Tune

03
JANUARY
2016

Tohoku University Research News of Engineering

From KS Steel to Spintronics

Toward the Spintronics Powerhouse

Junsaku NITTA × Gerrit BAUER

Research Highlight

Yasuo ANDO　Tetsuo ENDOH

TOHOKU UNIVERSITY

General Introduction

Tohoku University is renowned around the world as an institution with exceptional strengths in research of materials. In particular the Department of Materials Sciences and Engineering's programs are recognized as being the best in the world. It boasts a long history, having initially started off as Japan's first metals engineering department. It is here that the study of magnetic materials was started with the establishment in 1916 of the strongest magnetic material at that time; the KS steel. And it is here that the study of today's spintronics is gathering steam. Closely related to magnetism, spin is a property of elementary particles complementing charge and mass. Spin in electrons causes a behavior of miniature bar magnets. In the first application cases, spintronics made use of charge in addition to spin of the electrons such as giant magnetoresistance (GMR). Spin has been understood and accepted in physics since the 1920s. It took nearly three-quarters of a century for commercial exploitation to be realized. The application of spintronics is one of the most promising technological fields, as in storage devices with heads in hard disc drives that harness GMR, which results from spin, realized about a decade after GMR gained general recognition. Marked data density increases were enabled upon use of said spin as well as charge of solid-state materials. Spintronics - originated from the words "spin" and "electronics" - entails both the "off " and "on" electrical charges as well as the "down" and "up" magnetic spin (of electrons) to store information, among other activities covered by ferromagnetic materials, and is classified as a discipline under "condensed matter physics." The study of spintronics also enables device makers to place more information on a single processor in a "nonvolatile" fashion. It enables realization of circuits that consume less power and yet faster and denser than circuits that utilize just charge degree of freedom of electrons. The low power consumption of integrated circuits is critical for emerging applications such as Internet-of-Things (IoT) that connect everything in the world to the Internet. Further spintronics applications in sight include highly sensitive room-temperature magnetic sensors aiming at replacing magnetic resonance imaging (MRI) currently in use, but with refrigeration. Or heat-to-electricity conversion via spin current that enables thermoelectric power generation by a thin film, even painted film. There are more to come. Why not join!

Hideo OHNO
Professor and director,CSIS

From KS Steel To Spin-tronics

Cross Talk Interview

Text by S."Tex" POMEROY / Photographs by Masayoshi HARABUCHI

J.NITTA × G.BAUER

Tohoku University: A Spintronics Powerhouse

Up or Down, that's the Question

Now that traditional electronics is faced with "barriers" to Moore' Law such as excessive heat generation, the scientific pursuit for alternatives is becoming increasingly important. We had two leading lights in spintronics, namely Prof. Junsaku Nitta and Prof. Gerrit Bauer, discuss the current status of research at Tohoku University. They combine the experimentation prowess of Prof. Nitta with theoretical expertise of Prof. Bauer; together they strive to bring spintronics to an even higher level of understanding, for curiosity and in order to facilitate novel applications. Both approach that goal by looking beyond the conventional notion that the intrinsic angular momentum of the electron is digital, i.e. either up or down, since quantum mechanics allows the "spin" to point in any direction. Concrete results have been achieved, e.g., Prof. Nitta demonstrated electric (rather than magnetic) control of the spin rotation by making use of relativistic physics, while Prof. Bauer proposed new theoretical concepts such as magnetic nanostructures that can be switched by heat and may improve the efficiency of thermoelectric heat recovery.

– Prof. Nitta, Prof. Bauer, thank you for your time. Can you each provide our readers with a short self-introduction including the research now being conducted?

Junsaku Nitta: I had been a researcher after my graduate studies for Nippon Telegraph and Telephone Public Corp. (which is now NTT Corporation) in Japan. I then took on a variety of research activities related to my areas of interest in different locations, before I came to settle down here at Tohoku University. I am interested in the control of quantum states and devices, and am presently focused on spintronics. Actually I suppose I have been fascinated in "spins" since my elementary and junior/senior high school days when I was more concerned about soccer at first and then tennis, rather than studying. The difference is that now it is not a ball that I wish to exercise control over but the spin at the atomic level for materials in the smallest of all particles, the electron.

Gerrit Bauer: I followed a rather winding road to spintronics and Tohoku University. I was born in Germany, studied Chemical Engineering in the Netherlands and experimental physics in Germany again. I daresay I was also interested in the "bigger" picture, venturing out to Japan from 1984 to 1986, to conduct research at the Institute for Solid State Physics (of the University of Tokyo). Following my Japan stay I joined Philips' laboratories back in the Netherlands prior to becoming a Delft University of Technology professor. Only in my last days at Philips I was converted to spintronics and I am still devoted to the discipline today. I am now a regular professor at Tohoku University, living in Sendai (without my family like many of my Japanese colleagues), but I still maintain ties with Delft.

JN: Yes the grueling travels by Prof. Bauer in his quest for academic advances are well known amongst his friends and colleagues! In fact I am particularly glad that he can gather much information about spintronics and related research from around the world through his extensive professional network.

GB: And I am all too happy to share such information with Prof. Nitta and the other leading-edge researchers here at Tohoku University, which is renowned for its experimental research prowess worldwide. I think we can create much synergy by combining our individual fortes. Regarding my specific area of research now, I might classify myself as an applied theoretical physicist with an interest in devices. It is kind of surprising that I was more theory-oriented whilst at Philips. I enjoy working in the field of spintronics because it combines interesting physics with real-life applications. The rapid succession of new developments keeps the subject alive, recently by contributions of researchers from other fields such as phononics and photonics.

DEFINING SPINTRONICS WITHOUT DIRECTIONS?

— Might each of you provide us with a definition of "spintronics" - what is spintronics? What are the differences between "spintronics" and conventional "electronics"?

JN: Let me try defining the field from the solid state device stance: spintronics aims at the control of both charge and spin degrees of freedom of electrons in a variety of materials such as semiconductors, ferromagnetic metals and insulators. Spintronic devices are capable of communication, storage, and logic. The next generation of computers based on spintronics hardware turn on instantly, not needing to reload data and programs from magnetic hard drives or from solid state drives such as flash memories. They are faster and consume less power than conventional computers.

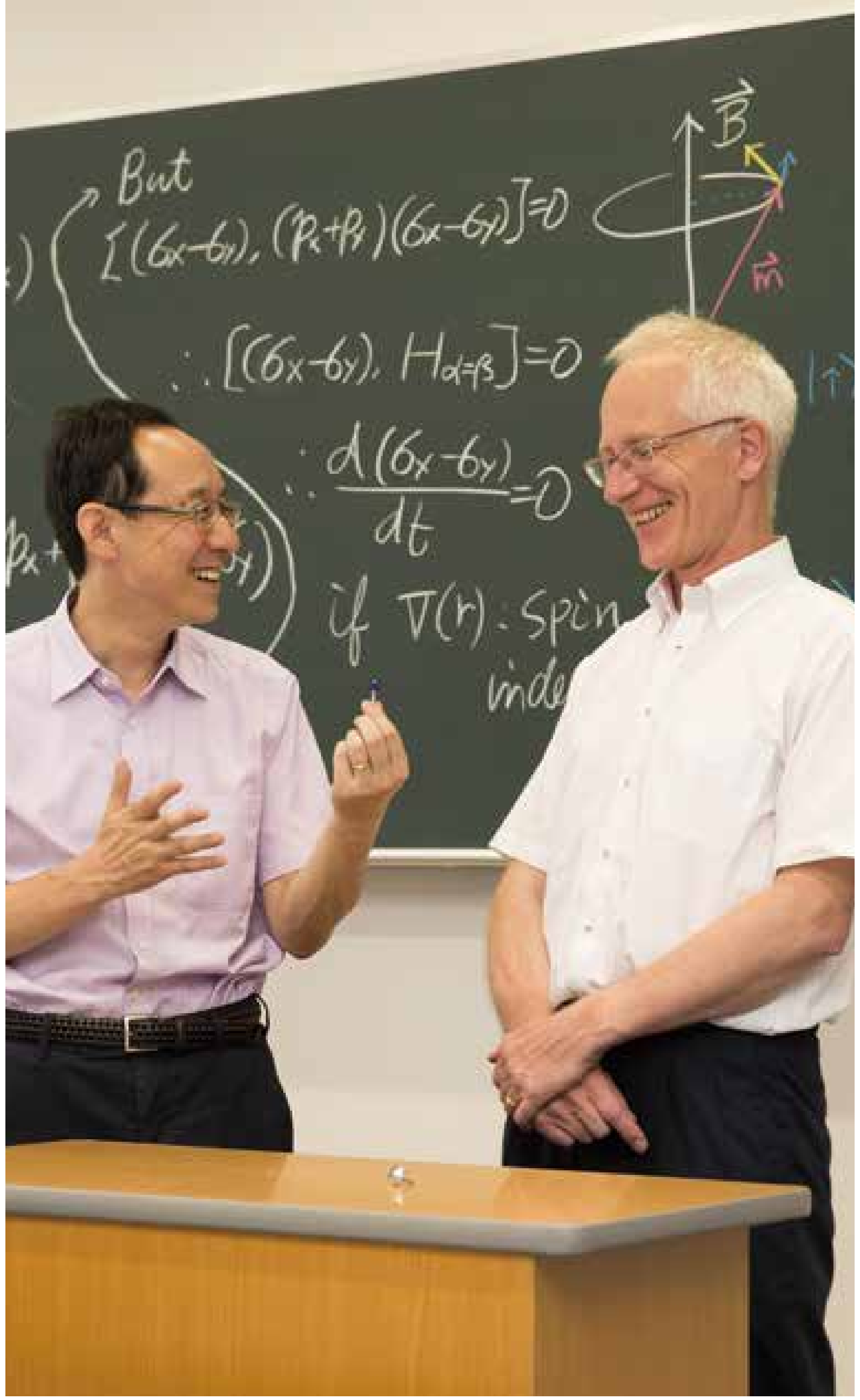
GB: From the quantum mechanics perspective, spintronics is about controlled manipulation of the electron spin degree of freedom. In ferromagnets this can be realized collectively: a large number of spins are locked into a common magnetization direction that can be set into synchronous motion by applied magnetic fields or electric currents. Semiconductor spintronics has the potential for spintronic devices that control single electron spins, either optically or electrically. In contrast to the magnetization order, single electron spins are very quantum mechanical objects. By coherent linear superposition of up- and down-spins, we may create states in which the spin points in any direction; therefore, single spin devices can form qbits, the analogue basic elements for future quantum computers.

JN: While quantum information processing is still a dream for the distant future, the read heads based on the tunnel magnetoresistance (TMR) are ubiquitous already in today's magnetic hard disk drives. They utilize aligned spin-polarized current flow in magnetic metals, in which the current of up and down spin species is not the same. Older (inductive) read heads used only the charge of the electrons and were much less sensitive. Quantum devices can be really superior to these classical ones, but developing applications will take time.

GB: Let me add that the magnetic random-access memory (MRAM) developed by Profs. Ohno and Endoh offers the speed of conventional static random-access memory (SRAM) with flash memory non-volatility. These are believed to be ready for the market soon. This is an already existing offering by spintronics: device with better performance at smaller sizes and lower power dissipation than non-magnetic alternatives. Its theoretical physics foundations are based on spin rotation and have been laid only two decades ago.

— What other kind of applications of spintronics are there and what do you envision for the future (that is, the state of things in the field including your research area)?

GB: I am now with the Laboratory for Theoretical Solid State Physics and Collaborative Research Center for Energy Materials (E-IMR) of the Institute for Materials Research (IMR) at Tohoku University, in addition to being an Affiliated Professor of WPI-AIMR. This environment encourages me to look into both the device as well as the theoretical physics aspects. I am motivated, for example, by the application potential for spintronics based on magnetic insulators with superior magnetic quality. They are ideal materials for close to dissipationless interconnects in highly integrated circuits. Beyond information technology, insulator spintronics might be useful to generate electric power from waste heat. Companies such as NEC and Denso believe that the spin Seebeck effect discovered by IMR researchers Profs. Saitoh and Uchida, can lead to thermoelectric power generators for wearable electronics or in automobiles.



Professor NITTA

Junsaku Nitta received Master's degree from Kyushu University in 1981. After that, he joined NTT Electrical Communication Laboratories. In 1990, he received Ph. D from Kyushu University because of his work on Control of Quantum Flux Propagation in Josephson Transmission Line. He stayed at University of Groningen in 1994-1995, and at Paul-Drude-Institute in 2003 as a visiting researcher. He was a group leader of Spintronics Research Group, NTT Basic Research Laboratories in 2001-2005. From 2005, he is a professor in Tohoku University, and he heads the Materials Quantum Science Laboratory in the Department of Materials Science. He is an Editor of Physica E: Low dimensional Systems and Nanostructures since 2008. His primary research interests lie in the field of spintronics based on spin-orbit interaction.

Professor BAUER

Gerrit Ernst-Wilhelm Bauer (*1956) holds an Engineering Degree (1980) in Chemical Technology from Twente University (The Netherlands) and Doctor Degree in Physics (1984) from the Technical University Berlin (Germany) for research at the Hahn-Meitner-Institute of Nuclear Research. After a postdoc at the Institute for Solid State Physics of the University of Tokyo (1984-86), he became a member of the Scientific Staff of the Philips Research Laboratories (1986-92). He was appointed Professor at Delft University of Technology in 1992, Professor of Tohoku University at the Institute for Materials Research in 2011 and Affiliated Professor at the Advanced Institute for Materials Research (WPI-AIMR) in 2013. His research focuses on theoretical condensed matter physics and spintronics (Researcher ID F-8273-2010).

JN: Having spent over two decades with NTT mostly working on Josephson junctions and superconductivity, I have seen some advances in my old research fields, but those did not impact our daily lives. Now I am focusing my research on a hot subject in spintronics often referred to as spin-orbitronics (spintronics based on the relativistic correction called spin-orbit interaction), which permits spin generation, manipulation, and detection solely by electrical means. I expect that spin-obitronics will provide much faster performance with much lower power consumption than conventional spintronics driven by magnetic fields or charge currents. My affiliation with Tohoku University, especially due to the fame of the School of Engineering as well as other research departments with excellent research in materials science and electronics devices, is very important for my research activities.

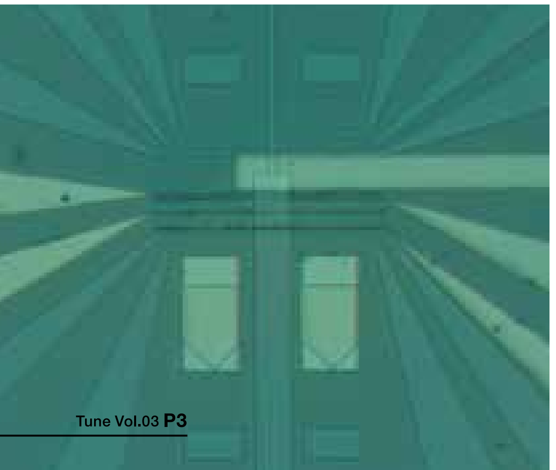
SPINTRONICS POWERHOUSE

– What differences do you see between the School of Engineering of Tohoku University and other Institutes when it comes to the field of Spintronics?

JN: One of our strengths exists in materials research! Whether it be ferromagnets, antiferromagnets, or ferrimagnets, I believe we have the facilities required in bringing forth new spin-related science and technology into this world. Our roots in basic magnetism research are strong ever since the school was established in 1919. Additionally, there are related activities in semiconductor electronics, from field-effect transistors to integrated circuits, allowing us to collaborate with experts in conventional electronics research, who are able to gauge the value of our progress in spintronics, and eventually put them to good use.

GB: The close research collaboration between the School of Engineering and the School of Science that spans the full spectrum of spintronics is unique in the world. This was reflected by the recent Tohoku Forum of Creativity on Spintronics that had the subtitle "From Mathematics to Devices". Indeed, while mathematicians ponder over the topology of relativistic materials, other groups study single electronic and nuclear spins related to spin-based quantum computing, manipulate spins by electric fields, and strive to make practical applications by developing new universal memories and logics. The latest endeavor is the quest for efficient energy harvesting pursued by the Collaborative Research Center for Energy Materials of the IMR. If you allow the pun, the advantage of Tohoku University is that we can see things from up to down and vice versa, helping us to think "out of the box". And last but not least Tohoku Unviversity is very internationally minded, and rapidly develops into a real global center of research in spintronics.

JN: Tohoku University cordially welcomes high-caliber researchers to visit and work at Aobayama Campus. I believe we will gain further fame as more research activities attract the public's attention through educational programs such as the Graduate Program in Spintronics (GP-Spin) and the Interdepartmental Doctoral Degree Program for Multi-dimensional Materials Science Leaders (MD program). Both are magnets for forward-looking students and researchers from around the world. I am sure that all of this will empower the School of Engineering in the field of spintronics. We will establish a world spintronic powerhouse through the gathering of young scientists via graduate-level spintronic studies and international collaborations. This is the way how spintronics continues the tradition of great inventions born at the School of Engineering such as the Yagi-Uda antenna sitting on top of roofs everywhere, the high power magnetron used in microwave ovens or the discovery invention of the KS magnet steel by K. Honda at the IMR.

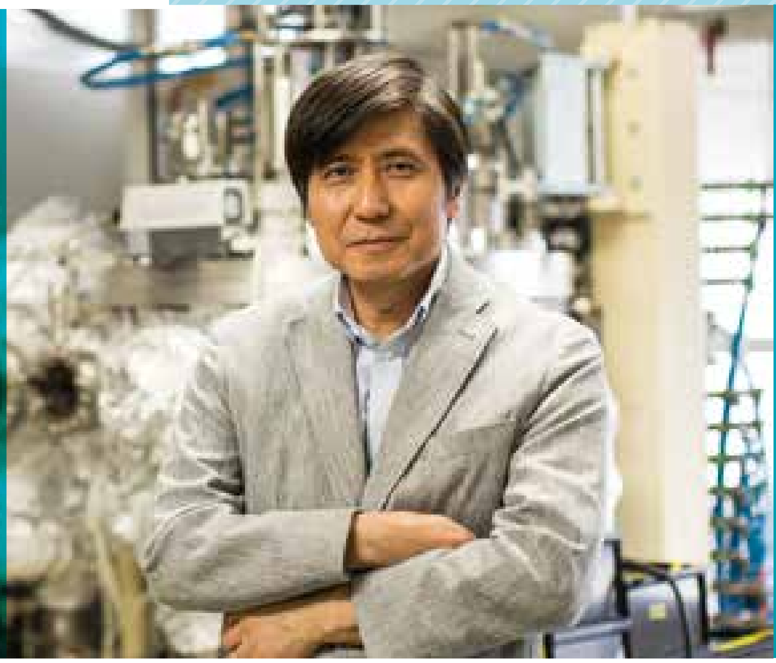


Photographs by Masayoshi HARABUCHI

High-sensitivity, high resolution magnetocardiography (MCG) for use at room temperature

Yasuo ANDO

School of Engineering, Tohoku University



We have succeeded in developing a sensor for the living body that can detect the bio-magnetic field with high sensitivity and high resolution. This was achieved by using a tunnel magnetoresistance (TMR) device to work at room temperature.
Since the TMR device was shown to exhibit a large magnetoresistance effect at room temperature by our group in 1994, many research and development of both the read head of high density hard disk and the non-volatile magnetic memory towards the application, has been promoted by many researchers at home and abroad. In recent years, the device is expected as a high-sensitivity high-resolution magnetic field sensor operating at room temperature. Considering the big market, it would be interesting of application to detecting a magnetic field from a living body.
In an aging society, the proportion of deaths due to diseases of the heart is a big weight, treatment of high-precision heart disease, and the need for prevention by early detection of the disease is growing. As a non-aggressive method of inspecting a heart, electrocardiogram (ECG) is in use widely. However, ECG is not enough in terms of spatial accuracy to identify essentially the disease site. On the other hand, the magnetic field directly from the current source has essentially very high spatial resolution.
In recent months, our group - in collaboration with Konica Minolta, Inc. – succeeded in detecting the heart's magnetic field by using the TMR device.
This device enables cardiac electric activity to be measured in a non-aggressive way, so that the diagnosis of heart conditions such as coronary heart disease or arrhythmia can be greatly improved.
In the future, a special shield room for detecting the bio-magnetic field would be unnecessary because this device has a large field range, so that heart conditions can be measured and treated in a more relaxed environment. The device is expected to make a difference in medical treatments, preventive health care and sports.

Profile:
Yasuo Ando received his Ph.D. degree from Tohoku University, in 1994. He was a Researcher at Konica Corporation, from 1986 to 1992, and he was an associate professor at Tohoku University, from 2001 to 2006. Currently, he is a Professor in the Graduate School of Engineering, Tohoku University. His research interest is focused on spintronics, in particular application of magnetic tunnel junctions to sensors, as well as development of new materials for spintronics. He is a Fellow Member of JSAP.

(a)MCG system with a sensor module and measurement system. The sensor module is set on a mannequin and detects an electriccardiogram (ECG) and MCG, simultaneously.
(b) Electric circuit with TMR sensor inside the module. (c)ECG signal (upper) and MCG signal (lower) on the Monitor.

Tohoku University, Konica Minolta, Inc. and JST (2015). Developing high-sensitivity, high resolution magnetocardiography for use at room temperature [Press release]. Retrieved from http://www.tohoku.ac.jp/japanese/2015/07/press20150723-01.html

CIES accelerates spintronics-based LSI and its practical application

Tetsuo ENDOH

School of Engineering and Center of Innovative Integrated Electronics System, Tohoku University

Toward practical applications from innovative core technologies created by Tohoku University, we have managed the international industry-academic consortium (CIES Consortium) consisting of seven industry–academic collaborations, and three major national projects (JST-ACCEL, ImPACT and NEDO projects) through our cooperation with a diverse range of Japanese and foreign companies from fields such as materials, equipment, devices, circuits and systems. CIES constructed the second such base for collaborative research between industry and academia in the world to be organized by a university for this academic area (other being in the U.S., and world first for the spintronics area) with first 300mm wafer process line and facilities for device characterization & physical analysis in Japanese university. CIES produced remarkable results, especially, recognized worldwide as research center for practical application of spintronics-based LSI with dozens of Japanese and foreign companies participating.
Recently, we have achieved a high performance interface type perpendicular-anisotropy magnetic tunnel junction (p-MTJ) stack, which is a key building block of spin transfer toque magnetoresistive random access memory (STT-MRAM), one of the most promising non-volatile memories. p-MTJ with CoFeB free layer and Co/Pt multilayer based synthetic ferrimagnetic (SyF) pinned layer has been developed to allow annealing at a temperature up to 420°C that compatible with complementary metal-oxide-semiconductor (CMOS) back end of line (BEOL) process by controlling boron diffusion for the first time. We demonstrated the 10 nmϕ p-MTJ with double CoFeB/MgO interface tolerable against 400°C annealing which is a requisite building block for realization of high density STT-MRAM in reduced dimensions. The progress enables us to step toward the practical use of spintronics-based LSI. Figure summarizes previous studies that were classified in a thermal tolerance and MTJ size. We demonstrated 10 nmϕ MTJ after 300°C annealing reported at a world authoritative International Electron Device Meeting (IEDM) in 2013. Recently, we reported the smallest 10nm p-MTJ with highest thermal tolerance over 400°C at IEDM2014. The p-MTJ with highest thermal tolerance was is required to get a fabrication process margin and smaller MTJ is needed to achieve high density MRAM at last.
In addition to the progress, Keysight Technologies, Inc. announced development of new STT-MRAM test solution based on collaboration with CIES (http://www.tohoku.ac.jp/en/news/research/news20150317_1.html). From above-mentioned, CIES has accelerated the research and development for practical application of spintronics based on the successful results in view of the production phase.

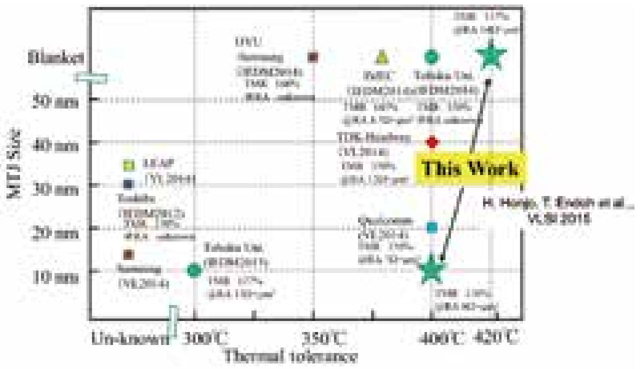


Figure Thermal tolerance vs. p-MTJ size. Most Small 10nm p-MTJ with highest thermal tolerance over 400℃ is achieved.

Profile:
Tetsuo Endoh joined Toshiba Co. in 1987 and was engaged in the R&D of NAND Memory. He became a lecturer at the Research Institute of Electrical Communication, Tohoku University in 1995. Now, he is director of the Center for Innovative Integrated Electronic Systems (CIES) and a Professor at the Department of Electrical Engineering, Graduate School of Engineering, Tohoku University. His current interests are novel 3D structured device technology, such as Vertical MOSFETs; high-density memory, such as SRAM, DRAM, 3D-NAND memory and STT-MRAM; and beyond-CMOS technology, such as spintronics-based non-volatile Logic. He is also interested in power-management technology, such as power ICs and power circuit technology.

Reference(s): 1)H. Honjo, H. Sato, S. Ikeda, S. Sato, T. Watanabe, S. Miura, T. Nasuno, Y. Noguchi, M. Yasuhira, T. Tanigawa, H. Koike, M. Muraguchi, M. Niwa, K. Ito, H. Ohno and T. Endoh, "10nmϕ perpendicular-anisotropy CoFeB-MgO magnetic tunnel junction with over 400℃ high thermal tolerance by boron diffusion control", 2015 Symposium on VLSI Technology Digest of Technical Papers, T160. 2)Tetsuo Endoh, "Nonvolatile Logic and Memory Devices Based on spintronics", 2015 IEEE International Symposium on Circuits and Systems (Invited)

News

TESP 2015

With 50 international students from 26 different nationalities, the sixth edition of the Tohoku University Engineering Summer Program (TESP) in robotics has been a success. The 2-week Summer Program offered lectures by world-class professors and research activities at the forefront of innovation. It has also been once again a chance for the participants to immerse in Japanese culture. Enjoying the traditional tea ceremony while dressed in Kimono is always one of the most anticipated activities of the summer school, not to mention the field trip, which brought the participants out of Sendai. Local Umen noodle, Samurai, Kokeshi dolls and the famous Shiraishi castle was on the agenda of one of the hottest days ever reported in Japan.

Vive la France!

France was in the spotlight from October 13th until 17th. The “Tohoku University French Week” offered during one week a different view of France through various events. Other than cheese and wine, France has several world-level characteristics such as a substantial number of recipients of scientific prizes and world-level top industries in all domains. Tohoku University has been the place of open discussions with special guests such as the President of Nihon Michelin Tire, Mr. Delmas, about the strong culture of internship and training in France and the educational system in France and Japan, not to mention a forum with the recipient of the French Academy Prize, Mr. Mizubayashi, regarding French as a language.

T.I.M.E.

The School of Engineering has hosted from October 15th to 17th the General Assembly of the Top Industrial Managers for Europe. T.I.M.E. Association is a network of leading engineering and technical Higher Education institutions, mainly from Europe, providing to the best students a unique opportunity to study for a long period of time in another T.I.M.E. institution, in order to gain a broader high-level scientific engineering and multi-cultural educations. It was founded in 1989 by 16 European members, all being regarded as the best of the higher education in their own country. Over the years, T.I.M.E. has gained new partners and is now composed of more than 50 members, graduating more than 5,000 students.

Open Campus

On July 29th and 30th, all research laboratories of the School of Engineering of Tohoku University opened wide their door and the students of each of them had to play an active part in promoting their laboratories, through oral presentations, public demonstrations and even attracting and bringing back to the laboratory people passing by. This year the open campus gathered under a scorching sun more than 8000 visitors, mainly high school students coming from all over Japan. It was for them a unique chance to explore and get informed about the research that is conducted here at the School of Engineering. The visit broadened their vision of what engineering is and will help them choose the major they will engage in once enrolled at the university.

New Aobayama Subway Station

Aobayama station is an underground station of the new Sendai Subway Tozai line that has been put into service on December 6, 2015. Aobayama station serves the Aobayama campus of Tohoku University, including the School of Engineering. Trains run from 5:00 to 23:00 at intervals as short as 5 minutes during peak period and it takes 9 minutes and 250 yen to come from Sendai station. The platform is on the 6th floor underground and is accessible through an elevator and a series of escalators. Tozai line is the second subway line for Sendai city. It runs from Yagiyama zoological park in the west through the city center to the eastern suburbs and is approximately 14 km with 13 stations, all underground.

Qatar-Tohoku Science Camp

Cultural exchanges between Qatar and Tohoku University have been once more fostered with the organisation of a Science Camp from November 22th until 27th. The Qatari delegation was composed of 15 students and several supervisors among which were members of the Qatar Friendship Fund. the Science Camp proposed several activities such as workshops, visits and laboratory tour. It has also been a chance for the Qatari delegation to experience Japanese culture. In addition to the tea ceremony, the students could experience special sports such as Sumo, Kendo and Karate in cooperation with the Tohoku University sport clubs.

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Tohoku University Research News of Engineering (Tune) is a biannual publication of School of Engineering (SoE), Tohoku University, Sendai, Japan. Each Tune volume provides the scientific community with the latest research results of SoE on a selected topic.