IEEE Magnetics Society Distinguished Lecturers for 2012

Magnetoresistance and Spin-Transfer Torque in Magnetic Tunnel Junctions

Shinji Yuasa
National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan

A magnetic tunnel junction (MTJ) consisting of a thin insulating layer (a tunnel barrier) sandwiched between two ferromagnetic electrodes exhibits the tunnel magnetoresistance (TMR) effect due to spin-dependent electron tunneling. Since the discovery of room-temperature TMR in the mid-1990s, MTJs with an amorphous aluminum oxide (Al-O) tunnel barrier have been studied extensively. Such MTJs exhibit a magnetoresistance (MR) ratio of several tens of percent at room temperature (RT) and have been applied to magnetoresistive random access memory (MRAM) and the read heads of hard disk drives. MTJs with MR ratios substantially higher than 100%, however, are desired for next-generation spintronic devices. In 2001, first-principle theories predicted that the MR ratios of epitaxial Fe/MgO/Fe MTJs with a crystalline MgO(001) barrier would be over 1000% due to the coherent tunneling of specific Bloch states. In 2004, MR ratios of about 200% were obtained for MgO-based MTJs [1]. MTJs with a CoFeB/MgO/CoFeB structure were developed for practical application and found to have MR ratios of above 200% and other practical properties [1], [2].

This lecture focuses on the physics of magnetoresistance and spin-transfer torque in MTJs and the application of MTJs to various spintronic devices such as magnetic sensors, spin-transfer-torque MRAM (STT-RAM or spin-RAM) with perpendicular magnetization, and novel spin-torque oscillators. In addition, new types of MTJs such as spin-filter junctions with a ferromagnetic tunnel barrier will be discussed.

[1] S. Yuasa and D. D. Djayaprawira, *J. Phys. D: Appl. Phys.*, vol. 40, p. R337, 2007.
[2] D. D. Djayaprawira, K. Tsunekawa, M. Nagai, H. Maehara, S. Yamagata, N. Watanabe, S. Yuasa, Y. Suzuki, and K. Ando, *Appl. Phys. Lett.*, vol. 86, 092502, 2005.

Shinji Yuasa received the Ph.D. degree in physics from Keio University in 1996.

After receiving his doctorate, he served as a Staff Scientist at the Electrotechnical Laboratory, Tsukuba, Japan, where he worked on spin-dependent transport in metallic magnetic multilayers. Since 2001, he has been a Staff Scientist at the National Institute of Advanced Industrial Science and Technology (AIST), working on the physics and device applications of MTJs. Since 2010, he has been a Director of the Spintronics Research Center at AIST. He has published more than 100 peer reviewed papers and has given more than 80 invited talks at international conferences.

For his achievement of the giant TMR effect in MgO-based MTJs, Dr. Yuasa has been awarded or co-awarded 20 prizes, including the Asahi Award in 2007. He is now serving as a program co-chair for the 2013 Joint MMM/Intermag Conference and is a member of the advisory committee for the MMM Conference and an editor of *Applied Physics Express*.

Contact: Prof. Shinji Yuasa, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan; e-mail: yuasa-s@aist.go.jp.

Digital Object Identifier 10.1109/TMAG.2011.2177739

0018-9464/$26.00 © 2011 IEEE

IP Bridge Exhibit 2030
Western Digital v. IP Bridge
IPR2024-01447

Science and Technology of Modern Permanent-Magnet Materials

George C. Hadjipanayis
Department of Physics and Astronomy, University of Delaware, Newark, Delaware

Permanent magnets (PMs) are indispensable for the electric, electronic and automobile industries, information technologies, automatic control engineering and many other commercial and military applications. In most of these applications, an increase in the magnetic energy density of the PM, usually presented via the maximum energy product $(BH)_{\max}$, immediately increases the efficiency of the whole device and makes it smaller and lighter. Worldwide demand for high performance PMs has increased substantially in the past few years driven by hybrid and electric cars, wind turbines and other power generation systems.

A dramatic improvement in the performance of PMs was made during the 20th century, with $(BH)_{\max}$ increased by more than 100 times, as a result of major advances in solid state physics, materials science and metallurgy. However, new energy challenges in the world require devices with higher energy efficiency and minimum environmental impact. The potential of 3d–4f compounds that revolutionized PM science and technology is nearly fully utilized, and the supply of 4f rare-earth elements is no longer assured.

This lecture will cover the major principles guiding the development of PMs, including the important role of microstructure on coercivity, and overview state-of-the-art theoretical and experimental research. Recent progress in the development of nanocomposite PMs, consisting of a fine (at the scale of magnetic exchange length) mixture of phases with high magnetization and large magnetic hardness will be discussed. Fabrication of such PMs is currently the most promising way to boost the $(BH)_{\max}$, while simultaneously decreasing, at least partially, the reliance on the rare-earth elements. Current efforts in the development of high performance non-rare-earth magnets and their future prospects will also be discussed.

George Hadjipanayis received the B.Sc. degree in physics from the University of Athens in 1969, and the M.Sc. and Ph.D. degrees in physics from the University of Manitoba, Canada, in 1974 and 1979, respectively.

He was an Assistant Professor (1982–1985) and Associate Professor (1986–1988) in the Department of Physics at Kansas State University. In 1989 he joined the faculty of the University of Delaware as a full Professor. In 1998, he was a Humboldt Senior Fellow at the Max Planck Institute, Stuttgart, Germany. In 1999, he assumed the position of Richard B. Murray Distinguished Professor of Physics and Astronomy and since 2003 has been the Chair of the Department of Physics and Astronomy at the University of Delaware. His areas of interest span hard magnetic materials with a focus on high performance permanent magnets and magnetic nanoparticles for storage media and biomedical applications. He has published more than 500 technical articles in peer-reviewed science and engineering journals, including book chapters, review articles, and invited technical feature articles on the topical areas of rare-earth magnetism, nanotechnology, and permanent-magnet materials, among others.

Prof. Hadjipanayi has been recognized for seminal advances in scholarship with the Francis Alison Award (2005) and by elevation to Fellow of the American Physical Society (2001).

Contact: Prof. George Hadjipanayis, Department of Physics and Astronomy, University of Delaware, Newark, DE USA; e-mail: hadji@udel.edu.

Spin Caloritronics

Gerrit Ernst-Wilhelm Bauer
Institute of Materials Research, Tohoku University, Japan, and Kavli Institute of NanoScience, TU Delft, The Netherlands

The spin degree of freedom of the electron affects not only charge, but also heat and thermoelectric transport, leading to new effects in small structures that are studied in the field of spin caloritronics (from *calor*, the Latin word for heat).

This lecture addresses the basic physics of spin caloritronics. Starting with an introduction into thermoelectrics and Onsager's reciprocity relations, the generalization to include the spin dependence in the presence of metallic ferromagnets will be addressed. Using this foundation, I will describe several recently discovered spin-dependent effects in metallic nanostructures and tunneling junctions as well as a multitude of spin-related thermal Hall effects in terms of a two-spin-current model of non-interacting electrons (an overview of the recent literature is given in [1]).

Next, I will argue that a different class of spin caloritronic effects exists that can be explained only by the collective spin dynamics in ferromagnets. The thermal spin transfer torque that allows excitation and switching of the magnetization in spin valves as well as the operation of nanoscale heat engines is complemented by thermal spin pumping. The latter generates the so-called spin Seebeck effect, which is generated by a heat current-induced non-equilibrium of magnons at a contact between an insulating or conducting ferromagnet and a normal metal. Under these conditions, a net spin current is injected or extracted from the normal metal that can be detected by the inverse spin Hall effect.

Both classes can be formulated by scattering theory of transport in the adiabatic approximation for the magnetization dynamics and computed in terms of material-dependent electronic structures. Further topics to be addressed are the relation between electric, thermal and acoustic actuation, as well as the application potential of spin caloritronics.

[1] G. E. W. Bauer, *Spin Currents*, S. Maekawa, E. Saitoh, S. Valenzuela, and Y. Kimura, Eds. Oxford, U.K.: Oxford University Press, in press, arXiv:1107.4395.

Gerrit Ernst-Wilhelm Bauer received the Engineering degree in chemical technology in 1980 from Twente University, The Netherlands, and the Doctor degree in physics in 1984 from the Technical University Berlin, Germany, for research carried out 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 of Physics at Delft University of Technology in 1992 and at Tohoku University in 2011. He coauthored more than 200 refereed scientific papers in the area of condensed matter physics, in the last two decades mainly in the field of magnetoelectronics/spintronics.

Prof. Bauer received the Wilhelm-Conrad-Röntgen Award from Würzburg University (2000), the Outstanding Referee Award by the American Physical Society (2008), and the Lars Onsager Medal from the Norwegian University of Science and Technology (2009). He became Fellow of the American Physical Society in 2010 "for exposing the interaction between spin transport, magnetization dynamics, charge and heat transport, and mechanical motion."

Contact: Prof. Gerrit Ernst-Wilhelm Bauer, Institute for Materials Research, Tohoku University, Japan; e-mail: G.E.W.Bauer@imr.tohoku.ac.jp and Kavli Institute of NanoScience, TU Delft, The Netherlands; e-mail: G.E.W.Bauer@tudelft.nl.

Soft Magnetic Thin Film Applications at Radio Frequencies

Masahiro Yamaguchi
Department of Electrical and Communication Engineering, Tohoku University, Sendai, Japan

Development of new passive component technologies will enable a "More-than-Moore" paradigm leading to innovative application-specific compact systems [1]. Ferromagnetic thin film materials, having high permeability at (and above) radio frequencies, are candidate materials for use in inductive passive components that are available in the forms of vacuum-deposited and electro-deposited metallic alloys, chemically synthesized nano-particulate composites, and traditional oxides, among others. Using these materials, the development of CMOS integrated inductors and integrated electromagnetic noise suppressors for radio frequency integrated circuits (RFIC) and point-of-load (POL) one-chip dc-dc converters in "3.9th Generation" mobile phones that use the Long Term Evolution standard, is attracting great interest from both academic and industrial communities.

This lecture begins with a review of new soft magnetic thin film applications at radio frequencies for future system-in-package (SiP) and system-on-chip (SoC) technologies. Proposed in the late 1970s, these thin film soft magnet applications have evolved from inductive read/write recording head technology to the frontiers of gigahertz frequency device applications. Discussions covered in this lecture include: 1) Development of international cross measurements of RF permeameters [2] to evaluate RF permeability and related ferromagnetic resonance (FMR) profiles of magnetic films; 2) small signal, high permeable, low loss applications to CMOS integrated inductors [3]; 3) small signal lossy application to CMOS integrated electromagnetic noise suppressor [4]; 4) small to medium signal applications as new metal/ferromagnetic multi-stack "conductors" to suppress skin effect utilizing negative permeability beyond the FMR frequency $[\mu_r' < 0, \mu_r'' \approx 0]$ [5]; and, 5) large current permeable application to POL type one-chip dc-dc converters. The lecture will conclude with an outlook that provides a perspective on the future of on-chip RF magnetics.

[1] J. P. Kent and J. Prasad, "Microelectronics for the real world: 'Moore' versus 'More than Moore'," presented at the IEEE 2008 Custom Integrated Circuits Conf., 2008, 15-4-1.
[2] M. Yamaguchi, Y. Miyazawa, K. Kaminishi, and K. I. Arai, "A new 1 MHz–9 GHz thin-film permeameter using a side-open TEM cell and a planar shielded-loop coil," *Trans. Magn. Soc. Jpn.*, vol. 3, pp. 137–140, 2003.
[3] M. Yamaguchi, K. Yamada, and K. H. Kim, "Slit design consideration on the ferromagnetic RF integrated inductor," *IEEE Trans. Magn.*, vol. 42, pp. 3341–3343, 2006.
[4] S. Muroga, Y. Endo, W. Kodate, Y. Sasaki, K. Yoshikawa, Y. Sasaki, M. Nagata, and M. Yamaguchi, "Evaluation of thin film noise suppressor applied to noise emulator chip implemented in 65 nm CMOS technology," *IEEE Trans. Magn.*, vol. 48, pp. 4485–4488, 2011.
[5] M. Yamaguchi, Y. Shimada, T. Inagaki, and B. Rejaei, "Skin effect suppression in RF devices using a multilayer of conductor and ferromagnetic thin film with negative permeability," presented at the Microwave Workshop and Exhibition 2008 (MWE 2008), Yokohama, 2008, WS08-03.

Masahiro Yamaguchi received the B.S., M.S., and Ph.D. (Dr. Eng.) degrees in electrical and communication engineering from Tohoku University, Sendai, Japan, in 1979, 1981, and 1984, respectively.

He was an Associate Professor with the Research Institute of Electrical Communication, Tohoku University, from 1991 to 2003. In 1995, he was a visiting Associate Professor at the University of Wisconsin-Madison. Since 2003, he has been serving as Professor in the Department of Electrical and Communication Engineering, Tohoku University. He is also with the New Industry Creation Hatchery Center (NICHe), Tohoku University, since 2010. His research interests cover RF permeability and FMR measurements for magnetic thin films, RF magnetic field measurements for IC chips to analyze and counter electromagnetic interference, and application of soft magnetic materials for on-chip RF devices including thin film inductor, noise suppressor, and skin-effect free multilayer conductor for telecommunication and micro-power-conversion technologies.

Prof. Yamaguchi established and served as the general chair for the International Workshop on High Frequency Micromagnetic Devices and Materials (MMDM, 2002–2008). He has served as the IEEE Magnetics Society Japan-Sendai Chapter Chair (2007), co-editor-in-chief for the Magnetics Society of Japan (2007–2010), and board member of Japan Institute of Electronics Packaging (2008–2010). He is currently the chairman of the committees on On-Chip RF Magnetics of the Institute of Electrical Engineers of Japan (2011–2014).

Contact: Prof. Masahiro Yamaguchi, Department of Electrical and Communication Engineering, Tohoku University, Sendai, Japan; e-mail: yamaguti@ecei.tohoku.ac.jp.