIMS is extremely advantageous for targeting high quality research even at graduate level. The graduate school is a kind of stringent program and requires certain numbers of publications in stipulated number of years, and it can give a big boost over your future research career within a very short time. Although its sounds pretty hard to accomplish the job, the world class facilities at NIMS makes it quite easier to achieve the desired goal to realize one's dream. Furthermore, working with world leading material scientists is a rarest opportunity in one's career to exercise his/her ability. In my vision, I can rate NIMS as one of the top 5% institutes in the world in materials science to cultivate the future professional materials scientists. Additionally, life in Japan is much easy with the extreme kindness and generosity of Japanese people.

Himansu Sekhar Nanda(Indian)
From April 2011 - present
NIMS Junior Researcher, Tissue Regeneration Materials Unit, MANA

At Mt. Fuji.

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cover image: laser assisted wide angle 3D atom probe

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