東北大学 電気通信研究所

研究室外部評価資料

(2013年度-2018年度)

Activity Report of Research Laboratory for External Review

April 2013 - March 2019
(FY.2013-2018)

Research Institute of Electrical Communication Tohoku University

スピントロニクス研究室

Spintronics

A. 研究室名 / Research Laboratory

スピントロニクス研究室
Spintronics

B. 構成員 / Faculty and Research Staff (as of May 1, 2019)

※ 欄を適宜追加削除等調整して下さい．期間内に異動等があった場合には，在籍期間を記載して下さい．

教授 / Professor

氏名 Name	大野 英男 Hideo Ohno (- March 2018)
分野名 Research Field	スピン機能工学研究分野 Functional Spintronics

准教授 / Associate Professor

氏名 Name	深見 俊輔 Shunsuke Fukami (February 2016 -)
分野名 Research Field	ナノスピン材料デバイス研究分野 Nano-Spin Materials and Devices

助教 / Assistant Professor

氏名 / Name	山ノ内 路彦 / Michihiko Yamanouchi (- April 2014) 金井 駿 / Shun Kanai (April 2014 -) リアンドロ ジャスティン / Justin Llandro (April 2016 -)

他 / Others

	日本学術振興会特別研究員 PD: 3 名（中山裕康、石川慎也、岡田篤）

C. 研究目的 / Research Purpose

本研究室では、高性能・低消費電力スピントロニクスメモリ・論理集積回路、及び新概念コンピューティングの実現を目指し、新奇スピントロニクス材料・素子の開発やそこで発現されるスピン物性、磁化ダイナミクスの理解、及びそれらの持つ機能性の開拓などに取り組んでいる。

Our research group aim to deepen understanding of spin-related physics and magnetization dynamics develop in novel spintronics materials and devices, and explore new functionalities based on the obtained findings. The goal of these activities is to realize high-performance and low-power spintronics memory, integrated circuit, and unconventional intelligent computing.

D. 主な研究テーマ / Research Topics

1. スピントロニクス材料・素子における電子・スピン物性とその応用に関する研究
2. スピン・軌道相互作用を用いた磁化の制御に関する研究
3. ナノ磁性体中の磁区や磁壁のダイナミクスに関する研究
4. 高性能・低消費電力スピントロニクスメモリ素子の開発
5. 金属磁性体素子のメモリ・論理集積回路、脳型情報処理応用に関する研究

1. Electrical and spin properties of spintronic materials/devices and their applications
2. Control of magnetization utilizing spin-orbit interactions
3. Dynamics of magnetic domains and domain walls in nanoscale magnets
4. 4evelopment of high-performance and low-power spintronic memory devices
5. Applications of metallic spintronics devices for nonvolatile memories, logic integrated circuits and brain-inspired computing

E. 学術論文等の編数 / The Number of Research Papers

FY	2013	2014	2015	2016	2017	2018	Total
(1) 査読付学術論文 Refereed journal papers	39	27	19	19	22	12	138
(2) 原著論文と同等に扱う 査読付国際会議発表論文 Full papers in refereed conference proceedings equivalent to journal papers	7	1	3	1	0	0	12
(3) 査読付国際会議 Papers in refereed conference proceedings	48	46	54	72	60	61	341
(4) 査読なし国際会議・シンポジウム等 Papers in conference proceedings	5	0	0	9	18	7	39
(5) 総説・解説 Review articles	0	1	0	3	2	2	8
(6) 査読付国内会議 Refereed proceedings in domestic conferences	0	0	0	0	0	0	0
(7) 査読なし国内研究会・講演会 Proceedings in domestic conferences	43	41	30	35	32	28	209
(8) 著書 Books	1	1	0	0	0	0	2
(9) 特許 Patents	5	4	6	4	12	12	43
(10) 招待講演 Invited Talks	19	35	32	45	41	32	204

F. 特筆すべき研究成果 / Significant Research Achievements (FY.2013-2018)

See Ref. 1. "#" mark indicates research carried out at a former organization.

2013-2018 年度の研究成果（論文・特許など）のうち，前半（2013-2015 年度）と後半（2016-2018 年度）それぞれで代表的な数件（2-3 件程度ずつ）について，参考資料を引用して，その特徴と学術的意義などを簡単に紹介する．英文のみ，もしくは和文と英文で記載．要約は 300 字程度．論文誌の要約/Abstract のコピー可．学術面での国際的インパクトならびに社会的影響を 100 字程度で記載．
必ずしも当該期間内に発表・出版したものに限るのではなく，例えば過去に発表したものでもこの期間内に成果が得られたり，評価されるようになったりしたものも含むものとする．
インパクトファクターや被引用件数など，できる限り第三者が定量的に評価できる指標を用いてアピールすること．それらの指標にはそぐわない場合には，その事情とそれに変わる適当な評価指標・尺度を示すこと．

[2013-2015]

1. H. Sato, E. C. I. Enobio, M. Yamanouchi, S. Ikeda, S. Fukami, S. Kanai, F. Matsukura, and H. Ohno, "Properties of magnetic tunnel junctions with a MgO/CoFeB/Ta/CoFeB/MgO recording structure down to junction diameter of 11 nm," *Applied Physics Letters*, vol. 105, pp. 062403(1)-(4), August 13, 2014 [IF: 3.521] [Times Cited: 155].

   Abstract: This paper and other relating papers/conference presentations describe magnetic tunnel junction technologies for spin-transfer torque magnetoresistive random access memory (STT-MRAM) applications. These works followed our earlier work [S. Ikeda et al. Nature Mater. 9, 721 (2010)] reporting a perpendicular-anisotropy magnetic tunnel junction and enhance the performance of current-induced magnetization switching and thermal stability factor based on in-depth investigations of the physics at nanometer scales. Also, the works have led to our later works on single-digit-nanometer shape-anisotropy magnetic tunnel junction device [K. Watanabe et al. Nature Commun. 9, 663, 2018].

   International impact on both academic and social aspects: Mass production of STT-MRAM by major semiconductor integrated-circuit manufacturing companies has started recently. Magnetic tunnel junction is the heart of the STT-MRAM and our studies have made significant contribution to the commercialization of the STT-MRAM. The STT-MRAM is promising technology to realize energy-efficient integrated circuits and IoT societies.

2. S. Fukami, M. Yamanouchi, S. Ikeda, and H. Ohno, "Depinning probability of a magnetic domain wall in nanowires by spin-polarized currents," *Nature Communications*, vol. 4, 2293(1)-(7), August 15, 2013 [IF: 11.88], [Times Cited: 42].

   Abstract: This paper and other relating papers/ conference presentations describe current-induced motion of magnetic domain wall for high-speed working memory and storage-class race-track memory applications. We have revealed key physics and technologies that are promising for the device applications above. We also demonstrated the world-smallest 20-nm magnetic domain wall motion device [S. Fukami et al., IEDM2013 3.5.1] and the world-first spintronics-based microcontroller [N. Sakimura et al. ISSCC2014, 10.5] based on the insights obtained in the fundamental studies.

   International impact on both academic and social aspects: Electrical manipulation of magnetic configuration is of a fundamental interest in spintronics field. Our works have provided a bridge from fundamental researches to device applications by delving the physics of magnetic texture and its dynamics. The obtained achievements are expected to promote the further growth of MRAM technologies where higher-speed operation should be required in future. Some of the insights obtained in these works have led to an establishment of ‘spin-orbitronics’ described below.

[2016-2018]

1. S. Fukami, C. Zhang, S. DuttaGupta, A. Kurenkov, and H. Ohno, “Magnetization switching by spin-orbit torque in an antiferromagnet-ferromagnet bilayer system,” *Nature Materials*, vol. 15, pp. 535-541, February 15, 2016 [IF: 38.887], [Times Cited: 318].

   Abstract: Current-induced torque acting on magnetization via the spin-orbit interaction, referred to as the spin-orbit torque, offers promising scheme to control magnetization direction in spintronics devices. One of the biggest obstacles for applications is a necessity of external magnetic field to determine the switching direction. This work showed for the first time that (1) antiferromagnetic PtMn exhibits sizable spin-orbit torque, (2) combining the spin-orbit torque with exchange bias in antiferromagnet/ferromagnet bilayer structure allows field-free magnetization switching, and (3) the magnetization, or the device resistance, can be controlled in an analog manner when the bilayer system is designed properly. (1) and (2) solved the deadlock of the spin-orbit torque switching, while (3) opened a new paradigm of spintronics research, so-called neuromorphic spintronics. Later, we utilized this property and showed an associative memory which is the world-first proof-of-concept demonstration of spintronics-based neuromorphic computing.

   International impact on both academic and social aspects: Antiferromagnetic spintronics, where unraveled physics and functionalities of antiferromagnetic materials are explored, is one of the active fields in recent spintronics. This work is recognized as a representative study in the antiferromagnetic spintronics as a new spin-transport phenomena and functionality of an antiferromagnetic metal were revealed. In addition, neuromorphic computing is an attractive topic in various fields from mathematics, condensed-matter physics, medical engineering to integrated circuits and computer science, because it has a potential to execute complex cognitive tasks that the conventional von Neumann computers are not excel at. The antiferromagnet/ferromagnet system exhibiting analog control of magnetization observed can be used as an artificial synapse in an artificial neural network and thus is promising for the neuromorphic computation.

2. S. Fukami, T. Anekawa, C. Zhang, and H. Ohno, “A spin-orbit torque switching scheme with collinear magnetic easy axis and current configuration,” *Nature Nanotechnology*, vol. 11, pp. 621-625, March 21, 2016. [IF: 33.407], [Times Cited: 152].

   Abstract: This work also studied the spin-orbit torque magnetization switching. Before this study, there were two schemes of magnetization switching; one uses out-of-plane magnetization (magnetization along the z direction) structure and the other uses in-plane and orthogonal-to-current magnetization (magnetization along the y direction) structure. This work showed a spin-orbit torque magnetization switching for a structure with in-plane and collinear-to-current (magnetization along the x direction) configuration. Subsequent studies [S. Fukami et al., VLSI2016, T06-5; Y. Takahashi et al., Appl. Phys. Lett. 114, 012410, 2019, etc.] revealed that the newly established scheme is promising for nano- or subnano-second magnetization switching which is not easily achieved by the conventional spin-transfer torque magnetization switching used in STT-MRAMs.

International impact on both academic and social aspects: The emergence of the third scheme of spin-orbit torque switching offers various opportunity to investigate the physics of spin-orbit torque. In fact, we revealed several unknown mechanisms of the spin-orbit torque magnetization switching such as the effect of field-like torque and high-speed magnetization dynamics. Also, the observed subnanosecond manipulation of magnetization is attractive for the MRAM application and several MRAM manufacturing companies are interested in a utilization of the spin-orbit torque for their future products.

G. 特筆すべき活動 / Significant Activities (FY.2013-2018)

See Ref. 2-9. “#” mark indicates research carried out at a former organization.

研究室外部評価参考資料の 2 以降を参照しながら，2013-2018 年度のなどの活動の中から特筆すべきものを取り出し，前半（2013-2015 年度）と後半（2016-2018 年度）に分けて簡単に紹介する．英文のみ，もしくは和文と英文で記載．

[2013-2015]

RIEC International Workshop on Spintronics

The 1st RIEC International Workshop on Spintronics was held on Feb. 8-9, 2005. Since then, we have organized the workshops almost every year and have dealt with exciting topics. Now, the RIEC workshop is recognized as an important interaction event of world-wide spintronics community. On November 18, 2015 – November 20, 2015, for example, we hold the 13th workshop in RIEC, Tohoku University and invited world-leading researchers including Johan Åkerman (University of Gothenburg), David Awschalom (University of Chicago), Geoffrey Beach (Massachusetts Institute of Technology), Tomasz Dietl (Polish Academy of Sciences), Claudia Felser (Max Planck Institute for Chemical Physics of Solids), Julie Grollier (Université Paris-Sud), Masamitsu Hayashi (National Institute for Materials Science), Burkard Hillebrands (TU Kaiserslautern), Masashi Kawasaki (University of Tokyo), Aurélien Manchon (King Abdullah University of Science and Technology), Teruo Ono (Kyoto University), Stuart Parkin (IBM), Andrei Slavin (Oakland University), Gen Tatara (RIKEN), Kang Wang (University of California, Los Angeles), Dieter Weiss (Universität Regensburg). The total number of participants is 185 (77 people from Tohoku University, 33 people from Japan (not Tohoku Univ), 75 people from overseas).

[2016-2018]

ImPACT Program “Spintronics integrated circuit” Project

ImPACT is a Japanese national program through which the Council for Science, Technology and Innovation, that serves as the government's command center for innovation policy, encourages high-risk, high-impact R&D, and aim to realize a sustainable and expandable innovation system. “Achieving Ultimate Green IT Devices with Long Usage Time without Charging (Program Manager: Masashi Sahashi)” is one of the ImPACT Program, where spintronics devices and integrated circuits are developed to realize ultralow power IoT systems.

The Spintronics Integrated Circuit Project (Principal Investigator: Hideo Ohno (FY2014-2017), Tetsuo Endoh (FY2018)) is one of the projects of the Sahashi ImPACT Program. Through this project, we carried out researches to demonstrate low-power edge devices based on nonvolatile spintronics technology. In the final year, we successfully demonstrated a 50 μW microcontroller unit operating at 200 MHz. The operation speed is fast enough to execute high-level tasks such as face recognition while the power is low enough to be operated under energy harvesting. The established technology should become a new foundation of future semiconductor integrated-circuit societies.