From KS Steel to Spintronics

Toward the Spintronics Powerhouse
Junsaku NITTA × Gerrit BAUER

Research Highlight
Yasuo ANDO  Tetsuo ENDOH
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 of that time, the K5 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” - it 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?

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Cross Talk Interview

Text by G.Bauer / Photographs by Masayoshi HARA

J. NITTA × G. BAUER

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. Nitto 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 efforts. 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 photonics and photomixing.

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

Jensaku 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 high school years 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 always 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 stay at the Philips laboratories back in the Netherlands prior to becoming a Delft University of Technology professor. Only in my last years 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
DEFINING SPINTRONICS WITHOUT DIRECTIONS?

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

JN: Let me try defining the field from the solid state device standpoint: 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 requiring 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 the controlled manipulation of the electron spin degree of freedom. In ferromagnets, this can be realized collectively: a large number of spins are linked to a common magnetization direction that can be set into a synchronous motion by applied magnetic fields or electric currents. Semiconductors 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 qubits, the analogous 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 (reductive) 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 Prof. 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 of 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 spinntronics are there and what do you envision for the future? What 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 the diverse and interrelated fields; therefore, single spin devices, where theoretical physics aspects prevail, are my focus. I am motivated, for example, by the application potential for spintronics based on magnetic insulators with superior magnetic quality. These materials are for close to dissipation 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 JMR researchers Prof. Sakudo and Uchida, can lead to thermoelectric power generators for wearable electronics or in automobiles.

Professor NITTA

Jumpei Nittea received his Master’s degree from Kyushu University in 1981. After that, he joined NTT Electrical Communication Laboratories. In 1995, 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 NTT Basic Research Laboratories in 2002 as a visiting researcher. He was a group leader of Spinsitronics Research Group, NTT Basic Research Laboratories in 2003-2005. From 2005, he is a professor in Tohoku University, and he leads the Materials Quantum Science Laboratory in the Department of Materials Science, he is an Editor of Physics E: Low dimensional Systems and Nanostructures since 2006. His primary research interest is in the field of spintronics based on spin-orbit interaction.

Professor BAUER

Dr. Erno-Winfried Bauer (1956) holds an Engineering Degree (1980) in Chemical Engineering from Technical University (Hamburg) and Doctor Degree in Physics (1984) from the Technische Universität in Berlin (Germany) for research at the Institute of Inorganic Chemistry, Berlin. After a position at the University of Tokyo (Japan) from 1985-1989, he became a member of the Scientific Staff of the Max-Planck Institute in Stuttgart and was established in 1991. Additionally, there are related activities in the field of spintronics 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 computing or manipulation of 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 fun, the advantage of Tohoku University is that we can teach things from up down and vice versa, helping us to think “out of the box”. And last but not least Tohoku University 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 Aoba 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 (OP-Spin) and the Interdisciplinary Graduate 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 spintronics powerhouse through the gathering of young scientists via graduate-level spintronics 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, and the discovery invention of the Ks magnet steel by K. Honda at the IMR.
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 head 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-invasive method of detecting 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-invasive 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 care and sports.

Towards 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 300nm wafer process line and facilities for device characterization & physical analysis in Japan 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-magnetostatic magnetic tunnel junction (p-MJT) stack, which is a key building block of spin transfer torque magneto-resistive random access memory (STT-MRAM), one of the most promising non-volatile memories. p-MJT with CoFeB free layer and CoPt multilayer based synthetic ferromagnetic (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 nm p-MJT with double CoFeB/MgO interface tolerant 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 MJT size. We demonstrated 10 nm p-MJT after 300°C annealing reported to a world authoritative International Electronic Device Meeting (IEDM) in 2013. Recently, we reported the smallest 10nm p-MJT with highest thermal tolerance over 400°C at IEDM2014. The p-MJT with highest thermal tolerance was required to get a fabrication process margin and smaller MTJ is needed to achieve high density MRAM at last. In addition to the progress, Keylight Technologies, Inc. announced development of new STT-MRAM test solution based on collaboration with CIES (http://www.tohoku.ac.jp/en/news/research/news20150317_i.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.
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 Uman noodles, Samurai, Kokeshi dolls and the famous Shirakawago 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. Dalmas, 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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