

10 Spintronics and Magnetism | Poster presentation : 10 Spintronics and Magnetism (Poster)

[7p-P03-1~47] 10 Spintronics and Magnetism (Poster)

[7p-P03-1]

Crystal structure and Magnetic properties of NiAs-type CrTe/NiAs-type MnTe bilayer grown by MBE

O(M2)Daichi Kumazawa¹, Ken Kanazawa¹, Shinji Kuroda¹ (1.Tsukuba Univ.)

[7p-P03-2]

Variation in anomalous Hall effect in thin films of altermagnet a-MnTe grown by MBE

OKeito Shoji¹, Shinji Kuroda¹ (1.Univ.tsukuba)

[7p-P03-3]

Circularly polarized light detection characteristics of spin photodiode based on dilute nitride semiconductor

OTakeru Omi¹, Daiki Mineyama², Itsu Tanaka², Kaito Nakama³, Hidetoshi Hashimoto³, Keisuke Minehisa³, Junichi Takayama², Fumitaro Ishikawa³, Akihiro Murayama², Satoshi Hiura²
(1.Hokkaido Univ., 2.IST,Hokkaido Univ., 3.RCIQE,Hokkaido Univ.)

[7p-P03-4]

Thickness dependence of diode efficiency in superconducting Fe(Se,Te)/FeTe thin-film heterostructure devices

OKaito Arizono¹, Kenshin Inamura¹, Junichi Shiogai^{1,3}, Tsutomu Nojima², Jobu Matsuno^{1,3}
(1.Dept. of Phys., Univ. of Osaka, 2.IMR, Tohoku Univ, 3.OTRI-Spin, Univ. of Osaka)

[7p-P03-5]

Observation of anisotropic spin dynamics in a (001) GaAs/AlGaAs heterointerface suitable for electrical spin wave injection

OKento Sugawara¹, Koga Akagi¹, Jun Ishihara¹, Daiki Sekine², Sota Yamamoto¹, Mineto Ogawa³, Tetsuya Uemura³, Makoto Kohda^{1,2,4,5} (1.Grad.School of Eng., Tohoku Univ., 2.QUARC, QST, 3.Hokkaido Univ., 4.CSIS, Tohoku Univ., 5.DEFS, Tohoku Univ.)

[7p-P03-6]

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O(M1)Makoto Segawa¹, Tatsuki Yoshida¹, Eiji Shikoh¹ (1.Osaka Metro. Univ.)

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Spin transport properties of photo-conductive molecular thin films induced by spin pumping and their photo-irradiation effects

O(M1)Keigo Okajima¹, Shouki Yamada¹, Yuri Matukawa¹, Eiji Shikoh¹ (1.Osaka Metro. Univ.)

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Spin-pumping-induced spin transport in molecular thin film bilayer structures

O(M1)Takeru Sano¹, Keito Takamatsu¹, Shusuke Waki¹, Eiji Shikoh¹ (1.Osaka Metro. Univ.)

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ORikuto Takai¹, Muhammad Arifin^{1,2}, Kohji Nakamura¹ (1.Mie Univ., 2.Gadjah Mada Univ.)

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OTakayuki Hojo¹, Daisuke Amie¹, Kenta Watanabe¹, Takahide Kubota¹, Masakiyo Tunoda¹, Mikihiro Oogane¹ (1.Tohoku Univ.)

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OIDuru Shigeta¹, Soichiro Tsujikawa¹, Jun Gouchi², Rie Y. Umetsu³, Takeshi Kanomata⁴, Yoshiya Uwatoko², Masahiko Hiroi¹ (1.Kagoshima Univ., 2.Univ. of Tokyo, 3.Tohoku Univ., 4.Tohoku Gakuin Univ.)

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OTakeru Sugimoto¹, Masaaki Tanaka¹, Fumiya Itoh¹, Ko Mibu¹ (1.Nagoya Inst.Tech.)

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Hayato Suzuki¹, Takuro Masui¹, Haruchika Tozawa¹, Daigo Akiyama¹, OMasamichi Sakai¹, Tatsuro Hanajiri², Satoshi Sumi³, Hiroyuki Awano³ (1.Saitama Univ., 2.Toyo Univ., 3.Toyota Technol. Inst.)

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OHikaru Goto¹, Yasuhiro Ikezoe¹ (1.NIT)

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OHayato Toeda¹, Yasuhiro Ikezoe¹ (1.NIT)

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OTaisuke Horaguchi¹, Takashi Manago¹ (1.Fukuoka Univ.)

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OTaisuke Horaguchi¹, Takashi Manago¹ (1.Fukuoka Univ.)

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○(M1)Kotaro Inatomi¹, Taisuke Horaguchi¹, Takashi Manago¹ (1.Fukuoka Univ.)

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○Takahiro Chiba^{1,2}, Ryunosuke Suzuki^{2,1}, Takashi Otaki², Hiroaki Matsueda^{2,3} (1.Yamagata Univ., 2.Togoku Univ., 3.CSIS)

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○(D)Itaru Sugiura¹, Yoichi Shiota^{1,2}, Ryusuke Hisatomi^{1,2}, Shutaro Karube^{1,2}, Teruo Ono^{1,2}, Takahiro Moriyama^{3,4} (1.ICR, Kyoto Univ., 2.CSRN, Kyoto Univ., 3.PRESTO, JST, 4.Nagoya Univ.)

[7p-P03-23]

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○Yuta Sasaki¹, Phillip Bentley¹, Katsuaki Nakazawa¹, Takanobu Hiroto¹, Shinji Isogami¹, Hirofumi Suto¹, Yukiko Takahashi¹ (1.NIMS)

[7p-P03-24]

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○(M2)Koki Kobayashi¹, Andi Gumarilang¹, Kohji Nakamura¹ (1.Mie Univ.)

[7p-P03-25]

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○(P)Koujiro Hoshi^{1,2,3}, Terufumi Yamaguchi⁴, Tomosato Hioki^{1,3,5}, Eiji Saitoh^{1,2,3,5} (1.Dept. Appl. Phys., Univ. Tokyo, 2.Inst. AI and Beyond, Univ. Tokyo, 3.CEMS, RIKEN, 4.Kobe Univ, 5.AIMR, Tohoku Univ.)

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○(M2)Tomoki Ishihara¹, Muhammad Alifin^{1,2}, Koji Nakamura¹ (1.Mie Univ., 2.Gadjah Mada Univ.)

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○(M1)Souki Mizota¹, Imai Kouki¹, Hombo Taichi¹, Mohan John Rex¹, Horibe Yoichi¹, Ishimaru Manabu¹, Asada Hironori², Fukuma Yasuhiro¹ (1.Kyushu Inst Tech, 2.Yamaguchi Univ)

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○Yusei Ono¹, Mitsuki Yoshino², Taichi Hombo¹, John Rex Mohan¹, Yoichi Horibe¹, Manabu Ishimaru¹, Hironori Asada², Yasuhiro Fukuma¹ (1.Kyushu Inst. Tech., 2.Yamaguchi Univ.)

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○Yuki Hibino¹, Tomohiro Taniguchi¹, Tatsuya Yamamoto¹, Hitoshi Kubota¹, Shinji Yuasa¹, Kay Yakushiji¹ (1.AIST)

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○(M2C)Yixi Li¹, Kohei Hamaya², Mizue Ishikawa¹ (1.Nihon Univ., 2.Osaka Univ.)

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○Takumi Ueda¹, Mizuki Matsuzaka¹, Chika Hashimoto¹, Kosuke Furukawa¹, Ryunosuke Miyamoto¹, Kotaro Kashima¹, Hideo Kaiju^{1,2} (1.Keio Univ., 2.CSRN, Keio Univ.)

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○Kotaro Kashima¹, Mizuki Matsuzaka¹, Miyamoto Ryunosuke¹, Koki Terai¹, Masafumi Abe¹, Kazuto Yamanoi^{1,2}, Yukio Nozaki^{1,2}, Masayuki Suda³, Hideo Kaiju^{1,2} (1.Keio Univ., 2.CSRN, Keio Univ, 3.Nagoya Univ.)

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○(M1)Rikuto Ogawa¹, Yoshio Miura¹ (1.KIT)

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○(D)Andi MuhNurFitrah Syamsul¹, Kohji Nakamura¹ (1.Mie Univ.)

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○(DC)Daisuke Amiie¹, Takayuki Hojo¹, Masakiyo Tsunoda^{1,2}, Mikihiro Oogane^{1,3} (1.Graduate school of Engineering, Tohoku Univ., 2.Tohoku Univ. Green X-tech, 3.Tohoku Univ. CSIS)

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○Ryuta Okazaki¹, Yuto Shibata¹, Mizuki Matsuzaka¹, Mizuki Wakamoto¹, Hiroaki Sukegawa², Hideo Kaiju^{1,3} (1.Keio Univ., 2.NIMS, 3.Keio spin center)

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Shintarou Nii¹, ○Chaoliang Zhang¹, Haoxiang He¹, Yupeng Wang¹, Takayuki Hojo¹, Takafumi Nakano^{1,2}, Mikihiro Oogane^{1,3} (1.Department of Applied Physics, Tohoku Univ., 2.Green X-tech, Tohoku Univ., 3.CSIS, Tohoku Univ.)

[7p-P03-40]

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○(M2)Yuta Igarashi¹, Junji Fujimoto¹ (1.Saitama Univ.)

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○Takahiro Funae¹, Hiroyuki Awano¹, Kenji Tanabe¹ (1.Toyota Tech.Inst.)

[7p-P03-42]

Current-induced domain wall motion in Gd-Fe wires with vertical composition gradient

○Jumpei Mizuno¹, Hiroyuki Awano¹, Kenji Tanabe¹ (1.Toyota Tech. Inst.)

[7p-P03-43]

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○(M1)Yusuke Oda¹, Rio Kawana¹, Mutsuhiro Shima¹, Keisuke Yamada¹ (1.Gifu Univ)

[7p-P03-44]

Characterization of structure and magnetic properties for Co_xPd_{100-x} alloy nanowires fabricated by electrodeposition and nanoporous template

○(M2)Afifah Nur Chairinnisa¹, Shunpei Matsuoka¹, Rio Kawana¹, Mutsuhiro Shima¹, Keisuke Yamada¹ (1.Gifu Univ.)

[7p-P03-45]

Fabrication and evaluation of Co electrodes for the creation of novel molecular nanodevices

○Koki Terai¹, Mizuki Matsuzaka¹, Takumi Ueda¹, Hideo Kaiju^{1,2} (1.Keio Univ., 2.CSRN, Keio Univ.)

[7p-P03-46]

Investigation of fabrication process for three-dimensional magnetic microstructure using nano-imprint technique

○Yuichiro Kurokawa¹, Kenji Tanabe², Keisuke Yamada³, Satoshi Sumi², Hiroyuki Awano², Hiromi Yuasa¹ (1.Kyushu Univ., 2.Toyota Tech. Inst., 3.Gifu Univ.)

[7p-P03-47]

First-principles prediction of nitride and fluoride compounds modification at the Fe/MgO interface for perpendicular magnetic anisotropy and voltage-controlled magnetic anisotropy

○Masato Tsuchida¹, Yosephine Novita¹, Kohji Nakamura¹ (1.Mie Univ.)

MBE 法による NiAs 型 CrTe/NiAs 型 MnTe 二層構造の作製と磁気特性

Crystal structure and Magnetic properties of NiAs-type CrTe/NiAs-type MnTe bilayer grown by MBE

筑波大院数物、[○](M2)熊澤大地、金澤研、黒田眞司

University of Tsukuba, Japan, [○]D.Kumazawa, K.Kanazawa, S.Kuroda

E-mail: s2420349@u.tsukuba.ac.jp

半導体スピントロニクス目標の一つに既存の半導体デバイスにスピンの自由度を加えることで更なるデバイスの高機能化の実現がある。その実現に向けた課題として、スピン注入および制御の技術の向上が挙げられる。私たちの研究室では、遷移金属化合物の磁化制御を対象に研究を行ってきた。先行研究では強磁性体 FeTe および反強磁性体 NiAs 型 MnTe の二層薄膜構造において、磁化曲線の磁場方向シフトとして交換バイアス効果が確認された[1]。本研究では、対象とする系を広げることが目的とし、先行研究とは異なる遷移金属化合物の強磁性体である NiAs 型 CrTe および反強磁性体 NiAs 型 MnTe の二層薄膜構造を作製し、磁気特性評価を行った。

試料作製は分子線エピタキシー (MBE) 法を用いて行った。Fig.1 に試料構造の模式図を示す。GaAs(111)A 基板上に MnTe 層を基板温度 400°C で 60 分積層した後に、基板温度 250°C で様々な積層時間 (10, 20, 30, 40 min) で CrTe 層を成長することで試料を作製した。成長時の分子線供給量比は $[Mn]/[Te] = 0.1$ 、 $[Cr]/[Te] = 0.03$ とした。磁気特性評価には SQUID を用いた。また、交換バイアス H_{EB} は $H_{EB} = (H_{C+} + H_{C-})/2$ として定義している。

Fig.2 は各試料の磁化の面内磁場依存性を示した曲線である。CrTe 層の積層時間が最も短い C/M_10min の試料で最も大きな負磁場方向へのシフト、すなわち最大の交換バイアスが確認され、その値は 608[Oe]であった。この結果は、CrTe/MnTe の系における交換バイアスは特に成長面内方向にはたらいっており、その大きさは強磁性体 CrTe 層の膜厚と負の相関関係にあることを示唆している。発表では、XRD による結晶構造評価の結果や磁化の面直磁場依存性、交換バイアスの温度依存性についても議論する予定である。

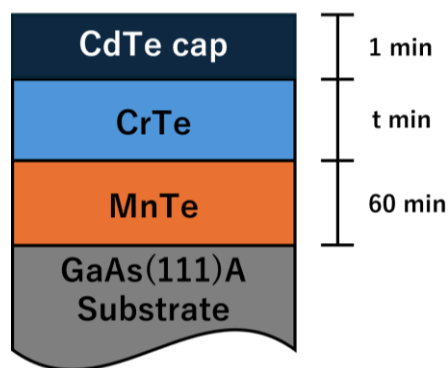


Fig.1 The sample structure of the CrTe/MnTe bilayer film.

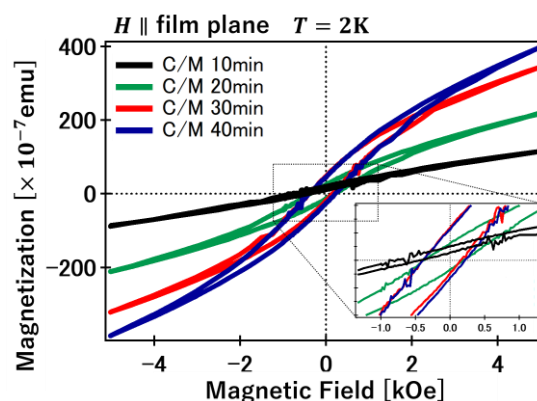


Fig.2 M - H curves of CrTe/ MnTe bilayer films at 2K.

The magnetic field was applied parallel to the film plane.

Variation in anomalous Hall effect in thin films of altermagnet α -MnTe grown by MBE

Grad. Sch. Pure & Appl. Sci., Univ. Tsukuba, °K. Shoji, and S. Kuroda

E-mail: s2420361@u.tsukuba.ac.jp

α -MnTe (NiAs structure) has been known as an antiferromagnetic material with zero net magnetization. However, it has recently been suggested that the magnetism of α -MnTe should be classified as altermagnetism due to the breaking of the inversion symmetry with respect to the positions non-magnetic Te atoms in the NiAs structure[1]. The peculiar properties of α -MnTe as an altermagnet have been experimentally demonstrated by the emergence of a finite spin splitting[2] and the ferromagnetic hysteresis in both the magnetoresistance and the anomalous Hall effect[3]. In this study, we performed Hall measurement on α -MnTe thin films in order to clarify the origin of anomalous Hall effect.

MnTe films were grown using MBE by supplying Mn and Te flux onto an InP(111)A substrate. The substrate surface was treated with or without cleaning using rf-excited hydrogen (H) plasma and the MnTe layer was deposited on it. By optimizing the growth conditions, the substrate temperature T_S at 400°C and the Mn and Te flux ratio at Te/Mn = 10, we successfully obtained pure α -MnTe without any extrinsic phase.

We performed the Hall measurement on the MnTe films with and without H-cleaning under the application of magnetic field perpendicular to the film plane. Figure 1 (a) shows the field-dependence of the anomalous Hall resistivity ($\rho_{xy} - H$), obtained by subtracting a linear component of the ordinary Hall effect from the measured Hall resistivity. The hysteresis was observed below 150K in the film without H-cleaning and the magnitude of ρ_{xy} was enhanced significantly at temperatures above 200 K. On the other hand, the hysteresis appeared up to 225 K in the film with H-cleaning, and the magnitude of ρ_{xy} was enhanced significantly at temperatures above 200 K. Figure 1 (b) shows the temperature dependence of ρ_{xy} at zero field (spontaneous ρ_{xy}) and the saturation value (saturated ρ_{xy}) for the films with and without H-cleaning. The spontaneous and saturation values exhibit in principle similar trend with the temperature variation[4], but the changes with temperature are more pronounced in the film with H-cleaning. The in-plane lattice constant of 0.4151nm in the InP (111) plane exhibits excellent lattice matching with that in c-plane of α -MnTe ($a = 0.4149$ nm). A slight difference in the InP surface treated with and without H-cleaning is likely to affect the stacking of MnTe on the InP surface, which may cause a difference in magnetic and transport properties of the MnTe layer. Details will be discussed at the presentation.

[1] L. Šmejkal *et al.*, Phys. Rev. X **12**, 031042 (2022). [2] J. Krempaský *et al.*, Nature **626**, 517 (2024).

[3] R. D. Gonzalez Betancout *et al.*, Phys. Rev. Lett. **130**, 036702 (2023). [4] H. Bangar, *et al.* arXiv 2505.14589 (2025).

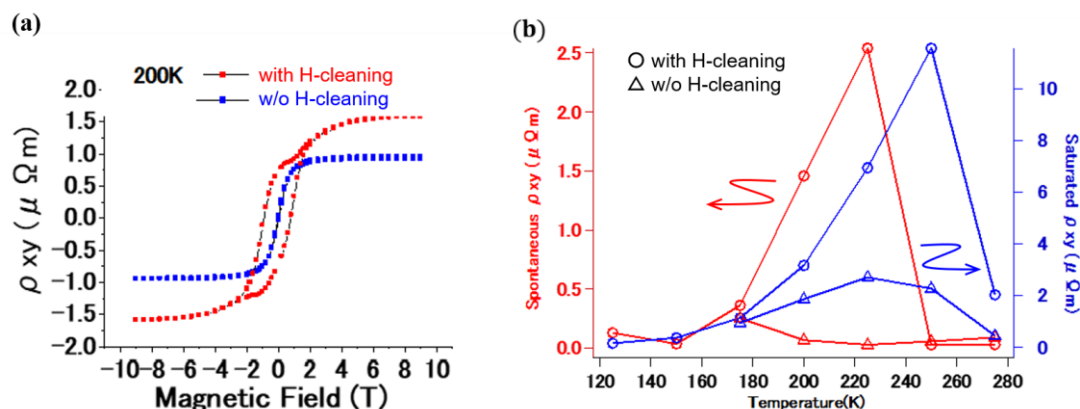


Fig. 1 (a) The magnetic-field dependence of anomalous Hall resistivity ($\rho_{xy} - H$) at 200K of the α -MnTe films with and without H-cleaning. (b) Temperature dependence of spontaneous (red marks) and saturated (blue marks) ρ_{xy} of the MnTe films with and without H-cleaning.

希薄窒化物半導体を用いたスピノフォトダイオードの円偏光受光特性 Circularly polarized light detection characteristics of spin photodiode based on dilute nitride semiconductor

北大工学部¹, 北大院情報科学², 北大量子集積³ ○大見 健琉¹, 峯山 大輝², 田中 壺²,
中間 海音³, 橋本 英季³, 峰久 恵輔³, 高山 純一², 石川 史太郎³, 村山 明宏², 樋浦 諭志²
School of Engineering, Hokkaido Univ.¹, IST, Hokkaido Univ.², RCIQE, Hokkaido Univ.³,
○T. Omi¹, D. Mineyama², I. Tanaka², K. Nakama³, H. Hashimoto³, K. Minehisa³,
J. Takayama², F. Ishikawa³, A. Murayama² and S. Hiura²
E-mail: omi.takeru.t2@elms.hokudai.ac.jp

次世代の省エネルギー情報システムに向けて、電子のスピノ偏極と光のスピノ偏極特性である円偏光を相互に変換する光電融合に期待がもたれており、そのスピノ光電変換を担うスピノ偏極発光ダイオードとスピノフォトダイオード (スピノ PD) の研究が必要である [1,2]。スピノ PD では、左右円偏光に応じて異なる方向にスピノ偏極した伝導電子を半導体層から強磁性体電極にトンネリングさせる。この際、強磁性体の磁化配向によってトンネル確率に非対称性が生じ円偏光を光電流差として検出できる。しかし、光電変換に用いられる非磁性の化合物半導体では、特に室温で伝導電子のスピノ偏極が容易に失われ、円偏光特性の電流検出効率が大きく低下してしまう [3]。そこで、本研究ではスピノフィルタリング効果 [4] により、室温で長いスピノ緩和時間を持つ希薄窒化物半導体を受光層に用いたスピノ PD を作製し、室温で円偏光受光特性を評価した。

試料構造を図 1 に示す。高周波窒素プラズマ支援分子線エピタキシー法によって $i\text{-GaN}_{0.025}\text{As}_{0.975}$ と $n\text{-GaN}_{0.025}\text{As}_{0.975}$ を有する半導体層を成長した。その後、電子ビーム蒸着法ならびにスパッタ蒸着法によって $\text{MgO}/\text{Co}_{0.4}\text{Fe}_{0.4}\text{B}_{0.2}/\text{Mo}$ から成るスピノ検出層を作製した。光弾性変調器と光チョッパーを用いて偏光状態と光強度を同時に周期変調したレーザー光 ($\lambda = 1075 \text{ nm}$) を試料に入射し、左右円偏光での光電流差 $\Delta i = i_{\sigma+} - i_{\sigma-}$ 、及び平均光電流 i_{photo} をロックイン測定した。測定結果を図 2 に示す。ここで、左右円偏光の識別性能を $F = \Delta i / 2i_{\text{photo}}$ と定義した。外部磁場の増加に伴って F 値が約 1.6% まで増加し、 $\pm 400 \text{ mT}$ で飽和した。強磁性体電極の磁化配向に応じた F 値の変化が観測され、室温で希薄窒化物半導体を用いたスピノ PD による左右円偏光の検出に成功した。

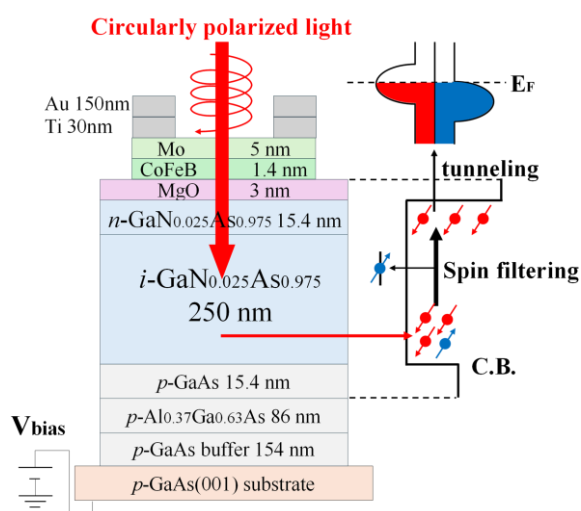


Fig. 1 Schematic illustration of a spin photodiode based on dilute nitride semiconductor, GaNAs.

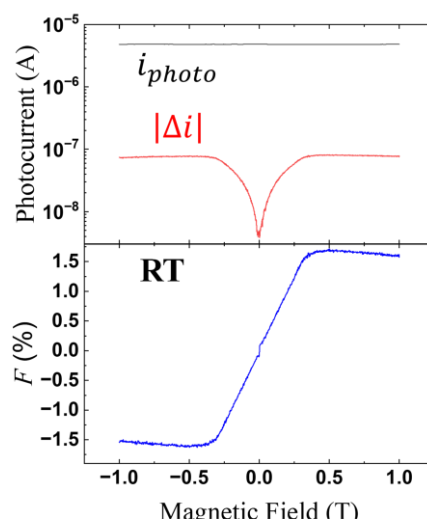


Fig. 2 Magnetic field dependence of i_{photo} , $|\Delta i|$ and corresponding F at room temperature (RT) with +0.2 V, a laser wavelength of 1075 nm and a laser power of 7.6 mW.

References:

- [1] K. Etou et al., Phys. Rev. Appl. **16**, 014034 (2021). [2] C. Rinaldi et al., Adv. Mater. **24**, 3037 (2012). [3] W. Van Roy et al., IEEE Trans. Electron Devices **54**, 933 (2007). [4] X. J. Wang et al., Nat. Mater. **8**, 198 (2009).

Thickness dependence of diode efficiency in superconducting Fe(Se,Te)/FeTe thin-film heterostructure devices

Dept. of Phys., Univ. of Osaka¹, OTRI-Spin, Univ. of Osaka², IMR, Tohoku Univ.³

[○]Kaito Arizono¹, Kenshin Inamura¹, Junichi Shiogai^{1,2}, Tsutomu Nojima³, Jobu Matsuno^{1,2}

E-mail: arizono@interface.phys.sci.osaka-u.ac.jp

Superconducting diode effect (SDE), *i.e.*, non-reciprocal response of the superconducting critical current against polarity of magnetic field or bias, has recently attracted much attention for potential application to ideal rectification devices [1]. We have recently demonstrated the observation of SDE in a superconducting 20-nm-thick Fe(Se,Te)/20-nm-thick FeTe heterostructure, which exhibits large superconducting critical parameters and spin-orbit interaction [2]. From comprehensive measurements of critical current and second harmonics resistance in a wide range of temperature and magnetic field, we have concluded that the asymmetric pinning potential of vortices, which are coupled to the spin-orbit interaction, plays a main role for inducing SDE [2]. Layer structure dependence of SDE in this heterostructure will provide further physical insight into the vortex-induced SDE. In this study, we investigate dependence of the Fe(Se,Te) layer thickness on SDE efficiency in the Fe(Se,Te)/FeTe thin-film heterostructure devices.

The Se capped t -nm-thick Fe(Se,Te)/20-nm-thick FeTe heterostructures (inset of Fig. 1) with $t = 10$, 20, and 40 nm were prepared on CaF₂(001) substrates by pulsed-laser deposition [3]. The 100- μ m-wide bar-shaped devices were patterned by photolithography and water lift-off technique. All three devices exhibit the clear SDE under in-plane magnetic field (B) perpendicular to the current, being consistent with our previous work [2]. Figure 1 shows the magnetic-field dependence of diode efficiency $\eta(B)$, which is characterized by $\eta = (I_c^+ - I_c^-)/(I_c^+ + I_c^-)$ for $t = 10$ nm, 20 nm, and 40 nm. Here, I_c^+ and I_c^- denotes the critical current for positive and negative bias, respectively. For all the thicknesses, the $|\eta(B)|$ value first linearly increases with increasing B and decreases with further increase of B , resulting in the peak structure. This peak structure in $\eta(B)$ is strongly dependent on t : As t increases, the peak value of $\eta(B)$ increases while the peak position shifts towards smaller B . In this talk, we will discuss the thickness dependence of $\eta(B)$ in the Fe(Se,Te)/FeTe heterostructures based on the model considering asymmetric pinning of vortices.

Reference [1] F. Ando *et al.*, Nature **584**, 373 (2020). [2] Y. Kobayashi *et al.*, Commun. Phys. **8**, 196 (2025). [3] Y. Imai *et al.*, Proc. Natl. Acad. Sci. USA **112**, 1937 (2015).

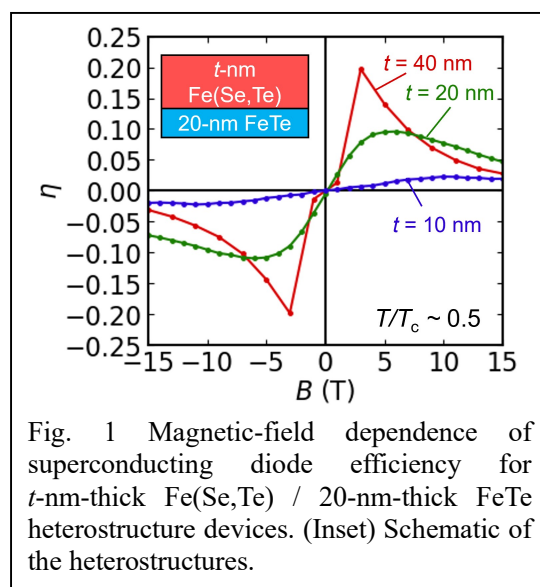


Fig. 1 Magnetic-field dependence of superconducting diode efficiency for t -nm-thick Fe(Se,Te) / 20-nm-thick FeTe heterostructure devices. (Inset) Schematic of the heterostructures.

Observation of anisotropic spin dynamics in a (001) GaAs/AlGaAs heterointerface suitable for electrical spin wave injection

Kento Sugawara¹, Koga Akagi¹, Jun Ishihara¹, Daiki Sekine², Sota Yamamoto¹, Mineto Ogawa³,

Tetsuya Uemura³, and Makoto Kohda^{1, 2, 4, 5}

1, Grad. School of Eng., Tohoku Univ., 2, QUARC, QST, 3, Hokkaido Univ, 4, CSIS, Tohoku Univ.,

5, DEFS, Tohoku Univ.

E-mail: sugawara.kento.t8@dc.tohoku.ac.jp

The Persistent Spin Helix (PSH) state emerged in semiconductor quantum wells when the Rashba and Dresselhaus spin-orbit interactions are balanced [1]. In this state, a uniaxial effective magnetic field aligns the spins in the two-dimensional electron gas (2DEG) into a spatially periodic structure known as an electron spin wave [2]. Recently, spin injection was demonstrated into a GaAs/AlGaAs single heterointerface 2DEG from Co₂MnSi [3], enabling electrical generation and detection of spin waves. In this study, we investigate whether the PSH state can be achieved in a 2DEG at a single heterointerface.

The sample was a (001) GaAs/AlGaAs heterojunction grown by molecular beam epitaxy. We measured electron spin dynamics using spatiotemporal magneto-optical Kerr rotation microscopy at $T = 8$ K and an in-plane magnetic field $B = 4$ T. Since the spin-orbit effective magnetic field is proportional to the electron momentum, comparing the spatial gradients of the spin precession frequency along the $[110]$ and $[1\bar{1}0]$ directions enables evaluation of the uniaxial effective field [4].

Figure 1(a) shows the time evolution of spin polarization. Since beating of two spin precession frequencies is observed, the data are fitted with a sum of two damped oscillatory functions to extract the spin precession frequency Ω . Figure 1(b) shows the position dependence of Ω along the x and y directions. For the x direction, no beating features are observed, and only a single Ω is extracted. Extracted Ω for both directions and both frequencies exhibit only slight spatial dependence. This might be attributed to a weak spin-orbit effective field or to spin signal from except for 2DEG.

This research was supported by JSPS KAKENHI Grant No. 21H04647 and JST FOREST, CREST, and PRESTO programs (Grant Nos. JPMJFR203C, JPMJCR22C2, and JPMJPR24L4).

[1] J. Schliemann *et al.*, Phys. Rev. Lett. **90**, 146801 (2003). [2] M. P. Walser *et al.*, Nat. Phys. **8**, 757 (2012). [3] Z. Lin *et al.*, Appl. Phys. Lett. **114**, 012405 (2019). [4] M. Kohda *et al.*, Appl. Phys. Lett. **107**, 172402 (2015).

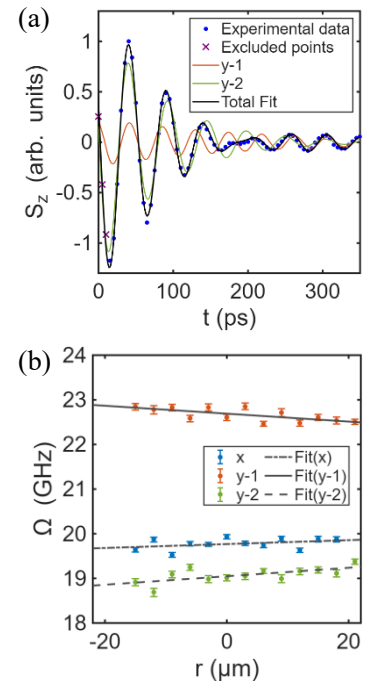


Fig. 1. (a) Time evolution of spin polarization along the y -direction. (b) Position dependence of the spin precession frequency.

強磁性金属によるスピン流-電流変換と分子薄膜中の純スピン流輸送

Spin-to-charge conversion in ferromagnetic metals and pure spin current transport in molecular thin films

阪公大院工¹, ^{○(M1)}瀬川 眞琴¹, 吉田 樹生¹, 仕幸 英治¹

Osaka Metro. Univ.¹, [○]Makoto Segawa¹, Tatsuki Yoshida¹, Eiji Shikoh¹

E-mail: sr25894b@st.omu.ac.jp

「強磁性層/中間層/強磁性層」構造はこれまでに様々な研究開発に用いられ、スピン偏極電流やスピンプンピングによる純スピン流によって中間層のスピン輸送が達成された[1,2]。しかしながら中間層が有機分子薄膜の場合、スピンプンピングによる純スピン流輸送を達成した研究は無い。本研究では検出層に強磁性金属を用い、有機分子薄膜を介した純スピン流輸送を実証することを目的とした。

熱酸化膜付き Si 基板上に $\text{Ni}_{80}\text{Fe}_{20}$ (膜厚 10 nm)/PTCDA 分子薄膜(30 nm)/Co(25 nm)の三層構造試料 (Fig. 1)を作製した。 $\text{Ni}_{80}\text{Fe}_{20}$ および Co は電子ビーム蒸着法、PTCDA は抵抗加熱法を用いて成膜した。一方の強磁性層の強磁性共鳴(FMR)によるスピンプンピングによって PTCDA 層に純スピン流を生成し、輸送されたスピン流を他方の強磁性層の逆スピンホール効果(ISHE)[3]によって検出することにより、PTCDA 層の純スピン流輸送特性を評価した。

Fig. 2(a)に三層接合試料の FMR スペクトルを示す。FMR 条件から 193 Oe と 308Oe の信号がそれぞれ、Co と $\text{Ni}_{80}\text{Fe}_{20}$ の FMR に由来すると判断した。Fig. 2(b)に同試料の $\text{Ni}_{80}\text{Fe}_{20}$ 層で検出された起電力特性を示す。2 つの強磁性体それぞれの FMR 磁界付近で起電力が検出され、その符号は静磁界の反転に伴い逆転した。これらの特性はスピンプンピングによって注入されるスピン流を ISHE により変換して得られる起電力の特性と一致した。以上より三層構造試料 sub./ $\text{Ni}_{80}\text{Fe}_{20}$ /PTCDA/Co において PTCDA 層のスピン流輸送を達成したと結論付けた。学会時には三層構造試料 sub./Co/PTCDA/ $\text{Ni}_{80}\text{Fe}_{20}$ を用いた実験結果を含む研究の詳細について議論する。

[1] D. Huang, et al., Phys. Rev. B 107, 214438 (2023).

[2] S. Samdani, et al., Phys. Rev. B 110, 134440 (2024).

[3] E. Saitoh et al., Appl. Phys. Lett. 88, 182509 (2006).

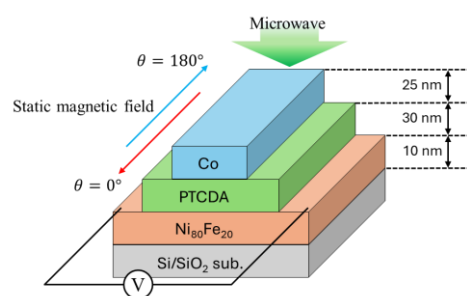


Fig. 1. Sample structure.

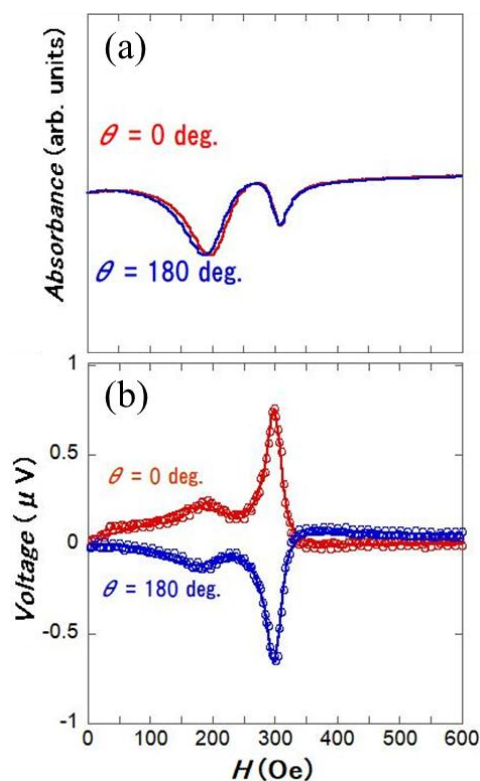


Fig. 2. (a) FMR spectra and (b) dictated voltage properties of a sample under the FMR, at 5 GHz.

スピンプンピングによる光導電性分子薄膜のスピントランスポート特性とその光照射効果 Spin transport properties of photo-conductive molecular thin films induced by spin pumping and their photo-irradiation effects

阪公大院工¹, °(M1)岡島 圭吾¹, (M2)山田 奨貴¹ 松川 裕利¹ 仕幸 英治¹

Osaka Metro. Univ.¹, °Keigo Okajima¹, Shouki Yamada¹, Yuri Matukawa¹, Eiji Shikoh¹

E-mail: sr25126a@st.omu.ac.jp

有機分子材料は主に軽元素で構成されていることからスピンの散乱に寄与するスピン軌道相互作用が重金属より比較的小さいのでスピントランスポート材料の候補として注目されている。これまでに様々な有機分子薄膜の動力的スピンプン注入によるスピントランスポートが実証されている[1,2]。特に、高分子材料においてキャリア密度が異なるとスピントランスポート特性が異なる傾向がある[2]。このことからスピントランスポートの担い手が材料のキャリア由来ならば、光導電性を有する分子材料を用いて、光によるキャリア密度制御を用いればスピントランスポートの制御が可能と考えられる[2]。本研究では光導電性を有する Rubrene 分子薄膜のキャリア密度を光照射で制御することにより、Rubrene 分子薄膜中のスピントランスポート特性の光制御を目的とした。

合成石英基板上に「ITO(膜厚 60 nm)/Rubrene(50nm)/ Ni₈₀Fe₂₀(25 nm)」の三層構造試料を製作した。各層は順に、RFスパッタリング法、抵抗加熱蒸着法、および電子ビーム蒸着法を用いて成膜した。Ni₈₀Fe₂₀ の強磁性共鳴(FMR)励起によるスピンプンピングを用いて有機分子薄膜にスピントランスポートを生成する。このスピントランスポートは分子薄膜中を流れ、ITO 層に吸収される。この吸収されたスピントランスポートは逆スピントランスポート効果(ISHE[3])によって電流へと変換され、電気抵抗を介して起電力として検出される。この起電力を観測できれば、分子薄膜のスピントランスポートの証拠となる。FMR の励起には電磁石による静磁界とネットワークアナライザから伝送線路に印加する高周波電流による高周波磁界を用いた。起電力特性の評価にはナノボルトメータを用いた。

Fig. 1 に FMR スペクトルと FMR 磁界(H_{FMR})付近にて ITO 層から検出された起電力特性を示す。起電力のピークが H_{FMR} 付近で観測され、静磁界の印加方向(θ)の反転に伴い、起電力の符号が反転した。このことから測定された起電力は ISHE による起電力の特徴と一致する[3]。これらのことから ITO/Rubrene/Ni₈₀Fe₂₀ の三層試料を用いて Rubrene 分子薄膜のスピントランスポートを達成したと結論づけた。学会時には光照射実験を含む研究の詳細について議論する。

[1] S. Watanabe, et al., Nature Phys., **10**, 308 (2014).

[2] E. Shikoh, et al., Solid State Commun., **379**, 115430(2024).

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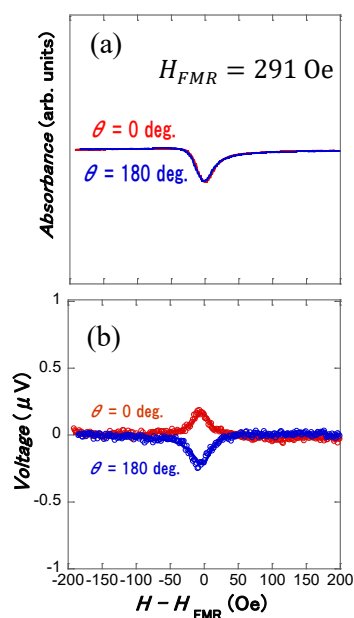


Fig. 1. (a) FMR spectra and (b) output voltage properties generated in a tri-layer structure sample under the FMR, at 5 GHz.

スピンプンピングを用いる分子薄膜二層構造のスピンの輸送

Spin-pumping-induced spin transport in molecular thin film bilayer structures

阪公大院工¹, °(M1)佐野 尊¹, (M2)高松 恵人¹, 脇 主助¹, 仕幸 英治¹

Osaka Metro. Univ. Eng.¹, °Takeru Sano¹, Keito Takamatsu¹, Shusuke Waki¹, Eiji Shikoh¹

E-mail: sr25892e@st.omu.ac.jp

主に軽元素で構成される有機分子材料はスピン軌道相互作用が弱くスピン流の散逸が少ないと考えられるため、長距離のスピン輸送が可能と考えられている。これまでに動力的スピン注入法によって様々な有機分子材料のスピン輸送が実証されてきた[1,2]。一方、その応用には二層以上の分子薄膜積層構造におけるスピン流輸送機構の解明が必要である。本研究室ではこれまでにPd/PTCDA 分子層/pentacene 分子層/ $\text{Ni}_{80}\text{Fe}_{20}$ の四層構造試料に対し、 $\text{Ni}_{80}\text{Fe}_{20}$ のスピンプンピングによるスピン輸送を実証した[3]。また、算出された PTCDA 層のスピン拡散長は Pd/PTCDA/ $\text{Ni}_{80}\text{Fe}_{20}$ 三層構造試料による評価[2]と比べて増加した。本研究ではこのスピン拡散長増加の要因を探るために pentacene 層と PTCDA 層の積層順序を入れ替えた Pd/pentacene/PTCDA/ $\text{Ni}_{80}\text{Fe}_{20}$ 四層構造試料 (Fig. 1) のスピン輸送特性を調査した。

電子ビーム蒸着法、抵抗加熱蒸着法を用い、熱酸化膜付き Si 基板上に Pd(膜厚 10 nm)/pentacene(30 nm)/PTCDA(d)/ $\text{Ni}_{80}\text{Fe}_{20}$ (25 nm) 四層構造試料 (Fig. 1) を作製した。 $\text{Ni}_{80}\text{Fe}_{20}$ 層の強磁性共鳴(FMR)励起によるスピンプンピングにより pentacene 層にスピン流を注入し、pentacene/PTCDA 層を輸送したスピン流は Pd 層の逆スピンホール効果(ISHE)[4]により起電力に変換される。この起電力の観測がスピン輸送の証拠となる。FMR の励起にはネットワークアナライザと電磁石を用いた。起電力の測定はナノボルメータを用いた。

Fig. 2 に試料の(a)FMR スペクトルと(b)FMR 励起下で Pd 層から検出された起電力特性を示す。 H_{FMR} 付近において起電力が観測され、静磁界の印加方向の反転に伴い起電力の符号も逆転した。これらの特性はスピンプンピングによって注入されるスピン流を ISHE によって変換して得られる起電力の特性と一致した[4]。以上より分子薄膜二層構造のスピン輸送に成功したと結論付けた。学会時には先行研究との比較を含め、研究の詳細について議論する。

[1] S. Watanabe, et al., Nature Phys., 10, 308 (2014). [2] K. Nishida, et al., Solid State Commun., 312, 113898 (2020). [3] 脇, 仕幸ら, 第 83 回応用物理学会秋季学術講演会, 21a-P02-10, (2022), [4] E. Saitoh, et al., Appl. Phys. Lett., 88, 182509 (2006).

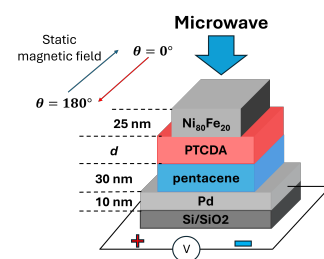


Fig. 1. Sample structure.

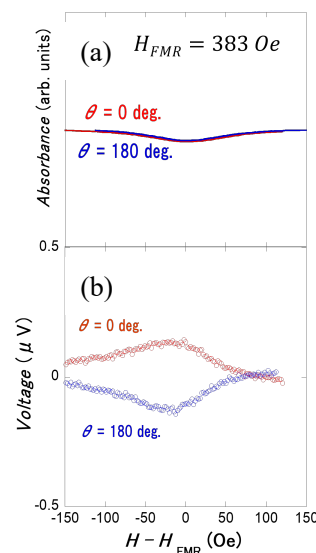


Fig. 2. (a) FMR spectra, and (b) detected voltage properties of a sample, at 5 GHz.

First-principles calculations of angle dependent XMCD/XMLD:

A case study of strain-induced D0₂₂-Mn₃Ga

Mie Univ¹, Gadjah Mada Univ² °(M2)Rikuto Takai¹, Muhammad Arifin^{1,2}, Kohji Nakamura¹

E-mail: 424M222@m.mie-u.ac.jp

Angle-dependent x-ray magnetic circular dichroism (XMCD) and x-ray magnetic linear dichroism (XMLD) are known to be powerful tools for analyzing electronic and spin structures. We have recently developed a computational code for the angle-dependent XMCD/XMLD spectra based on all-electron full-potential linearized augmented-plane-wave (FLAPW) method[1]. This approach is applied to the strained D0₂₂-Mn₃Ga – a material of potential interest owing to its tunable high spin polarization, low Gilbert damping, reduced saturation magnetization, and large perpendicular magnetic anisotropy (PMA) [2]. Angle-dependent XMCD, measurements were performed by varying both the x-ray incidence and magnetization directions from out-of-plane ($\theta = 0^\circ$) to in-plane ($\theta = 90^\circ$) in 15° increments. For the XMLD analysis, difference spectra between out-of-plane and in-plane linear polarizations were calculated. First-principles calculations at the Mn L_2 and L_3 edges of Mn₃Ga show weak angular dependence at the Mn(2b) site but pronounced dependence at the Mn(4d) site. With a nearly constant L_2/L_3 intensity ratio, XMCD sum-rules analysis indicates that the magnetic dipole term, m_T , is primarily responsible for the observed variations. The XMLD results reveal a finite quadrupole moment Q_{zz} at the Mn(4d) site, which we analyzed in relation to the expression $m_T = -SQ_{zz}$. This study focuses on the electron-theoretical XMLD method and discusses, how strain influences the quadrupole moment and magnetic anisotropy of Mn₃Ga.

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(110)配向 Co 基ホイスラー合金単結晶薄膜の作製と評価

Fabrication and characterization of (110) oriented epitaxial Co-based Heusler alloy thin films

東北大工¹, °北條峻之¹, (D) 網家大輔¹, (D) 渡部健太¹, 窪田崇秀¹, 角田匡清¹, 大兼幹彦¹
 Tohoku Univ.¹, °Takayuki Hojo¹, (D) Daisuke Amii¹, (D) Kenta Watanabe¹, Takahide Kubota¹,
 Masakiyo Tsunoda¹, Mikihiro Oogane¹
 E-mail: takayuki.hojo.d1@tohoku.ac.jp

トンネル磁気抵抗(TMR)センサは、室温で動作可能な高感度磁気センサであり、その磁場分解能は 1 Hz で 940 fT/Hz^{0.5} と極めて優れている[1]。これは、現在最も高感度とされる SQUID に迫る性能である。TMR センサのさらなる高感度化には、高い TMR 比と小さな磁気異方性が不可欠であり、これらの特性を兼ね備えた材料の開発が進められている。中でも、センダストや Co 基ホイスラー合金などの立方晶系単結晶材料が有望視されているが[2,3]、これら単結晶材料は固有の結晶磁気異方性を有するため、(001)配向した単結晶薄膜では形状磁気異方性や誘導磁気異方性によって容易に一軸異方性を付与することが難しい。そこで本研究では、Co₂FeAl_{0.28}Si_{0.72} (以下 CFAS) 合金を(110)方位に単結晶成長させることで、薄膜面内に一軸異方性を導入することを試みた。

Al₂O₃ (11-20)単結晶基板上に、Ta (20 nm)/ Cr (60 nm)/ CFAS (50 nm)/ Ru (5 nm) 多層膜をマグネトロンスパッタリング法により成膜した。ここで、Ta および Cr は格子不整合を緩和する下地層として機能している。図 1(a)に示す XRD による $2\theta/\omega$ スキャンの結果から Ta、Cr、CFAS 層はいずれも(110)方位にエピタキシャル成長していることが確認された。 ϕ スキャンの結果からは、Ta 層にわずかな双結晶成分が見られるものの、Cr および CFAS 層は単結晶成長していることが分かる。以上より、(110)結晶配向の単結晶 CFAS 薄膜の作製に成功した。図 1(b)には VSM によって測定した磁化曲線を示す。赤および青の実線は、それぞれ薄膜面内の CFAS [1-10]および CFAS [001]方向に磁場を印加した場合の結果であり、[1-10]方向が磁化容易軸、[001]方向が磁化困難軸となる一軸磁気異方性が形成されていることが分かる。この面内磁気異方性は結晶磁気異方性エネルギー、弾性エネルギー、並びに磁気弾性エネルギーによって決定される。発表当日は、これらに加えて磁気異方性の詳細な解析結果についても併せて報告する予定である。

本研究は、SIP project、BRIDGE project、SCOPE project、NEDO leading project、JST K-program、CSIS、CIES、JSPS、GP-Spin (東北大学)、X-nics の支援を受けて行われた。

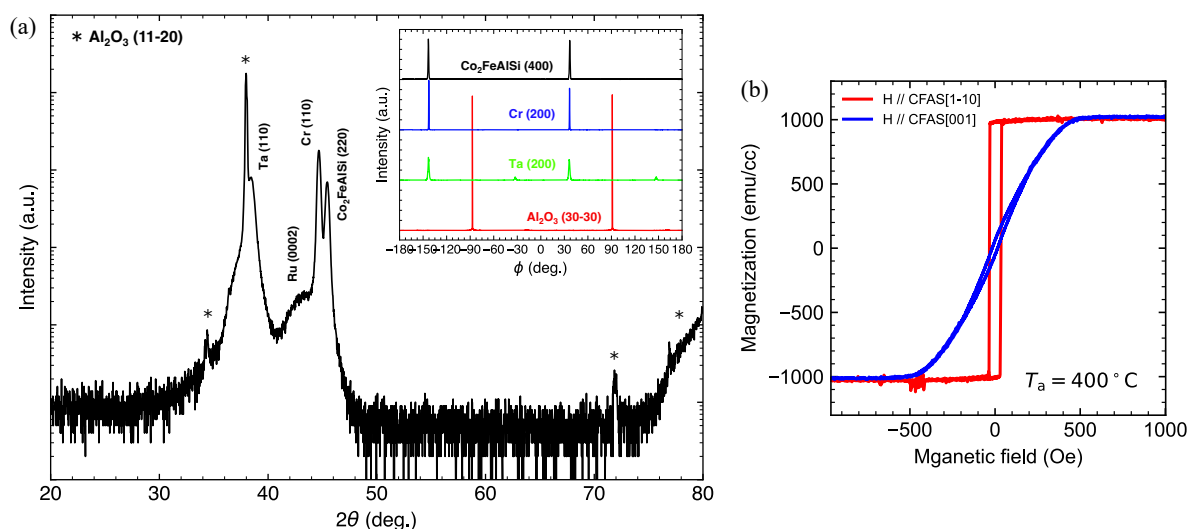


図 1 (a) 薄膜の $2\theta/\omega$ スキャンおよび ϕ スキャンの結果と、(b)磁化曲線の結果

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4 元系ホイスラー合金 CoFeCrAl の磁気体積効果

Magnetovolume effect of quaternary Heusler alloy CoFeCrAl

鹿大院理工¹, 東大物性研², 東北大金研³, 東北学院大院工⁴

○重田 出¹, 辻川 総一郎¹, 郷地 順², 梅津 理恵³, 鹿又 武⁴, 上床 美也², 廣井 政彦¹

Kagoshima Univ.¹, Univ. of Tokyo², Tohoku Univ.³, Tohoku Gakuin Univ.³

○I. Shigeta¹, S. Tsujikawa¹, J. Gouchi², R. Y. Umetsu³, T. Kanomata⁴, Y. Uwatoko², M. Hiroi¹

E-mail: shigeta@sci.kagoshima-u.ac.jp

スピンギャップレス半導体 (SGS) は、アップスピンの価電子バンド端と伝導バンド端がフェルミエネルギー E_F で接し、ダウンスピンのバンドは E_F においてギャップが存在する。この特殊なバンド構造を反映して、少数キャリアかつ高スピン分極率の特徴を有する機能性材料として期待されている。第一原理バンド計算から SGS であると予想されるホイスラー合金 CoFeCrAl の結晶構造や磁化特性、輸送特性、磁化の圧力効果について調べた。

試料はアーク溶解法で合成した。粉末 X 線回折測定を行い、結晶構造を評価した。超伝導量子干渉計 (SQUID) と試料振動型磁力計 (VSM) を用いて磁化測定を行い、物理特性測定システム (PPMS) を用いて電気抵抗を測定した。SQUID とピストンシリンダー型圧力セルを使用して高圧下磁化測定を行った。

粉末 X 線回折測から超格子ピークの(111)や(200)が観測されたことから、合成した試料が高規則度の $L2_1$ 構造を持つことが確認された。CoFeCrAl のキュリー温度 T_C は、室温より十分高い 522 K であった。10 K での磁化曲線 $M(H)$ から常圧下における自発磁化 M_s は $2.01 \mu_B/\text{f.u.}$ と見積もられ、磁気モーメントが Slater-Pauling 則に従うことから、 E_F においてダウンスピンの状態密度にギャップが開いていることが示唆される。電気抵抗の温度依存性は、室温から 50 K まで金属的な振る舞いを示したものの、50 K から 2 K で半導体的な振る舞いが観測された。これは、CoFeCrAl のアップスピンバンドが E_F 付近で有限の状態密度をもつことを反映したものであると考えられる。10 K での $M(H)$ の圧力依存性を図 1 に示す。挿入図は、図 1 から得られた M_s の圧力依存性である。 M_s が圧力に依存しない特性は、 E_F で CoFeCrAl のダウンスピンバンドの状態密度にギャップが存在することに起因していると考えられる。以上の実験結果は、CoFeCrAl が SGS に近い状態密度を持ち、スピン分極率が高い機能性材料であることを支持するものである。

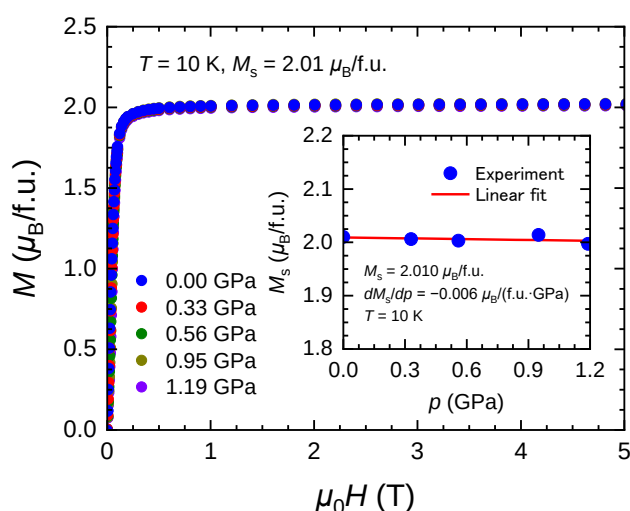


図 1: 高圧下における CoFeCrAl の磁化測定

六方晶 Fe_3Sn 及び Fe_3Sn_2 合金薄膜の作製と磁気特性評価

Preparation and investigation on magnetic properties for hexagonal Fe_3Sn and Fe_3Sn_2 alloy films

名工大工〇(M1) 杉本 壮琉, 田中 雅章, 伊藤 史弥, 壬生 攻

Nagoya Institute of Technology

°Takeru Sugimoto, Masaaki A. Tanaka, Fumiya Itoh, and Ko Mibu

1. はじめに

六方結晶族の Fe_3Sn 合金や Fe_3Sn_2 合金は Fe の磁気モーメントがカゴメ格子状に配列し、その配列に起因した内因性の異常ホール効果や異常ネルンスト効果を示すといわれており [1-3]、近年この特性を用いた磁気センサなどへの応用に向けた研究が盛んに行われている。 Fe_3Sn 合金や Fe_3Sn_2 合金はメスバウアー原子種である Fe と Sn を含むためこれらの原子種を対象とした局所的な磁性評価が可能である。本研究では、 Fe_3Sn 合金薄膜の異常ホール効果と局所的な磁性との相関関係の調査を目的に研究を行った。

2. 実験方法

膜厚 3 nm の Pt バッファ層を蒸着した $\text{Al}_2\text{O}_3(0001)$ 基板上に、Fe と Sn を原子層レベルで交互に蒸着して膜厚 30 nm の Fe-Sn 合金薄膜（目的物質）を成膜した。製膜温度は 50 ~ 400 °C の間で変化させた。作製した試料に対して、X 線回折(XRD)測定、SQUID 磁化測定、ホール効果測定、および ^{57}Fe と ^{119}Sn のメスバウアー分光測定を行った。

3. 実験結果

XRD 測定から、 Fe_3Sn_2 及び Fe_3Sn 合金薄膜が六方晶(0001)配向して成長していることが分かった。また、メスバウアー分光測定から、 Fe_3Sn 合金や Fe_3Sn_2 合金以外の物質も生成され、製膜温度によりその割合が異なることがわかった。これらの結果から、製膜温度が 100°C

の試料では Fe_3Sn_2 及び Fe_3Sn 合金の割合がもっとも大きいことがわかった。作製した試料のホール測定を行い、見積もったホール抵抗率 ρ_{xy} から異常ホール係数 R_s を算出した。

Fig. 1 に ^{57}Fe メスバウアー分光測定と ^{119}Sn メスバウアー分光測定から得られた Fe_3Sn_2 及び Fe_3Sn 合金の割合と異常ホール係数 R_s との関係を示す。試料内の Fe_3Sn_2 及び Fe_3Sn 合金の割合が大きいほど、異常ホール係数 R_s が大きいことがわかり、異常ホール係数 R_s の原因が Fe_3Sn_2 及び Fe_3Sn 合金に由来することが示唆された。

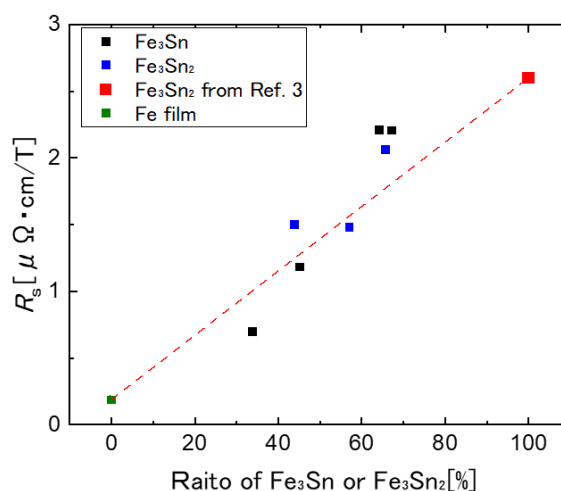


Fig.1 Anomalous Hall coefficient R_s as a function of the ratio of Fe_3Sn or Fe_3Sn_2

[1] D. Khadka *et al.*, Phys. Rev. Mater. **4**, 084203 (2020).

[2] O. Chen *et al.*, Sci. Adv. **8**, eabk1480 (2022).

[3] K. Khan *et al.*, Nanoscale **14**, 8484(2022).

スピン注入に対する GdFeCo/YH₂ 界面実効面積

Effective Contact Area in GdFeCo/YH₂ Junction for Spin Injection

埼玉大理工¹, 東洋大², 豊田工大³

鈴木 颯人¹, 増井 拓郎¹, 戸沢 遥哉¹, 秋山 大伍¹,

酒井 政道¹, 花尻 達郎², 鷺見 聡³, 栗野 博之³

Saitama Univ.¹, Toyo Univ.², Toyota Technol. Inst.³

Hayato Suzuki¹, Haruchika Tozawa¹, Daigo Akiyama¹, Takuro Masui¹, Masamichi Sakai¹,

Tatsuro Hanajiri², Satoshi Sumi³, Hiroyuki Awano³

E-mail: sakai@fms.saitama-u.ac.jp

【緒言】磁気的 2 重ヘテロ構造 (MDHJ) におけるスピン-電荷結合界面抵抗、スピン蓄積信号、およびスピン流密度は、共に、強磁性金属 (F) と非磁性金属 (N) との界面を貫通する電流密度に比例するので[1]、消費電力を増やすことなく素子性能を上げるには、電流経路長を変えることなく F/N 界面接触面積を出来るだけ小さくすればよい。我々は、MDHJ をフェリ磁性金属 GdFeCo と電子正孔補償金属 YH₂ との組合せから構成し、これまでに N 領域中のスピン輸送を調べてきた[2]。本講演では、F 領域から N 領域へのスピン注入機構に注目する。

【実験方法】MDHJ の N 領域で発生する逆スピン Hall 効果 (ISHE) を、GdFeCo から構成するソース・ドレイン電極に関する 4 種類の磁化配置 : (i) 上向き平行配置 (↑↑)、(ii) 下向き平行配置 (↓↓)、(iii) 反平行配置 I (↓↑)、および(iv) 反平行配置 II (↑↓) の下で測定する。↑↑配置のスピン流の向きは、保磁力以上の逆磁場を印加して、下向き↓↓にすると反転するので、発生する ISHE 電圧の極性も反転する。次に、初期状態を↑↑にし、磁気モーメントに反対向きの弱い外部磁場 (約 1 mT) を印加しながら、片方の F 領域中、N 領域に近い場所を紫外レーザー (波長 405 nm) によって加熱し GdFeCo (Curie 温度約 200 °C) を常磁性化する。その後、室温に戻せば、レーザー照射された領域のみが磁化反転して、↓↑配置が得られる。同様なことを、初期状態↓↓に施せば、↑↓配置が得られる。

【結果・考察】測定結果から、 $\alpha \equiv R_T(\uparrow\uparrow) - R_T(\downarrow\downarrow)$ 、 $\beta \equiv R_T(\uparrow\uparrow) - R_T(\downarrow\uparrow)$ 、 $\gamma \equiv R_T(\uparrow\downarrow) - R_T(\downarrow\downarrow)$ に対して、 $\alpha = 3.7 \text{ m}\Omega$ 、 $\beta = 1.6 \text{ m}\Omega$ 、 $\gamma = 1.3 \text{ m}\Omega$ が得られた。原理上、 $R_H(\downarrow\downarrow) = -R_H(\uparrow\uparrow)$ 、 $R_H(\uparrow\downarrow) = -R_H(\downarrow\uparrow)$ 、 $\alpha = 2R_T(\uparrow\uparrow)$ および $\beta + \gamma = \alpha + 2R_T(\uparrow\downarrow)$ なので、 $R_T(\uparrow\uparrow) = 1.85 \text{ m}\Omega$ および $R_T(\uparrow\downarrow) = -0.4 \text{ m}\Omega$ が得られる。したがって、 $R_T(\uparrow\downarrow)/R_T(\uparrow\uparrow) = -0.22$ である。この比は、電子スピン流拡散長 $\ell_e = 45 \text{ }\mu\text{m}$ 、正孔スピン流拡散長 $\ell_h = 56 \text{ }\mu\text{m}$ 、電子スピン Hall 角 $\theta_{\text{SHE}}^{(e)} = -1^\circ$ 、正孔スピン Hall 角 $\theta_{\text{SHE}}^{(h)} = 1.2^\circ$ にすれば、従来理論[1]をアンビポーラ系に拡張した ISHE 抵抗表式[2]を使って説明できる。また、 $R_T(\uparrow\uparrow) = 1.85 \text{ m}\Omega$ を説明するには、F/N 界電流密度 (J^*) の N チャネル電流密度 (J) に対する比を、 $J^*/J_c = 720$ にする必要がある。このことは、F/N 界面実効面積が、N チャネル断面積 (約 $6 \text{ }\mu\text{m}^2$) の約 720 分の 1 であることを意味する。

[1] Fert A and Lee S H 1996 *Phys. Rev.* **B53** 6554

[2] Yamazaki I et al 2025 *J. Phys. :Condens. Matter* **37** 065804

GdFeCo と YH₂ から構成したスピンバルブ構造におけるスピン蓄積抵抗 Spin Accumulation Resistance in Spin Valve Structure composed of GdFeCo and YH₂

埼玉大理工¹, 東洋大², 豊田工大³

増井 拓郎¹, 戸沢 遥哉¹, 秋山 大伍¹, 曳町 光紀¹, 松田 希望¹,

酒井 政道¹, 花尻 達郎², 鷲見 聡³, 栗野 博之³

Saitama Univ.¹, Toyo Univ.², Toyota Technol. Inst.³

Takuro Masui¹, Haruchika Tozawa¹, Daigo Akiyama¹, Mistuki Hikimachi¹, Nozomi Matsuda¹,

Masamichi Sakai¹, Tatsuro Hanajiri², Satoshi Sumi³, Hiroyuki Awano³

E-mail: sakai@fms.saitama-u.ac.jp

【緒言】 グラフェン並みの室温スピン拡散長を示すと考えられる観測データが、電子-正孔補償金属 YH₂ に対して報告されている[1, 2]。これらは逆スピン Hall 効果(ISHE)という観測方法およびその観測用に作製した Hall-bar 構造と云う限定的条件下で得られたものである。本研究ではこれらに異なる観測方法かつ異なる素子構造にもとづいて、長距離スピン輸送特性の検証実験を行う。

【実験方法】 作製したスピンバルブ構造中心部の顕微鏡写真を Fig. 1 に示す。電極配置は文献[3]にほぼ同様である。先行研究[1, 2]の Hall-bar 構造に比べて、強磁性金属 (F) 領域に GdFeCo を、非磁性金属 (N) 領域に YH₂ を使った点は同じであるが、電極形状・配置は全く異なる。2つの GdFeCo 電極間の N チャネル長は約45 μm である。このスピンバルブ構造には ISHE 測定用電極が設置されている。ISHE 測定では、Fig. 1 左右の Cu 電極から注入された電流の1部は、GdFeCo 領域を介して YH₂ 領域に供給され、上下の Cu 電極によって Hall 電圧が検出される。スピン蓄積信号測定では、Fig. 1 右側の Cu-GdFeCo 間に電流を供給し、左側 Cu-GdFeCo 間に発生する電圧を検出する。

【結果・考察】 ISHE 測定結果を Fig. 2 に示す。印加磁場は素子面に対して垂直に印加しているので、F 領域の磁気モーメントも素子面に対して垂直である。Hall 抵抗全体を(a)に、ローレンツ力による正常 Hall 効果成分除去後を(b)に示す。F 領域の磁化過程に連動したヒステリシス信号は、F 領域を介して N 領域に注入されたスピン流が ISHE によって、横方向に電荷蓄積をもたらしたと解釈できる。このことから、報告されている YH₂ の長距離スピン輸送特性は、先行研究において作製・使用された Hall-bar 構造特有な現象でなく、GdFeCo と YH₂ との組合せに特徴的な現象であると云える。N 領域へのスピン注入が確認できたので、現在、同じ素子に対するスピン蓄積信号測定を行っている。

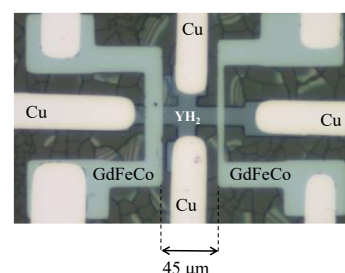


Fig. 1 Optical microscopy image of the spin valve structure used in the present measurements. The N channel (YH₂) length is approximately 45 μm .

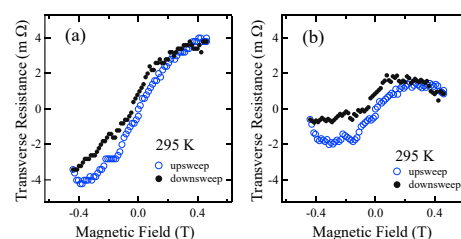


Fig. 2 Room temperature Hall resistance measured by using the spin valve structure shown in Fig. 1: (a) Total Hall resistance and (b) The residual Hall resistance, which is obtained by subtracting the ordinary Hall resistance from (a).

[1] Sato K et al 2023 *J. Phys. Scr.* **98** 045912

[2] Yamazaki I et al 2025 *J. Phys. : Condens. Matter* **37** 065804

[3] Valenzuela S O and Tinkham M 2006 *Nature* **442** 179

永久磁石を用いた汎用性の高い磁気浮上装置の開発

Development of a Versatile Magnetic Levitation Device Using Permanent Magnets

日工大院工 ○後藤 輝, 池添 泰弘

Hikaru Goto and Yasuhiro Ikezoe

Graduate School of Engineering, Nippon Institute of Technology

°E-mail: y.ikezoe@nit.ac.jp

永久磁石を用いた反磁性磁気浮上は、浮上させた物体を室温で静的な環境で半永久的に保持できるという特徴を持ち、重力下での実験環境とは大きく異なる特殊な環境が容易に得られる。また、超電導磁石を用いた反磁性磁気浮上装置と比較すると、安定浮上条件を満たす磁気力場の範囲が広いことも大きな特徴である。したがって、浮上状態を保ったまま、液体から固体への状態変化を起こしたり、水溶液から溶質を再結晶させたりすることも可能である。我々はこれまでに長方形の側面を持つ永久磁石を接触させたときに稜線部に形成される細長い谷状の隙間の磁場分布を精密に計算することによって、その隙間に液体や固体を安定に磁気浮上させることが可能となるような磁石配置を複数例示してきた¹⁾。今回、磁石配置を工夫することによって、安定浮上条件が劇的に緩和されるような磁石配置を発見したので報告する。

Figure 1-(a)に磁石配置の例を示した。下側に1対の直方体磁石（幅4.5 mm、奥行10 mm、高さ12 mm）、上側に1対の円柱磁石（直径3 mm、高さ3 mm）が配置されており、2つの円柱磁石の隙間には x 方向に d mmの隙間が設けられている。また、円柱磁石下面と直方体磁石の上面は h mm離れている。磁場分布 simulation (Simcenter MAGNET, Siemens)においては、下側の磁石の最表面を $z = 0$ とし、直方体磁石の稜線のフィレット半径を0.5 mm、円柱磁石の円周部のフィレット半径を0.2 mmと設定した。この磁石配置では、下側の直方体磁石対が上向きの強い磁気力を発生させ、上側の円柱磁石対が非接触安定浮上のための磁場変調の役割を担っている。Fig. 1-(b)は $d = 1$ mm, $h = 0, 0.5, 1$ mmの場合の、下側磁石の隙間における z 軸方向の磁場分布のシミュレーション結果である。円柱磁石と下側の磁石の距離 h が大きい方が最大磁場は大きかった。Fig. 1-(c)は、 $(x, y) = (1$ mm, 0 mm)を通過して z 軸と平行な線上の磁場から z 軸上の磁場を引いた値(ΔB)の z 方向の分布を表していて、 ΔB が正の場合は x 方向の磁場分布が下に凸になり、非接触安定浮上が可能となる。 $h = 1$ mmの場合には、 z 軸上の広い範囲で ΔB が正となっていて、安定浮上領域がこれまでの10倍以上に広がる。このような系ではマイクロシリッジ等で浮上液滴を導入するような実験も実現できる可能性があり、本系は、将来の磁気浮上実験を劇的に進化させることが期待される。

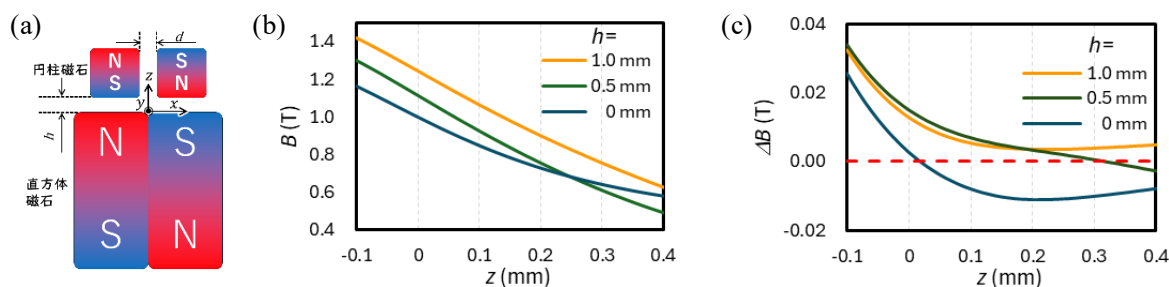


Fig. 1 (a) Configuration of the magnets. (b) Magnetic field distribution along the z -axis. (c) Distribution of the magnetic field difference, ΔB , between the values at $x = 1$ mm and $x = 0$ mm along the z -axis.

[1] T. Naito, *et al.*, *Appl. Phys. Lett.* **125**, 264102 (2024)

ハルバツハ配列を利用した永久磁石磁気浮上装置の開発

Development of a Permanent Magnet Levitation System Using a Halbach Array

日工大院工 °戸枝隼人, 池添 泰弘

Hayato Toeda and Yasuhiro Ikezoe

Graduate School of Engineering, Nippon Institute of Technology

°E-mail: y.ikezoe@nit.ac.jp

永久磁石を用いた反磁性磁気浮上は、非常に安価に装置を作ることが出来る上に、室温の静的な環境下で、消費エネルギーはほぼゼロの状態では物体を浮上させ続けることが出来る¹⁾。永久磁石を利用して強い磁場を得るためには、狭い空間に磁場を集中させることが鍵となっていて、例えば、直方体の磁石を接触させたときに接触面の端に出来る細長い空間は、強磁気力場の発生に適した空間となる。このように、一般に永久磁石を用いて強い磁気力場を発生させるには、磁石を2個以上利用するが、磁石を組み合わせる際に磁石の持つ引力を利用する場合、永久磁石の配置に制限が加わる。一方で、磁石の磁化の向きを無視して、特定の空間の磁場の増大だけを目的とすれば、ハルバツハ配列のように、磁石間で反発力が発生するような磁石配置を使うことによって、非常に強い磁場を作ることが出来る。そこで、本研究では、ハルバツハ配列に似た磁石配置を利用して、強力な磁場を発生し得る磁気浮上装置の開発に取り組んだ。

Figure 1-(a)に磁石配置の例を示した。磁場分布 simulation (Simcenter MAGNET, Siemens)に使用した磁石は、材質が N52 の直方体磁石 (5 mm x 2 mm x 10 mm、エッジのフィレット半径は 0.5 mm) で、Type A は磁石 1 対のみ、Type B は Type A に両側面から水平な磁場を重畳する形で同じ磁石を 1 対追加したものである。Type B の側面に追加された磁石と中央の磁石は反発し合う形で配置され、ハルバツハ配列に類似しており、Type B の磁気力場 $B\partial B/\partial z$ の大きさは、Type A ($2,006 \text{ T}^2/\text{m}$) に比べて劇的に増大して $2,533 \text{ T}^2/\text{m}$ に達することがわかった。また、非接触安定浮上を実現するには、水平方向の磁場分布が下に凸になる必要があるので、Type C として、Type B の上側に同じ磁石を異なる向きで 1 対追加したシステムの磁場分布も計算したところ、磁気力場 $B\partial B/\partial z$ はさらに増大して $2,588 \text{ T}^2/\text{m}$ に達することがわかった。Fig. 1-(b)は Type C の原点付近の xz 平面における磁場強度の 2 次元マップで、水平方向に下に凸になった磁場分布が上方まで明確に表れていることから、多様な物質の磁気浮上が一つの磁石配置で実現できることもわかる。これらの結果は、ハルバツハ配列に類似した磁石配置が、磁気浮上のための磁場分布のデザインに極めて有用であることを示しており、磁気浮上装置開発に大きな進展をもたらすことが期待される。

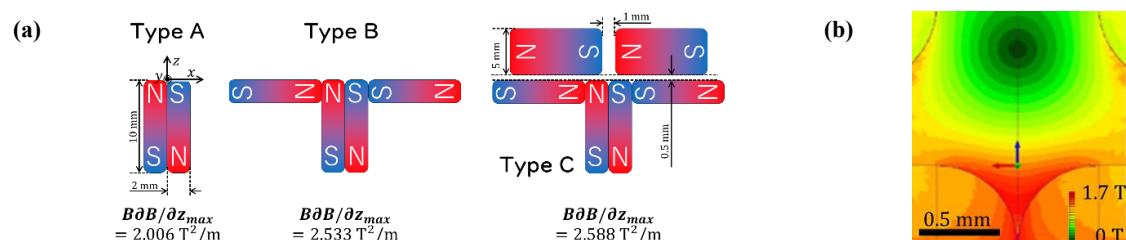


Fig. 1 (a) Configuration of magnets. Although Types A, B, and C have different appearances, they are all composed of identical permanent magnets combined with different orientations. (b) Two-dimensional magnetic field distribution around the origin.

[1] T. Naito, *et al.*, *Appl. Phys. Lett.* **125**, 264102 (2024)

マグノントランジスタに向けたスピン波の伝搬特性解析

Analysis of Spin Wave Propagation Characteristics for Magnon Transistor

福岡大理, °(M1) 後藤広哉, 洞口泰輔, 眞砂卓史

Fukuoka Univ. °H. Goto, T. Horaguchi, and T. Manago

E-mail: sd251003@cis.fukuoka-u.ac.jp

〔研究背景〕

現在、スピン波を用いたマグノントランジスタが提案され、新たな論理デバイスとして期待されている[1]。しかし、導波路に YIG を用いており Si プロセスとの相性の問題から微細化が難しい。本研究では、Si プロセスにおいて微細化が容易である Py を導波路に用いたマグノントランジスタにおけるスピン波伝搬の 2 次元シミュレーションを行い、トランジスタ動作の可否を調べた。

〔計算手法〕

スピン波の伝搬の計算には COMSOL を用いた。高さ 130 nm、長さ 204.8 μm の Py 導波路から 80 nm 上にシグナル線 1 μm 、グラウンド線 50 μm のソースアンテナとドレインアンテナ、そしてシグナル線 1 μm 、グラウンド線 1 μm のゲートアンテナを設置して、ゲートアンテナ下には構造周期 2.0 μm のマグノニック結晶を作製した (Fig. 1)。このようなマグノントランジスタにソースアンテナ・ゲートアンテナから個別に、もしくは同時に電流を流してドレインアンテナ下の磁化のデータを得た。得られたデータに Python のプログラムを用いて伝搬特性を解析した。

〔結果〕

Fig. 2(a)はゲートアンテナ($x = 0 \mu\text{m}$ 付近)に振幅 1 mA、周波数 6.74 GHzの正弦波電流を印加した際の x 軸方向に沿ったスピン波強度分布である。励起周波数と同じ 6.74 GHzのスピン波がゲート付近へ局在し、ゲート信号の空間的閉じ込めに成功している。そして、Fig.2 (b)はソースアンテナとゲートアンテナにそれぞれ振幅 10 mA のガウシアンパルス電流と、振幅 1 mA・周波数 6.74 GHzの正弦波電流を個別に印加した場合のスピン波強度(合成強度、青実線)と、それらの電流を同時に印加した場合のスピン波強度 (ソース・ゲート同時、緑実線)を比較したものである。この図からゲートマグノンによるソースマグノン伝搬の抑制が見られており、スピン波トランジスタ動作が可能であると考えられる。

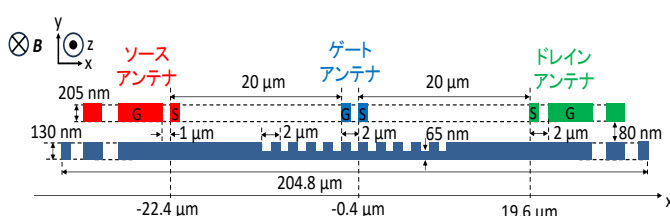


Fig. 1 Schematic sample structure of magnon transistor.

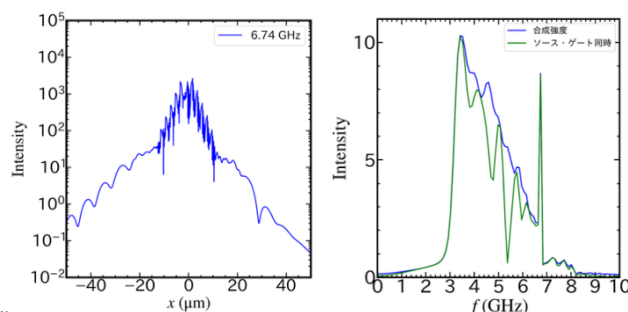


Fig. 2 (a) Spinwave (6.74 GHz) intensity distribution excited by a gate antenna and (b) transmitted spinwave intensity under a drain antenna.

<参考文献> [1] Chumak, A. V. et al. Nat. Commun. 5:4700 (2014).

障壁幅変調によるスピン波バンド構造の制御と Kronig-Penney モデルによる解析

Wall Width Modulation Effects on Magnonic Band Structure: A Kronig-Penney Model Analysis

福岡大理, °洞口 泰輔, 眞砂 卓史
Fukuoka Univ., °Taisuke Horaguchi, Takashi Manago
E-mail: t.horaguchi@fukuoka-u.ac.jp

【背景・目的】

スピン波とは磁化の歳差運動が位相差を伴って磁性体中を伝わる波であり、次世代の情報伝送媒体として注目されている。人工的に形状や材料に微細な周期構造を導入した磁性体（マグノニック結晶）では、波数選択的なスピン波の伝搬制御が可能であり、各種デバイスへの応用が期待されている[1]。たとえば、Fig. 1 のように x 軸方向に凹凸形状の障壁を周期的に配置した1次元マグノニック結晶では、構造周期と同程度の波長のスピン波伝搬が抑制され、バンド中にギャップが形成されることが知られている[2]。スピン波バンド構造はマグノニック結晶の幾何形状に大きく依存するが、特に凹凸形状における「障壁と谷の幅比」がどのようにバンドギャップに影響を与えるかは十分に検討されていない。本研究では、この幅比の変化が1次元マグノニック結晶のバンド構造に及ぼす影響を、(1)マイクロマグネティクス計算、(2)Kronig-Penney モデルによる理論解析、の両手法で定量的に評価し、そのメカニズムを明らかにした。

【マイクロマグネティクス計算】

様々な障壁幅 d_{wall} を持つマグノニック結晶におけるスピン波の伝搬を Mumax³[3]を用いて計算した。計算後、磁化の空間分布と時間発展波形をFFT処理することで各構造におけるスピン波のバンド構造を明らかにした。構造周期は $D = 2.0 \mu\text{m}$ で一定とし、障壁幅を変化させることで幅比を系統的に変化させた。外部磁場は y 方向に印加し、MSSW (magnetostatic surface spin wave) モードが励起される条件とした。Fig. 2(a)に示すように、第1バンドギャップは幅比約1:1で最大化される一方、第2バンドギャップは幅比0.6:1.4および1.3:0.7付近で局所的極大を示すという、非単調な挙動を示した。

【スピン波分散関係を考慮した Kronig-Penney モデル】

1次元マグノニック結晶中の周期ポテンシャルをFig. 1のようにモデル化した。平面波を仮定し、Blochの定理と境界での連続条件を用いると、一般的なKronig-Penneyモデルと同様にバンド構造解析は次式の解の存在条件問題に帰着する。

$$\cos(KD) = \cos(k_2a) \cos(k_1b) - \frac{k_1^2 + k_2^2}{2k_1k_2} \sin(k_2a) \sin(k_1b), \quad (a = l_{\text{wall}}, b = D - l_{\text{wall}})$$

上記のモデル化に基づき、MSSWモードのスピン波分散関係を取り入れたKronig-Penneyモデルを構築し、第1・第2バンドギャップ幅を計算した(Fig. 2(b))。この結果はマイクロマグネティクス計算の結果と良く一致しており、凹凸形状の障壁を周期的に配置した1次元マグノニック結晶のバンド構造は、Kronig-Penneyモデルによって定量的に記述可能であることが明らかとなった。この結果は、今後のマグノニック結晶設計における有効な指針となることが期待される。

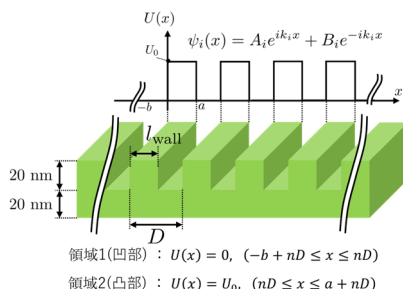


Fig.1 Schematic image of a 1D magnonic crystal and a potential model for spin waves.

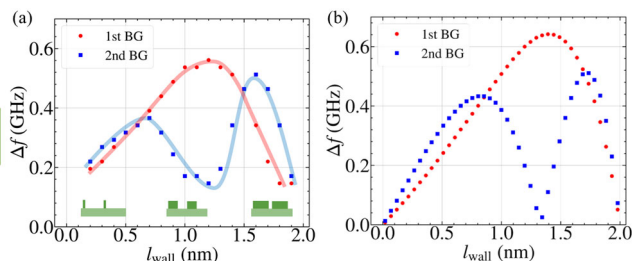


Fig.2 Wall width dependence of the 1st and 2nd bandgap widths obtained by (a) micromagnetic simulation and (b) Kronig-Penney model.

- [1]A. V. Chumak *et al.*, Nat. Commun. **5**, 4700(2014). [2]S. A. Nikitov *et al.*, JMMM **236**, 320–330 (2001).
[3]A. Vansteenkiste *et al.*, AIP Adv. **4**, 107133(2014).

1次元マグノニック結晶における非線形マグノン散乱

Nonlinear Magnon Scattering in 1D Magnonic Crystals

福岡大理, [○]洞口 泰輔, 眞砂 卓史

Fukuoka Univ., [○]Taisuke Horaguchi, Takashi Manago

E-mail: t.horaguchi@fukuoka-u.ac.jp

【背景・目的】

マグノニック結晶はスピン波(マグノン)の波長程度のスケールで人工的に微細な周期構造を導入した磁性体である。こうした構造では、構造周期に近い波長のスピン波の伝搬が抑制され、バンドギャップが形成されることが知られている[1]。また、ゲート信号によってマグノンを選択的に干渉・散乱させるマグノントランジスタ[2]のように、マグノンの散乱現象を利用したスピン波デバイスの提案もなされている。このようなデバイス応用においては、マグノン散乱のメカニズム、特に非線形散乱過程に対する理解が不可欠である。非線形マグノン散乱には、3マグノン散乱や4マグノン散乱に代表される現象があり、これまで主にバルクや一様薄膜を対象として多くの研究が行われてきた。しかし、マグノニック結晶のような周期構造を有する複雑な磁性体における非線形マグノン散乱の系統的な調査は少ない。本研究では、Fig. 1に示すように、 x 軸方向に凹凸形状の障壁を周期的に配置した一次元マグノニック結晶において、非線形マグノン散乱の挙動をマイクロマグネティクス計算により調査した。

【計算手法】

凹凸構造の幅をそれぞれ $1.0\ \mu\text{m}$ とした構造周期 $D = 2.0\ \mu\text{m}$ の1次元マグノニック結晶(Fig. 1)において、(i)マグノンバンド構造計算、(ii)非線形マグノン励起計算の2種類の計算をMumax³[3]を用いて行った。それぞれの計算で得られた磁化の応答をFFT処理し周波数・波数空間でのマグノンの分布を解析した。(i)のマグノンバンド計算では y 方向に磁化を飽和させた状態に対して時間・空間方向のsinc関数の積により構成された磁場パルスを印加した。これにより広帯域なマグノン励起が可能となり、マグノンバンドの位置・形状が明らかとなる。(ii)の非線形励起計算では同様に磁化を飽和させた状態に対して、磁化と平行な一様交流磁場 B_{rf} (振幅 $7.0\ \text{mT}$ 、周波数 $10\ \text{GHz}$)を印加した。この配置はParallel Pumpingと呼ばれる。Parallel-Pumping時のマグノンの分布と(i)で得たマグノンバンド構造を比較し、非線形散乱の様子を調べた。

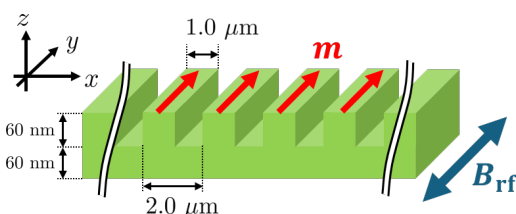


Fig.1 A schematic image of a 1D magnonic crystal and a parallel pumping configuration.

【結果】

Parallel Pumpingでは入力周波数 f_{rf} の半分の周波数 $f_{\text{rf}}/2$ を持つマグノンが励起される。これは波数 $k = 0$ の一つのマグノンが波数 $\pm k (\neq 0)$ の2つのマグノンへと散乱する3マグノン散乱として説明される。Fig. 2(a)は(i)で得られたバンド構造と(ii)の非線形励起計算で得られたマグノン分布を重ねて示したものである。非線形励起により周波数 $f_{\text{rf}}/2 = 5.0\ \text{GHz}$ かつ $\pm k (\neq 0)$ のマグノンバンド上に散乱マグノンが生じていることが確認できた。Fig. 2(b)は散乱先周波数(5 GHz)付近の拡大図であり、一様薄膜のマグノンバンドには存在しない低周波・高 k 領域のバンドへの散乱が確認され、マグノニック結晶に特有の非線形散乱の存在を示唆している。当日は、非線形マグノン励起の周波数依存性および励起磁場の閾値に関する詳細な計算結果についても報告する予定である。

[1]S. A. Nikitov *et al.*, JMMM **236**, 320–330 (2001).

[2]A. V. Chumak *et al.*, Nat. Commun. **5**, 4700(2014).

[3]A. Vansteenkiste *et al.*, AIP Adv. **4**, 107133(2014).

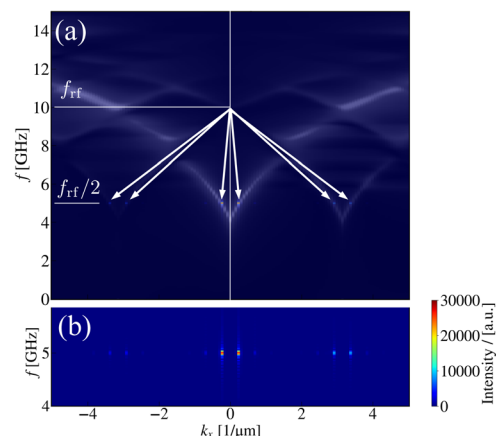


Fig.2 (a) An overlaid plot of the magnon band structure obtained from linear excitation using a sinc function field and the magnon distribution excited by nonlinear excitation via parallel pumping. (b) Enlarged view around the scattered frequency (5 GHz), showing nonlinear excitation of low frequency magnons.

接合マグノニック結晶におけるスピン波伝搬特性の評価

Spin-wave propagation characteristics in magnonic crystal junction

福岡大理, [○](M1) 稲富 孝太郎, 洞口 泰輔, 眞砂 卓史

Fukuoka Univ. [○]K Inatomi, T Horaguchi, and T Manago

E-mail: sd251001@cis.fukuoka-u.ac.jp

【研究背景】

近年、スピン波の伝搬を制御するマグノニック結晶 (Magnonic crystals ; MCs) に注目が集まっている。MC を用いたスピン波電子デバイスへの応用の観点から、MC 構造がスピン波に与える影響へのより深い理解が望まれる。本研究では、障壁と障壁幅の比率が異なる 2 つの MC を接合した接合マグノニック結晶におけるスピン波伝搬特性をマイクロ・マグネティック・シミュレーションにより調査した。

【計算手法】

スピン波の計算には Mumax3 を用いた。81.92 μm $\times$ 50 μm $\times$ 20 nm の Py 導波路上に、Py 障壁を 2 μm 周期で 41 セット設置した。左側 26 セットは障壁幅 W [μm]、右側 15 セットは障壁幅 $2.0-W$ [μm]とした (Fig. 1)。また、障壁幅 W [μm]のみ、 $2.0-W$ [μm]のみのマグノニック結晶についても計算した (Fig. 2, 3)。アンテナによって生成される磁場の空間分布は MATLAB を用いてあらかじめ求め、得られた磁場分布を用いて Mumax3 でパルス幅 50 ps のスピン波励起により、スピン波の伝搬を計算した。また、20 mT の静磁場を短辺方向に印加し、スピン波の伝搬方向は Py の長辺方向 (MSSW モード) とした。その後、スピン波の分散関係やスペクトルを解析した。

【結果】

Fig. 4 は障壁幅 $W = 1.5 \mu\text{m}$ の接合 MC について、スピン波強度スペクトルを規格化したもの (青の実線) とそれぞれ接合していない場合のスピン波強度スペクトル (Fig. 2 と Fig. 3 のスピン波スペクトル) の和を取り規格化したもの (赤の実線) をプロットしたものである。なお今回のデータは接合 MC の界面からスピン波伝搬方向に 0.3 μm 地点のものであり、接合していない単純な MC のデータも接合 MC とアンテナからの距離が同じ地点のものを参照している。Fig. 4 より 1st バンドギャップの前に接合 MC にだけ明らかな伝搬ピークが発現していることが確認できる。

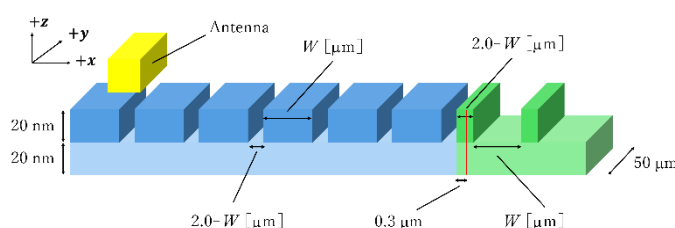


Fig. 1 Magnonic crystal junction

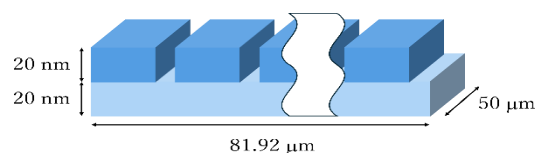


Fig. 2 Magnonic crystal
(wall width = $W = 1.5 \mu\text{m}$)

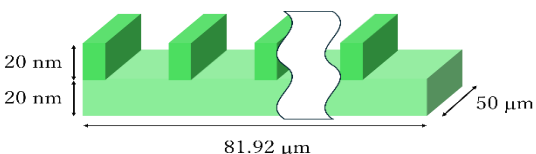


Fig. 3 Magnonic crystal
(wall width = $2.0-W = 0.5 \mu\text{m}$)

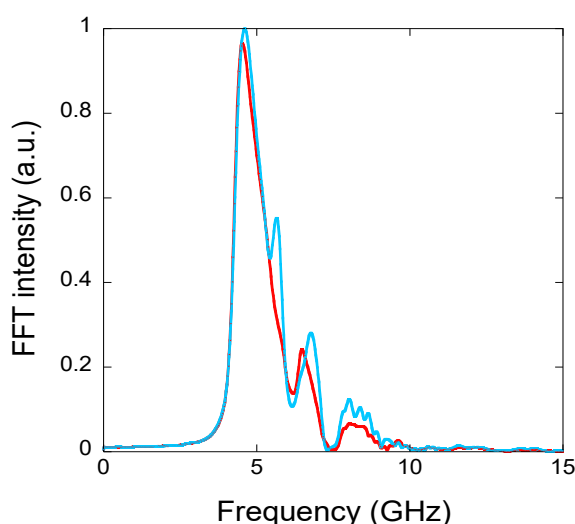


Fig. 4 Spin wave intensity of a magnonic crystal junction (blue line) and the sum of the spectrum of different magnonic crystals (red line).

深強結合共振器マグノニクスにおける量子真空とエンタングルメント

Quantum Vacuum and Entanglement in Deep-Strongly Coupled Cavity Magnonics

山形大工¹, 東北大工², 東北大 CSIS³ ○千葉 貴裕^{1,2}, 鈴木 龍之介², 大瀧 貴史², 松枝 宏明^{2,3}

Yamagata Univ.¹, Tohoku Univ.², CSIS³ ○T. Chiba^{1,2}, R. Suzuki², T. Otaki², H. Matsueda^{2,3}

E-mail: t.chiba@yz.yamagata-u.ac.jp

In recent years, the rapid development of quantum information technology—represented by quantum computers—has been remarkable. One of the fundamental physics underpinning the development is polariton in which electromagnetic waves and matter are strongly coupled. In particular, the polariton state defined by $g/\omega_{c(m)} \geq 1$ is referred to as the deep-strong coupling (DSC) [1], where ω_c and ω_m are the characteristic (angular) frequencies of the electromagnetic wave and the matter, respectively, and g is the coupling strength (in angular frequency units). In the DSC regime, it becomes difficult to distinguish between the electromagnetic-wave and matter modes, leading to the emergence of a nontrivial ground-state characterized by nonclassical correlations and virtual excitations. Such ground-states have been observed so far only in superconducting quantum circuits under extremely low-temperature conditions [1].

Here, we theoretically study DSC phenomena in a cavity magnonics system [2] in which a uniform magnetization dynamics (magnon) of an easy-axis ferromagnet is coupled to a microwave magnetic field (photon) of a single-mode LC resonator. Based on the minimal quantum mechanical model which can correctly reproduce classical dynamics, we show that a nontrivial frequency shift, which is characterized by an asymmetric Rabi-like splitting with $g/\omega_c \approx 1$ at the original modes crossing point, emerges in the DSC regime (see Fig. 1). We also formulate a connection between the frequency shift and the virtual particle number as well as the entanglement entropy at the ground-state, thereby enabling experimental access to these quantum resources. By utilizing soft magnons [3] in an easy-axis ferromagnet, we further demonstrate that these quantum quantities diverge at the critical magnetic field that gives a zero-excitation gap ($\omega_m = 0$).

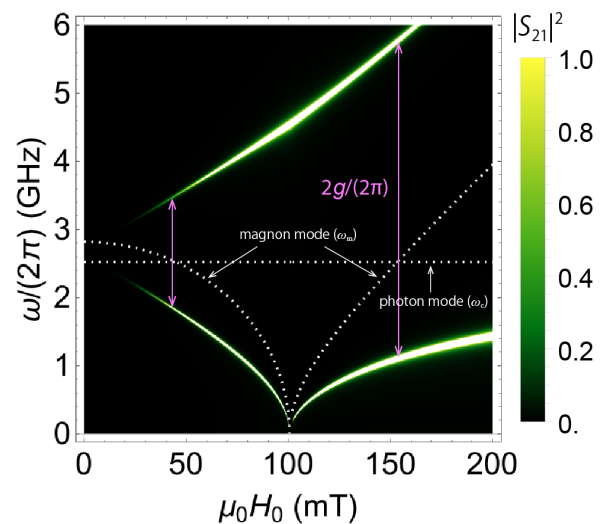


Fig.1. Calculated transmission amplitude $|S|^2$ of the hybridized modes as functions of an input frequency $\omega/(2\pi)$ and an external magnetic field $\mu_0 H_0$. Here a ferromagnet is assumed to be $\text{Y}_3\text{Fe}_5\text{O}_{12}$ with millimeters scale rod shape [2]. Soft-magnon-like polariton emerges around $\mu_0 H_0 = 100$ mT.

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Spatial mapping of effective magnetic field at the Py/NiO interface

ICR, Kyoto Univ.¹, CSRN, Kyoto Univ.², PRESTO, JST³, Nagoya Univ.⁴,

^o(D)Itaru Sugiura¹, Yoichi Shiota^{1,2}, Ryusuke Hisatomi^{1,2}, Shutaro Karube^{1,2},

Teruo Ono^{1,2} and Takahiro Moriyama^{3,4}

E-mail: sugiura.itaru.78s@st.kyoto-u.ac.jp

Antiferromagnets have attracted attention in spintronics owing to their robustness against external perturbations, absence of stray field, and capability for ultra-fast operation. Although understanding of domain states is essential for advancing performance of antiferromagnet-based devices, observation techniques for these domains are currently limited owing to the negligible spontaneous magnetization. It is still desirable to develop accessible techniques for imaging antiferromagnetic domains. In this study, we developed a spatial imaging technique for antiferromagnetic domains by heterodyne-magneto-optical-Kerr (MOKE) measurements taking advantage of magnetization dynamics of a ferromagnets adjacent to antiferromagnet [1].

Thin multilayer NiO (30 nm)/Ni₈₀Fe₂₀ (5 nm)/Cu (3 nm)/SiO₂ (3 nm) was deposited on a single crystalline MgO(001) substrate by magnetron sputtering. The film was patterned into a 4- μ m-wide strip attached to a coplanar waveguide. Fig. 1(a) shows the magnetization dynamics measurement set-up with simultaneous electrical homodyne detection and optical heterodyne detection. Fig. 1(b) spatially maps the amplitude $|S_{21}|$ of the optical signal from the polar Kerr effect which depicts the area where the ferromagnetic resonance of NiFe is excited with the in-plane magnetic field $\mu_0 H_{\text{ext}} = 50$ mT with the angle $\varphi = 45^\circ$ and 135° and the microwave frequency $f = 10$ GHz. The contrast observed for $\varphi = 45^\circ$ and 135° suggests that an anisotropy field acting on NiFe is spatially distributed by the underlying T-domains of NiO. The field directions $\varphi = 45^\circ$ and 135° respectively correspond to the in-plane projection of preferential Néel vector orientations in NiO[-110] and [-1-10] of the epitaxial NiO [2]. In the presentation, we will discuss the T-domain distribution of the NiO and validity of our measurement technique.

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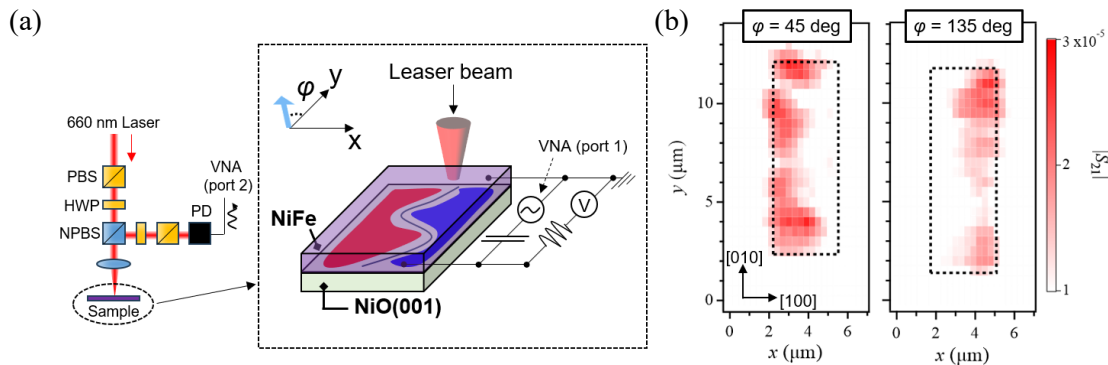


Fig. 1 (a) Schematic illustration of the measurement set-up. The red and blue areas in the inset indicate difference in the anisotropy field acting on NiFe due to the underlying T-domains of NiO. (b) Spatial mapping of the $|S_{21}|$, where black dot frame is the NiFe strip obtained by the reflection light intensity.

Structural analysis and damping evaluation of epitaxially grown $L1_0$ -FePt thin films

NIMS., °Yuta Sasaki, Phillip David Bentley, Katsuaki Nakazawa, Takanobu Hiroto,

Shinji Isogami, Hirofumi Suto, Yukiko K. Takahashi

E-mail: SASAKI.Yuta@nims.go.jp

$L1_0$ -FePt has attracted significant interest as a magnetic recording material owing to its large perpendicular magnetic anisotropy (PMA), large saturation magnetization, and chemical stability. Its large magnetoresistance and high spin injection efficiency make it a promising candidate for spintronic applications with operation frequencies above 100 GHz. [1,2] However, despite these promising magnetic properties, the relatively large magnetic damping constant of $L1_0$ -FePt thin films is not suitable for spintronic device applications. In this study, we investigated the magnetization dynamics of $L1_0$ -FePt thin films grown on different substrates, MgO, MgAl_2O_4 (MAO) and SrTiO_3 (STO). We demonstrated that the modification of the microstructure in FePt is crucial for achieving a lower damping constant and realizing novel FePt spintronic devices. [3]

$L1_0$ -ordered FePt thin films with a thickness of 36 nm were fabricated via DC magnetron sputtering on single-crystalline MgO(001), MAO(001) and STO(001) substrates. Prior to deposition, each substrate was annealed at 650 °C for one hour in vacuum to eliminate surface contamination. FePt films were grown with a substrate temperature of 500 °C. Structural characterization was performed using XRD. The magnetization dynamics was investigated by using the all-optical time resolved magneto-optical Kerr effect (TRMOKE). During the TRMOKE measurements, magnetic fields up to 7.0 T were applied at various magnetic field angles θ_H with respect to the film normal.

As seen in Fig.1(a), XRD data of the FePt films grown on MgO, MAO and STO substrates showed well-defined superlattice peaks corresponding to the $L1_0$ phase. TRMOKE data for all the samples showed a clear oscillational signal as seen in Fig. 1(b). The STO sample showed a minimum damping value of 0.030, whereas the MgO and MAO samples exhibited a higher value of 0.059 and 0.037, respectively. Detailed analysis of microstructure and magnetic damping constant will be discussed in the presentation.

This work was partially supported by the JST-CREST (Grant No. JPMJC22C3), MEXT-LEADER (Grant No. JPMXS0320230032), and the JSPS-KAKENHI (Grant Nos. JP21K14218 and JP18H03787).

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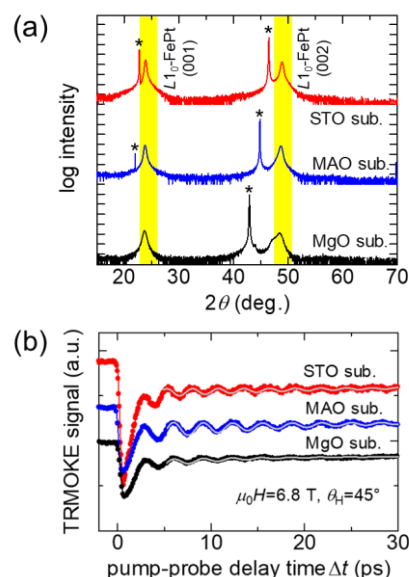


Fig. 1. (a) XRD patterns of FePt thin films deposited on MgO, MAO and STO substrates. (b) Typical wave forms of the TRMOKE data for the films deposited on MgO, MAO, and STO substrates. Solid curves are the fitting results.

Ab-initio study of magnon in altermagnet Hexagonal FeS**Mie Univ., °Koki Kobayashi, Andi Gumarilang, Kohji Nakamura****E-mail: 424M214@m.mie-u.ac.jp**

Ultra-fast spin operations in terahertz (THz) frequency range have become a demand for future communication technologies, and antiferromagnets are promising candidates to convey this frequency range via collective spin excitation, called magnon [1]. Hexagonal FeS exhibits collinear antiferromagnetic order along the c-axis below the Néel temperature (~ 600 K), and many theoretical and experimental studies have focused on pressure-induced [2] structural and electronic transition in FeS, while detailed investigations into its magnon excitation spectrum remain limited. However, to fully utilize them for THz spintronics devices, it is essential to understand its fundamental magnetic characteristics related to magnon dispersion. Here, we carry out ab-initio calculations of magnons in hexagonal FeS to evaluate the spin-exchange interactions, magnetic anisotropy, and magnon dispersion using full-potential linearized augmented plane-wave (FLAPW) method [3] with generalized gradient approximation with Hubbard correction (GGA+U). The spin-exchange interactions are obtained based on linear response theory, the magnetic anisotropy constants are obtained by the force theorem to spin-orbit coupling (SOC) and magnetic dipole-dipole interaction (MDI) approximation, and the magnon dispersions are obtained by using linear spin wave theory (LSWT) [4]. The calculated band structure exhibits spin-splitting despite antiferromagnetic order, which is a key feature of an altermagnet. The first- and third-nearest neighbor, J_1 and J_3 , stabilize the antiferromagnet order along the c-axis, while the J_2 connects two parallel Fe site and stabilize the (001) in-plane ferromagnetic order. Due to different surrounding of the two Fe sites within unit cell, the J_2 of each Fe site differs by an amount of approximately 6 meV. From the magnetocrystalline anisotropy (MCA) calculation, we confirm the in-plane magnetic anisotropy in agreement with experiments [5]. The antiferromagnetic resonance frequency is about 3THz, which is lifted by the in-plane MCA constant. At the edge of the Brillouin zone, the degeneracy between two magnon frequencies is lifted due to the difference in J_2 between two Fe sites, and the frequency of the higher mode is approximately twice that of the lower one. The calculated dispersion reveals two separated magnon modes, opening the prospect of dual-frequency information channels. Similarly, mode-dependent transport has been predicted in altermagnets: specific magnon mode can be selectively suppressed along particular directions, thereby enabling route-controlled spin and heat currents [6].

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スピン波の定在波による高次高調波を伴う共鳴スピンプンピング

Resonant spin pumping with high harmonic generation by standing spin waves

東大工¹, 東大 BAI², 理研 CEMS³, 神戸大⁴, 東北大 AIMR⁵

Dept. Appl. Phys., Univ. Tokyo¹, Inst. AI and Beyond, Univ. Tokyo², CEMS, RIKEN³, Kobe Univ⁴

AIMR, Tohoku Univ.⁵

星幸治郎^{1,2,3}, 山口皓史⁴, 日置友智^{1,3,5}, 齊藤英治^{1,2,3,5}

E-mail: koujirohoshi@g.ecc.u-tokyo.ac.jp

フェルミ面のネスティング効果とは、ネスティングベクトルと呼ばれるある波数ベクトル Q だけ電子のフェルミ面をずらし、元のフェルミ面もしくは他のフェルミ面と一致した時に、電子の静的な応答関数が Q で発散的に増大することである。このフェルミ面のネスティング効果に関連し、動的な応答関数の発散は、コーン異常と呼ばれるフォノンバンド分散の変形をもたらし、具体的にはフォノンモードのソフト化を誘起する。フォノンの波数がネスティングベクトル Q の時、ソフト化が最大となりフォノンの周波数は 0 になる。この時、電荷やスピン自由度における長周期秩序の自発的形成へとつながり、CDW（電荷密度波）や SDW（スピン密度波）などの秩序として現れる。従来のフェルミ面のネスティング効果は静的なネスティングベクトルに起因するが、動的に励起された波数ベクトルによる動的なフェルミ面のネスティング効果も期待できる。この時、電子の応答関数は動的に発散的な増大が期待され、従来の静的な系では実現し得なかった新たな物性現象を誘起しえる。

本研究では、スピン分裂したバンド間の動的なフェルミ面のネスティング効果による電子の応答の高次高調波生成を実証した。具体的には、強磁性体中の交流磁場下のスピン波励起を Landau-Lifshitz-Gilbert 方程式を用いて計算し、Brouwer 公式 [1, 2] を用いてスピン流を数値的に計算した。計算の結果、非線形マグノン散乱によるスピン波の定在波の励起によって、急峻なピークとディップを含む交流スピン流が生成されることが分かった。さらに、この交流スピン流は高次高調波を示すことが分かった。また、あるフェルミエネルギーにおいて、高調波の次数が爆発的に増大することが分かった。講演では、詳細な計算方法と計算結果について報告する。

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原子層挿入した Pt/Co 界面構造におけるスピホール伝導度と電気誘起磁化の第一原理計算

First principles calculations of spin Hall conductivity and electric-induced spin polarization in Pt/Co interfaces modified by atomic-layer insertions

三重大院工¹, Gadjah Mada Univ.², [○](M2)石原 智規¹, M. Alifin^{1, 2}, 中村 浩次¹

Mie Univ.¹, Gadjah Mada Univ.², [○]Tomoki Ishihara¹, Muhammad Alifin^{1, 2}, Kohji Nakamura¹

E-mail: 424M203@m.mie-u.ac.jp

スピホール／軌道ホール効果によるスピン流／軌道流生成の研究において、軽元素から重金属元素に至るバルクでの理解はかなり進んできた。しかし、素子には界面のスピン流／軌道流や強磁性体磁化の反転メカニズムの微視的解明が必要である。例えば、界面のスピンホール伝導度 (SHC) がバルク値に比べ著しく小さくなることが示されている[1]。また、軌道ホール効果と組み合わせることで磁化反転効率を向上させる機構の提案もなされている。この背景のもと、我々は Co/Pt 二層薄膜界面における SHC と軌道ホール伝導度 (OHC) の第一原理計算を進め、SHC の界面減衰を抑制するための組成勾配の提案を進めてきた[2]。本発表では、さらに軽元素から重金属元素に至る原子層を界面に挿入した Co/M/Pt 薄膜における SHC と OHC の第一原理計算を報告するとともに、電流印加による電気磁気効果 (ME) の第一原理計算プログラム開発を行い、それぞれの系に適用した結果についても報告する。第一原理計算には、一般化勾配近似に基づく全電子フルポテンシャル線形化補強平面波法[3]を用い、SHC や OHC、スピン ME 感受率 χ_S 、軌道 ME 感受率 χ_L は久保公式から評価した。プリスティン Co/Pt 薄膜には、8 原子層 Pt(111)と単原子層 Co からなる Co₁/Pt₈を用い、単原子層金属からグラフェンをはじめとする二次元物質原子層を界面に挿入した。計算の結果、界面原子挿入により、SHC や χ_S は元素種に顕著に依存し、OHC や χ_L は単調に変化することがわかった。例えば、Fe, Ru, Os 原子層挿入した場合、SHC はプリスティン Co/Pt の値に対して、18%, 9%, 20%減少、OHC は 10%, 51%, 52%に変化した。発表では、これらの影響を各原子層における伝導度や ME 感受率からも考察する。

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多元素添加白金アモルファス薄膜の構造安定性とスピンホール効果

Spin Hall Effect and Thermal Stability in doped Pt amorphous films

九州工業大¹, 山口大², ○(M1)溝田 壮生¹, 今井滉基¹, (M2)本坊 太一¹, ジョン モハン レッ
クス¹, 堀部 陽一¹, 石丸 学¹, 浅田 裕法², 福岡康裕¹

Kyushu Inst. Tech.¹, Yamaguchi Univ.², ○S. Mizota¹, K. Imai¹, T. Hombo¹, J. R. Mohan¹, Y. Horibe¹,
M. Ishimaru¹, H. Asada², Y. Fukuma¹

E-mail: mizota.soki942@mail.kyutech.jp

次世代メモリとして注目されているスピン軌道トルク型磁気メモリ (SOT-MRAM) の性能は、電氣的スピン変換効率(θ_{SHE})と抵抗率 (ρ_{xx})に強く依存する。近年、高エネルギーP イオン注入によって Pt 薄膜をアモルファス化し、 θ_{SHE} を 0.75 まで向上させた例が報告されており[1]、構造制御を活用した新たな指針として注目されている。しかしこの方法では、400°C程度の BEOL アニールング処理によりバンドギャップ 1.02 eV を有する PtP₂層が形成されることで抵抗率が上昇し、さらに再結晶による θ_{SHE} の低下の可能性など、熱処理耐性に課題がある。一方、Pt 薄膜中に散乱中心を形成することで θ_{SHE} を向上させる手法として、反応性スパッタ法による N₂導入が報告されている[2]。また、また、Fe-Pt 系における報告では、反応性スパッタによって窒素を導入することで、熱処理後も構造の変化が抑制されることが報告されている[3]。そこで本研究では、N₂や Cu を添加した Pt 薄膜を作製し、 θ_{SHE} の変化、構造状態、熱処理耐性との相関を評価した。Si/SiO₂ 基板上に、N₂ 混合ガスを用いた反応性スパッタ法により、10 nm 厚の Cu-doped PtN_x 薄膜を成膜した (N₂流量比 Q = 10, 20%)。各試料に対して、加速エネルギー30keV、照射密度 5.0×10^{16} および 1.0×10^{17} ions/cm² の条件で P イオンを注入した。注入後、200~400°Cの条件で熱処理を行った。初めに、XRD 測定により構造評価を行った。P イオン照射により、熱処理前の試料はアモルファス化していることを確認した。400°Cでの熱処理により PtP₂相の形成が確認され、Q=20%では Q=10%と比較して PtP₂相の結晶粒径が小さく、結晶粒成長が抑制されていることが分かった。また、この PtP₂の析出により、試料の抵抗率は大きく増加 (4~5 倍) した。スピントルク強磁性共鳴測定を用いてスピンホール効果の評価を行った。400°Cでの熱処理により θ_{SHE} はやや増加する傾向を示しており、Q=10%では $\theta_{\text{SHE}}=0.38$ 、Q=20%では $\theta_{\text{SHE}}=0.31$ を得た。

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スパッタ法により作製した酸素添加白金薄膜のスピントロニクス効果

Spin Hall effect in O-doped Pt layers prepared by sputtering

九工大¹, 山口大², ○(M2)小野 雄世¹, (M1)芳野 光希², (M2)本坊 太一¹,

(P)モハン ジョン レックス¹, 堀部 陽一¹, 石丸 学¹, 浅田 裕法², 福間 康裕¹

Kyushu Inst. Tech.¹, Yamaguchi Univ.², °Y. Ono¹, M. Yoshino², T. Hombo¹,

J. R. Mohan¹, Y. Horibe¹, M. Ishimaru¹, H. Asada², Y. Fukuma¹

E-mail: yono@fukuma-lab.info

ニューロモルフィックコンピューティングの実現に向けて、電力効率のよいスピントロニクスデバイスが必要とされている。白金(Pt)やタンタルでは、x 方向に電流を印加した場合、スピントロニクス効果により y 方向に偏極したスピン流が生成される。近年、界面等の寄与から異なる方向にスピン偏極成分をもつスピン流の生成が報告されている^{[1],[2]}。高い電流からスピン流への変換効率かつ z 方向に偏極したスピン流を生成できる材料を作製できれば、外部補助磁場(x 方向)なしでのスピン軌道トルク磁化反転の実現が期待される。本研究では、酸素を添加した Pt 薄膜を作製し、酸素濃度の傾斜によりスピントロニクス効果がどのように変化するかを調べた。

Si/SiO₂ 基板上に、PtOx(10%, 10 nm), PtOx(20%, 10 nm), PtOx(0, 5, 10, 15, 20%, 2 nm×5 層=10 nm)の PtOx(Gradient)を反応性スパッタリング法によって堆積した。その後、NiFe(10 nm)/Al₂O₃(10 nm)を作製した。スピントロニクス強磁性共鳴(ST-FMR)測定を利用してスピントロニクス効果の評価を行った。外部磁場の印加角度 ϕ を変化しながら ST-FMR 測定を行い、得られたスペクトルから整流電圧信号の対称成分(S)と反対称成分(A)を算出した。この結果からフィッティングを行い、S および A の各成分を図 1 に示す。均一な単層膜ではスピントロニクス効果から予想される y 成分が主であるが、PtOx(Gradient)では異なる方向にスピン偏極成分をもつスピン流からの寄与がみられた。

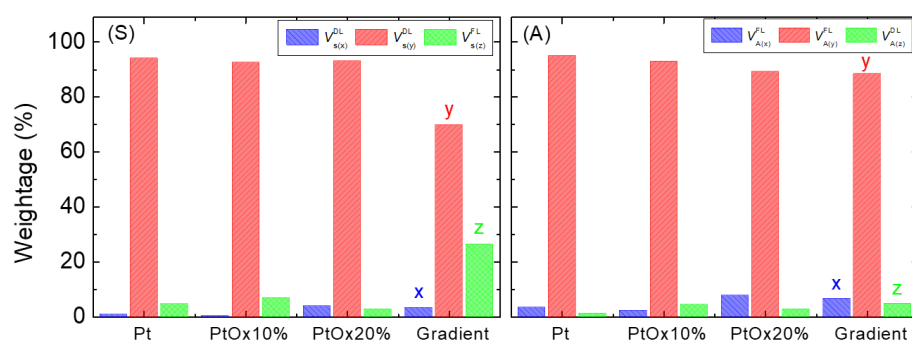


Fig. 1 Proportions of each directional component in symmetric and asymmetric ST-FMR voltage signals.

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Control of Interlayer Chiral Coupling by thermal annealing under oblique magnetic field application

○Yuki Hibino, Tomohiro Taniguchi, Tatsuya Yamamoto, Hitoshi Kubota, Shinji Yuasa,
and Kay Yakushiji
AIST

E-mail: y-hibino@aist.go.jp

Interlayer Dzyaloshinskii-Moriya interaction (interlayer DMI) in ferromagnet/non-magnet/ferromagnet (FM/NM/FM) structure promotes interlayer chiral coupling (ICC) between two ferromagnets which result in nontrivial chiral spin structures [1-4]. Such magnetic coupling enables field-free spin-orbit torque (SOT) switching of out-of-plane magnet, which can be used in high-density SOT-MRAM [5]. While the microscopic in-plane asymmetry of the structure is a key factor in the emergence of interlayer DMI, the physical origin and how to control the chirality of ICC are still unclear. Here, we offer a new method to control the chirality of the ICC by means of a post-annealing process under an oblique magnetic field.

We prepared the following FM/NM/FM structure on a thermally oxidized Si substrate: Sub. / Ta (5) / Ru (3) / Pt(2.6) / [Pt(0.4)/Co(0.4)]₄ / Ir (0.46) / Co-Fe-B (1.4) / MgO / Ta (3). Inside the parentheses show the thickness of each layer in nanometers. Here, [Pt/Co]₄ and Co-Fe-B are perpendicularly and in-plane magnetized, respectively (hereafter referred as PML and IML). After the deposition, the FM/NM/FM structure was annealed at 330 °C for an hour. The annealing process was performed under a magnetic field of 1T applied along the polar angle θ_H from the out-of-plane direction (Fig. (a)). The in-plane magnetization curves of IML along the x-axis are shown in Fig. (b). A significant shift of bias field (ΔH_s) was observed between the two polarities of the magnetization of PML (+M and -M states), which originates from the ICC acting on IML. Figure (c) shows the dependence of ΔH_s in the same structure on θ_H . Surprisingly, ΔH_s shows significant angular dependence, in which the sign of ΔH_s is reversed at $\theta_H = 90$ degrees, indicating that the chirality of the ICC is reversed. The results provide a new method to control and design the interlayer magnetic coupling, which could be applied for spintronic devices.

This work was partly supported by Grant-in-Aid for JSPS KAKENHI (23H01477), Japan.

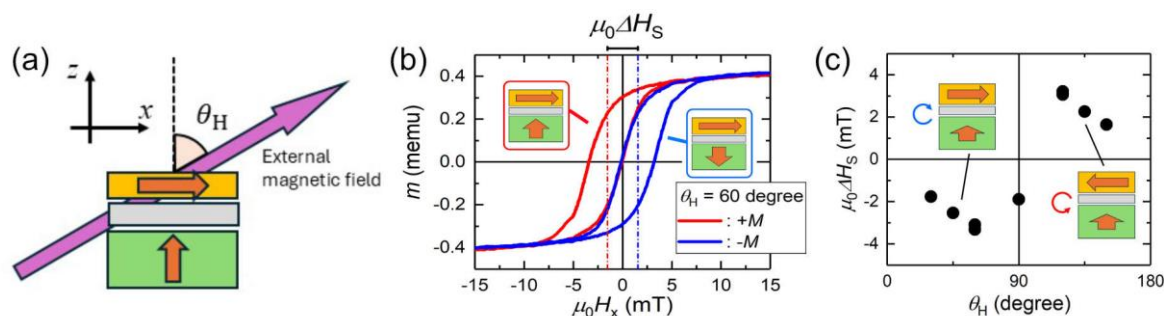


Figure: (a) Schematic of magnetic field configuration during annealing process. (b) Magnetization curve under +M and -M state. (c) θ_H dependence of ΔH_s .

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Electrical detection of spin-polarization in nonmagnetic heavy metals induced by circularly polarized light

Science Tokyo¹, ICR, Kyoto Univ.², °Soichiro Mochizuki¹, Itaru Sugiura², Teruo Ono²,

Takuya Satoh¹, Kihiro T. Yamada¹

E-mail: mochizuki.s.7c36@m.isct.ac.jp

Circularly polarized light can transfer its spin angular momentum to electrons in condensed-matter materials via helicity-dependent electric dipole transitions inside spin-orbit split electronic structures. This helicity-dependent optical excitations can create spin-polarized states and spin currents in the conduction bands. While the optical generation of spin-polarized states and spin currents has been extensively electrically investigated in III-V semiconductors [1] and topological insulators [2], it is not studied for heavy metals with strong spin-orbit interactions.

Here, we report the observation of spin-polarized states in nonmagnetic heavy metals under the irradiation of circularly polarized light. Thin heavy metal films were deposited on glass substrates by dc sputtering at room temperature. These thin films were processed into Hall devices by a standard photolithography and ion-milling techniques. Circularly polarized light with a wavelength of 532 nm was focused on the center of a Hall cross with a diameter of 6 μm by an objective lens. The light circular polarization was modulated at a frequency of 50 kHz using a photoelastic modulator. We applied dc currents I_{dc} in the longitudinal direction and measured the Hall (transverse) voltages V_{xy} using a lock-in amplifier. Fig. 1 shows V_{xy} as a function of I_{dc} for Pt with a thickness of 20 nm. We find that the slope of V_{xy} , which represents Hall resistance R_{xy} , depends on the laser intensity. At a laser power of 100 mW, the value of R_{xy} reaches approximately 100 m Ω . In the presentation, we will show more details of our experiments and discuss the results.

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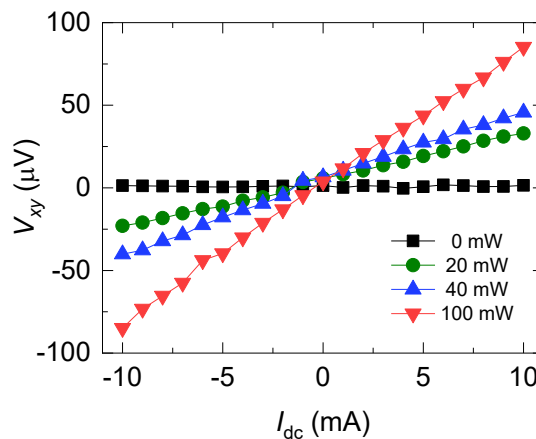


Fig. 1 Hall voltages V_{xy} as a function of applied dc current I_{dc} in Pt with a thickness of 20 nm.

n^+ -Si 層におけるスピン蓄積信号の不純物濃度依存性

Dependence of Spin Accumulation Signals on Impurity Concentration in Heavily Doped n -Type Silicon Layers



日大工¹, 阪大基礎工² ○(M2C)李 奕禧¹, 浜屋 宏平², 石川 瑞恵¹

Nihon Univ. College of Engineering¹, Osaka Univ.²,

°(M2C) Yixi Li¹, Kohei Hamaya², Mizue Ishikawa¹

E-mail: ceek24016@g.nihon-u.ac.jp

1. はじめに

近年、半導体エレクトロニクスにおいてスピントロニクスが次世代技術として注目されている。中でも Si スピン MOSFET^[1]は、高速動作・高性能・低消費電力といった特長を持つ新規デバイスとして期待されているが、性能指標の一つである MR (磁気抵抗) 比が小さく、実用化には至っていない。MR 比が低い原因を明らかにすることは、Si スピン MOSFET の実現に向けた重要な課題である。MR 比の抑制要因の一つとして、ソース・ドレイン領域の高濃度 n 型 Si 層中での不純物濃度の影響が考えられる。不純物濃度が高いほどスピン散乱が増大するため、スピン拡散長の低下を招く。そこで本研究では、高濃度 Si 層中でのスピン拡散長と不純物濃度の関係を評価するため、スピン蓄積信号の不純物濃度依存性を評価することとした。

2. 実験結果

評価に用いたデバイス構造を Fig. 1 に示す。60 nm 厚の高濃度 n 型 SOI(Si on Insulator)基板上に CoFe(15 nm)/MgO(1.5 nm)層を形成し、リソグラフィプロセスを用いて素子を作製した。高濃度 n 型 SOI 層の不純物濃度は Hall 効果測定(印加電流 : 1 mA, 印加磁場 : 3000 Oe)により評価し、室温において 5.20×10^{19} [/cm³]であった。スピン蓄積信号の測定には、3 端子 Hanle 効果測定(印加電流 : 4 mA, 印加磁場 : -500 ~ 500 Oe)を用いた。

作製したデバイスの室温での 3 端子 Hanle 信号の測定結果を Fig. 2 に示す。フィッティング^[2]の結果、スピン拡散長は $0.54 \mu\text{m}$ と比較的短い値であった。これは、これまでに我々が得た結果^[3]の半分程度であり、ゲルマニウム(Ge)中でのスピン拡散長^[4]と同程度である。当日は種々の不純物濃度を有する複数のデバイスにおいてスピン蓄積信号の測定結果を示し、それらの不純物濃度依存性について議論する。

本研究の一部は、科学研究費補助金(24K17326)の支援を受けて行われた。

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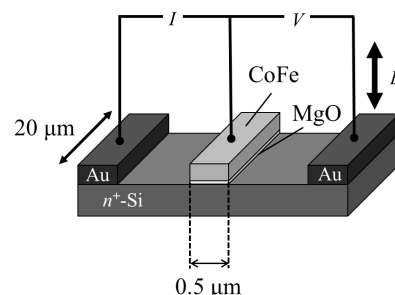


Fig. 1 Schematic of Three-Terminal Hanle Measurement Setup

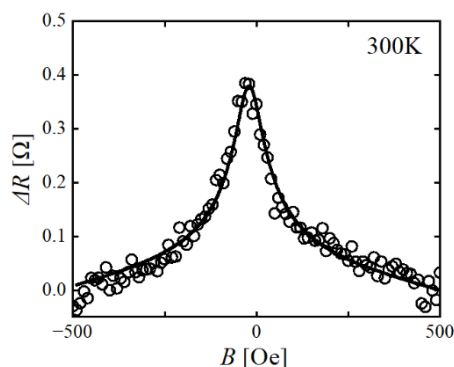


Fig. 2 Results of Three-Terminal Hanle Signal Measurements.

Fabrication of nanoscale magnetic tunnel junctions utilizing thin-film edges

°Takumi Ueda¹, Mizuki Matsuzaka¹, Chika Hashimoto¹, Kosuke Furukawa¹,

Ryunosuke Miyamoto¹, Kotaro Kashima¹, and Hideo Kaiju^{1,2}

¹Keio Univ. and ²CSRN, Keio Univ.

E-mail: taku130205@keio.jp

Since the observation of tunnel magnetoresistance (TMR) effect at room temperature in magnetic tunnel junctions (MTJs), research on MTJs has been actively conducted [1]. MTJs with various shapes have been reported, and the junction area of MTJs ranges from milli-/micro-meters to nanometers [1–3]. Recently, we have successfully fabricated nanojunctions using molecules sandwiched between Ni₇₈Fe₂₂ (Py) thin-film edges [4]. This device is magnetically stable, and the resistance of its electrodes is relatively small. Therefore, the device can realize a high signal-to-noise ratio and low power consumption. In this study, towards the observation of TMR effect, AlO_x-based nanoscale MTJs with the structure shown in Fig. 1 are fabricated, and their structural, electrical and magnetic properties are investigated.

We have fabricated Py and FeCo thin-film electrodes for the nanoscale MTJs shown in Fig. 1. The Py and FeCo thin films were deposited on glass substrates by sputtering, and glass/Py/glass (S-Py) and glass/FeCo/glass (S-FeCo) were fabricated by thermal pressing and mechanical cutting. The cut surfaces were polished, and AlO_x thin films were deposited on the polished surfaces. Prior to device fabrication, we investigated magnetic, structural and electrical properties of S-Py and S-FeCo by magneto-optical Kerr effect spectroscopy, conductive atomic force microscopy (c-AFM) and scanning electron microscopy (SEM). In the fabricated MTJs, we measured magnetoresistance (MR) by DC four-probe method under magnetic field.

Fig. 2 shows the coercivities of S-Py and S-FeCo with respect to the pressure during the thermal pressing. With increasing the pressure, the coercivity increases, enabling the realization of the antiparallel configuration in devices, which is required for the observation of TMR effect. Fig. 3 shows the c-AFM image of the surface of S-FeCo covered with AlO_x thin films, in which the thickness d of FeCo film is 39 nm obtained by SEM observation. A uniform electrical conduction along the FeCo edge covered with AlO_x thin films is observed. Similarly, it is also observed in S-Py. These results indicate that the fabricated S-Py and S-FeCo can be used as electrodes of the nanoscale MTJs. Although the fabricated MTJs exhibit TMR effect, it is not clear, which may originate from the magnetization configuration of the magnetic electrodes. To achieve more pronounced and reproducible TMR effect, the optimization of the magnetic electrodes will be required.

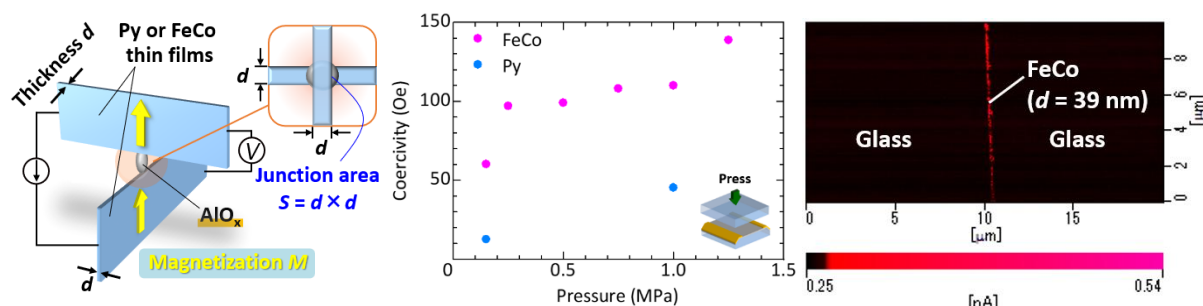


Fig. 1 Schematic of nanoscale MTJs utilizing thin-film edges.

Fig. 2 Coercivity of S-Py and S-FeCo with respect to the pressure.

Fig. 3 c-AFM image of the surfaces of the S-FeCo covered with AlO_x.

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Chirality-induced spin selectivity in organic spin valves utilizing Co/Pt multilayers with perpendicular magnetic anisotropy

[○]Kotaro Kashima¹, Mizuki Matsuzaka¹, Ryunosuke Miyamoto¹, Koki Terai¹, Masafumi Abe¹,

Kazuto Yamanoi^{1,2}, Yukio Nozaki^{1,2}, Masayuki Suda³, and Hideo Kaiju^{1,2}

¹Keio Univ., ²CSRN, Keio Univ., and ³Nagoya Univ.

E-mail: kotaro_kashima@keio.jp

Recently, molecular spintronics is an attractive research field due to its unique properties, such as the potential for achieving large magnetoresistance (MR) ratios in organic spin valves (OSVs). Organic molecules mainly consist of light elements, which contributes to weak spin-orbit coupling (SOC). The weak SOC can suppress the spin scattering in molecular layers. Therefore, OSVs are expected to show a large MR ratio. First-principles calculations predict large MR effects originating from orbital hybridization of ferromagnetic elements and organic molecules [1]. However, while the observed MR ratio is 40% in OSVs at a low temperature of 11 K [2], the MR ratio is as small as approximately 2% at room temperature [3]. Here, we focus on chirality-induced spin selectivity (CISS), where chiral molecules act as spin filters. High spin polarization originating from CISS [4–6] is expected to lead to the observation of a large MR ratio in CISS-based OSVs at room temperature. Since the MR curve of CISS-based OSVs corresponds to the magnetization curve of magnetic layer, the MR effect is expected to be observed under a low magnetic field by using Co/Pt multilayers with perpendicular magnetic anisotropy. In this study, we fabricate Au/S-1,1'-Bi-2-naphthol (BINOL)/[Co/Pt]₂ and Au/R-BINOL/[Co/Pt]₂ OSVs, and investigate their spin transport properties.

Fig. 1 shows a schematic illustration of Au/S(or R)-BINOL/[Co/Pt]₂ OSVs, which were fabricated by using DC magnetron sputtering and spin coating. For device patterning, photolithography and shadow mask were used in the bottom [Co/Pt]₂/Cr and top Au layers, respectively. The junction area of the OSVs was 100 × 250 μm². The magnetic properties were measured by focused magneto-optical Kerr effect. The MR effects were evaluated by DC 4-probe method under a magnetic field at room temperature.

Fig. 2 shows the magnetization curve of the bottom electrode under perpendicular magnetic field. A clear hysteresis loop is observed in the bottom electrode, in which the coercivity H_c is 182 Oe. This means Co/Pt multilayers with perpendicular magnetic anisotropy are successfully fabricated. Fig. 3 shows the MR curve in Au/S-BINOL/[Co/Pt]₂ OSVs. The MR curve corresponds to the magnetization states of Co/Pt multilayers. In addition, the MR curves of Au/S-BINOL/[Co/Pt]₂ and Au/R-BINOL/[Co/Pt]₂ OSVs exhibit opposite polarities in their resistance changes. These results indicate that a clear MR effect due to CISS is successfully observed in Au/BINOL/[Co/Pt]₂ OSVs under a low magnetic field.

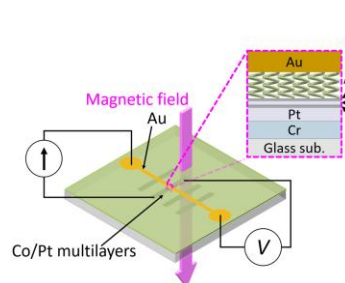


Fig. 1 Schematic illustration of Au/S(or R)-BINOL/[Co/Pt]₂ OSVs.

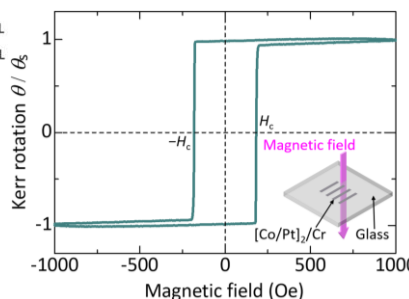


Fig. 2 Magnetization curve of the bottom electrode.

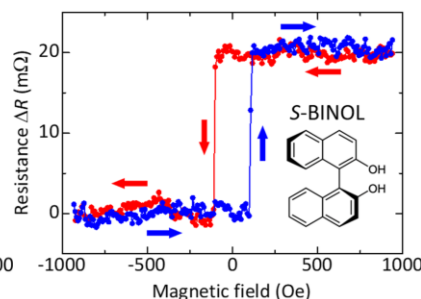


Fig. 3 MR curve in Au/S-BINOL/[Co/Pt]₂ OSVs.

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Fe/Mgo(110) 界面におけるトンネル電流に関する理論研究

Theoretical study on tunneling current of Fe/Mgo(110) interface

京都工芸繊維大学¹, [○](M1)小川大空翔¹, 三浦良雄¹

Kyoto Institute of Technology¹, [○]Rikuto.Ogawa¹, Yoshio Miura¹

E-mail: m25621006@edu.kit.ac.jp

円偏光を発振する半導体スピンレーザーは、光にスピンの情報を乗せることで多くの情報を伝送できる。この実現には、半導体中にスピン偏極電流を注入する必要がある、レーザーの活性層としてはⅢ-V族化合物が広く用いられている。なかでも GaAs/AlGaAs 多重量子井戸において(110)面が(001)面よりも長いスピン緩和時間とフォトルミネッセンス寿命を持つことから注目が集まっている^[1,2]。

そこで本研究では GaAs/AlGaAs(110)に対してスピン偏極電流の注入源となりうる Fe/MgO(110)接合のスピン依存伝導を理論的に解明するために Fe/MgO/Fe 磁気トンネル接合 (MTJ) のトンネル磁気抵抗 (TMR) 効果の第一原理計算を行った[3]。その結果、Fe/MgO/Fe(110)-MTJ は Fe/MgO/Fe(001)-MTJ と比べて TMR 比は一桁以上小さいことが判明した。これは Fig. 1(a)-(d)に示すように、高い透過率に寄与する bcc-Fe の 4s バンドと $3d(3z^2-r^2)$ バンドがフェルミエネルギー付近において up-spin と down-spin 状態の両方に存在し、その結果 MR 比が小さくなっていることが分かった。また、Fe(110)構造を面内方向に+4%歪ませることにより down-spin 状態において 4s バンドが高エネルギー側にシフトすることが判明した(Fig.1 (e))。この結果は、MTJ の面内格子定数を制御することにより、大きな TMR 比が得られる可能性を示唆している。講演では Fe/MgO/Fe(110)-MTJ における TMR の歪依存性の計算結果を議論する。謝辞：本研究は JSPS 科研費 JP24H00426 の助成を受けたものです。

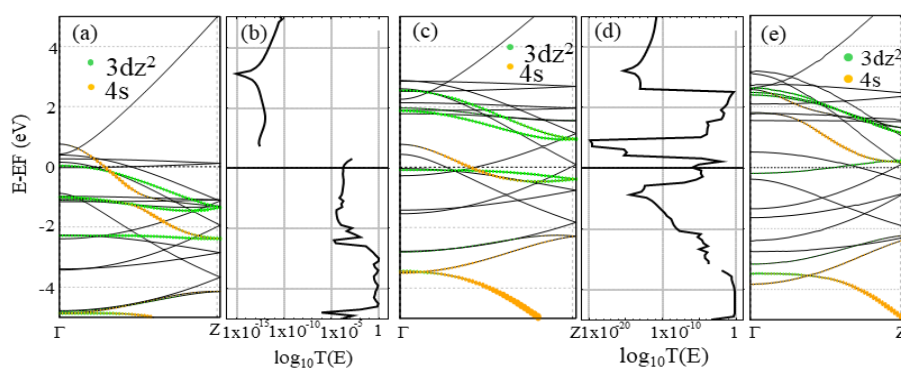


Fig.1. Band structure of bcc-Fe(110) for (a) up-spin and (c) down-spin states. Transmittance of Fe/MgO/Fe(110) MTJ at $(k_x, k_y) = (0, 0)$ in parallel magnetization for (b) up-spin and (d) down-spin states. (e) Band structure of down-spin state of bcc-Fe (110) with +4% tensile strain. Note that the z-direction is the perpendicular direction to the (110) MTJ plane.

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キラルな分子を用いたスピントロニクスデバイスにおける磁気抵抗効果

Magnetoresistance effect of spintronic devices utilizing chiral molecules

慶大理工¹, 慶大スピンセンター²

○阿部 雅史¹, 鹿嶋 倅太郎¹, 松坂 美月¹, 海住 英生^{1,2}

Keio Univ.¹, CSRN, Keio Univ.²

○Masafumi Abe¹, Kotaro Kashima¹, Mizuki Matsuzaka¹, and Hideo Kaiju^{1,2}

E-mail: go-pomipomi@keio.jp

有機分子は主に軽元素で構成されているためスピン軌道相互作用が小さく、スピン散乱の抑制による磁気抵抗(MR)比の向上が期待される。しかし、現状の有機スピンバルブ(OSV)素子において MR 比は室温で 6%^[1]と高くない。そこで、本研究ではキラルな分子がスピンフィルターの役割を果たすキラル誘起スピン選択性(CISS)効果に着目した。キラルな分子では CISS 効果に由来する高いスピン偏極率が報告されている^{[2][3]}ことから、キラルな分子を用いた OSV において室温で巨大な MR 効果の観測が期待できる。本研究では室温における MR 効果の観測を目指し、スピコート法で成膜可能なキラル分子 2,2-diphenyl-3,3-(4-biphenanthrol) (VAPOL) (Fig. 1) を用いた、Ni/R-VAPOL/Au デバイスおよび Ni/S-VAPOL/Au デバイスの作製および構造・電気磁気特性の評価を目的とした。

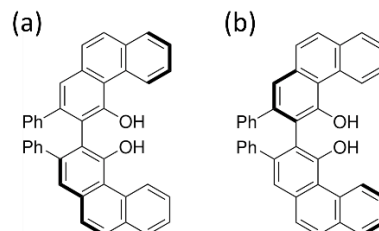


Fig. 1 Molecular structure of (a) R-VAPOL and (b) S-VAPOL.

DC マグネトロンスパッタ法とスピコート法を用いてガラス基板上に Ni, VAPOL, Au を成膜し、Ni/VAPOL/Au デバイスを作製した。構造特性評価には原子間力顕微鏡、Ni 薄膜の磁気特性評価には磁気光学カー効果、デバイスの電気磁気特性評価には磁場中直流 4 端子法を用いた。

Ni 薄膜上の VAPOL 薄膜の表面粗さ R_a は R-VAPOL で 0.37 nm, S-VAPOL で 0.30 nm となり、平坦な分子薄膜の成膜に成功した。Fig. 2 に、Ni 薄膜の磁気特性を示す。±4 kOe 程度で磁化が飽和したことから、Ni 薄膜は垂直磁化を示したと考えられる。この結果は Ni 薄膜がキラルな分子を用いた OSV の磁性層として適していることを示している。これらの材料を用いて Ni/VAPOL/Au デバイスを作製することで、本デバイスにおいて MR 効果の観測に成功した。本 MR 効果は R-VAPOL および S-VAPOL 由来の CISS 効果に起因すると考えられる。詳細な実験結果については講演会当日に報告する。

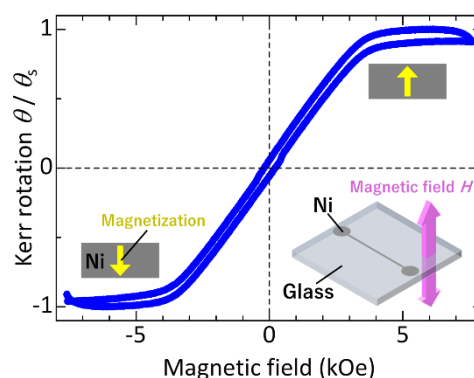


Fig. 2 Magnetic properties of Ni films.

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Machine Learning and DFT Prediction for Tailored Clean Crystallization for Lattice-Mismatched MgO/Fe

Mie Univ.¹, °Andi Muhammad Nur Fitrah Syamsul¹, Kohji Nakamura¹

E-mail: 424de01@m.mie-u.ac.jp

Magnetic Tunnel Junctions (MTJs) with Perpendicular Magnetic Anisotropy (PMA) are central to spin-transfer torque MRAM, with the Fe/MgO interface offering strong PMA and voltage-controlled magnetic anisotropy (VCMA) [1,2]. However, lattice mismatch between Fe and MgO can introduce interfacial strain, leading to structural defects that compromise crystal quality and stability. These effects are further influenced by synthesis methods and oxidation states, as seen in related systems like Fe₄N/MgO [3,4]. While DFT is commonly used to study such interfaces, most studies are limited to small unit cells, restricting access to a wider configuration space. To address this, we apply the Global Optimization with First-principles Energy Expressions (GOFEE) method to explore low-energy interfacial structures in Fe/MgO (001) using a 3×3×1 supercell with two monolayers of Fe and MgO [5]. Calculations are performed using the Linear Combination of Atomic Orbitals (LCAO) method with the Perdew–Burke–Ernzerhof (PBE) functional, a (2,2,1) k-point grid, and a double-zeta polarized basis set. Two initial conditions are considered: a clean interface and an oxidized one where one oxygen atom is shifted toward the Fe layer without altering stoichiometry. For each condition, GOFEE method is performed by applying a 1.1 Å rattle to Mg and O atoms while keeping Fe atoms fixed. After 50 GOFEE iterations, the clean interface reliably produces crystalline MgO, while the oxidized configuration does not, indicating that initial oxygen placement strongly influences interface quality.

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Fabrication of Fcc(111)-Oriented MTJs on Bcc(110)-Oriented FeAlSi Films for TMR Sensors Application

Graduate school of Engineering, Tohoku Univ.¹, Tohoku Univ. Green X-tech²,
Tohoku Univ. CSIS³



°D. Amiie¹, T. Hojo¹, M. Tsunoda^{1,2}, M. Oogane^{1,3}

E-mail: daisuke.amiie.p5@dc.tohoku.ac.jp

Magnetic tunnel junction (MTJ)-based tunnel magnetoresistance (TMR) sensors enable high-sensitivity magnetic field detection and are expected to realize applications in the medical field [1]. However, larger TMR ratio is required for TMR sensors to be widely deployed in practical applications. Recently, it has been suggested that MTJs with fcc(111)-orientation can significantly improve TMR ratio [2]. In this study, we fabricated fcc(111)-oriented MTJs on bcc(110)-oriented FeAlSi epitaxial thin films to obtain both high TMR ratio because of fcc(111)-orientation and low magnetic anisotropy due to soft magnetic properties of FeAlSi.

The multilayer films were deposited using an ultrahigh vacuum sputtering system capable of fabricating high-quality multilayer structures. A schematic of the fabricated structure is shown in Fig. 1. XRD $2\theta/\omega$ and ϕ scan results (Fig. 2) confirmed that Ru(hcp(0001)), CoFe(fcc(111)), and IrMn(111) grew epitaxially as single-crystalline layers on FeAlSi(110). The MgO layer was also confirmed to be (111)-oriented in the sample with a thickness of 20 nm. These results indicate successful fabrication of fcc(111)-oriented MTJs on bcc(110)-oriented FeAlSi. Magnetoresistance characteristics will also be reported in the presentation. This work was supported by the SIP project, BRIDGE project, the X-nics project, the SCOPE project, CSIS, CIES and the AIE-WISE Program.

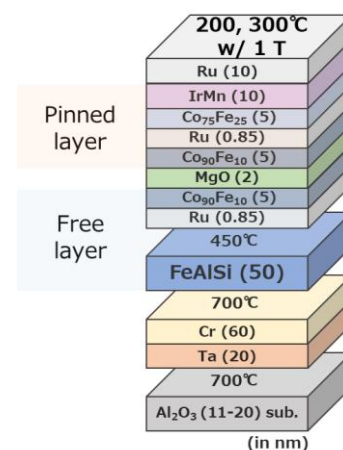


Fig.1 Stacking structure of the fabricated MTJ sample

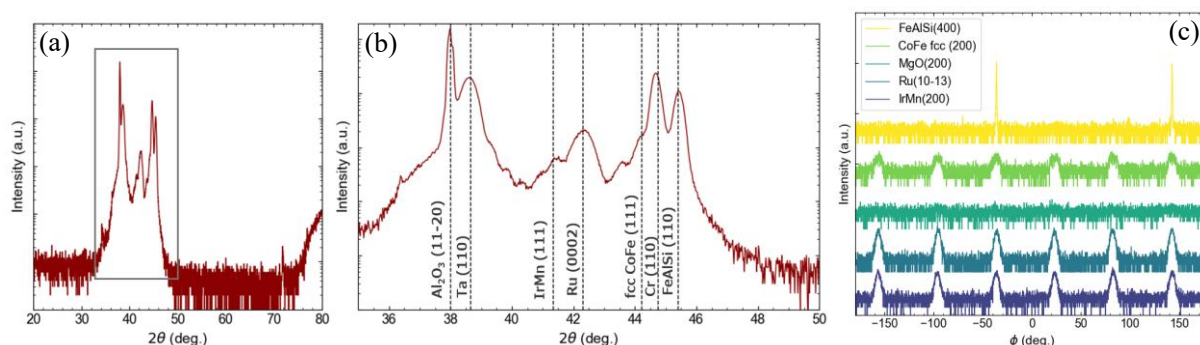


Fig.2 XRD results : (a) $2\theta/\omega$ scan confirming the out-of-plane orientation; (b) magnified view of the 35° – 50° region; and (c) ϕ scan indicating in-plane epitaxial alignment.

[1] T. Nakano et al., Appl. Phys. Lett. **126**, 160503 (2025)

[2] K.Masuda et al., Phys. Rev. B, **101**, 144404 (2020)

Insulator thickness dependence of magnetocapacitance in magnetic tunnel junctions and calculation modeling

Ryuta Okazaki¹, Yuto Shibata¹, Mizuki Matsuzaka¹, Mizuki Wakamoto¹,
Hiroaki Sukegawa², and Hideo Kaiju^{1,3}

¹Keio Univ., ²NIMS, and ³CSRN, Keio Univ.

E-mail : ryuta_horizon@keio.jp

Magnetic tunnel junctions, which consist of a thin insulator (I) sandwiched between two ferromagnetic (FM) layers, exhibit a large tunnel magnetocapacitance (TMC) at room temperature [1]. Recently, a large TMC ratio of 456% has been observed over an optimized frequency and bias voltage range in FeCo/MgAl₂O₄/FeCo(001) MTJs [2]. However, previous studies have demonstrated that the TMC peak appears at low frequencies, and that the observed TMC is approximately 50% in the high frequency region [3]. For device applications, a larger TMC at higher frequencies is desirable. According to the Debye-Fröhlich (DF) model, a large TMC is predicted at higher frequencies in MTJs with a thin insulator, in which the electric dipoles formed at the FM/I interfaces follow the changes in the AC electric field. In this study, we report the largest TMC beyond 650% for MTJs with a thin MgO barrier in the high frequency region at room temperature.

The MTJs were prepared using an ultra-high vacuum magnetron sputtering system with a base pressure of 5×10^{-7} Pa, with the following layer sequence: Si/SiO₂ substrate/[Ta (5)/Ru (20)]₃/Ta (5)/FeCoB (3.5)/FeCo (0.7)/MgO ($d_{\text{MgO}} = 1\text{--}2$ nm)/annealing/FeCoB (3.5)/FeCo (0.7)/Ir₂₀Mn₈₀ (8)/Ru (8) (unit: nm). The MTJs stacks were patterned into a junction area of $5 \times 10 \mu\text{m}^2$ with an elliptical shape using photolithography, Ar ion-beam etching, and SiO₂ insulation sputtering. The frequency characteristics of the TMC for MTJs were measured by an AC four-probe method at room temperature.

Fig. 1 shows the frequency characteristics of TMC in MTJs with $d_{\text{MgO}} = 1.18, 1.22$, and 1.27 nm. The calculation of TMC is performed using the extended DF model incorporating the transmittance of quantum tunneling effect into the high-frequency capacitance term. As shown in Fig. 1, the TMC ratio decreases with increasing the frequency for $d_{\text{MgO}} = 1.27$ nm, whereas it increases up to 661% at 1 MHz for $d_{\text{MgO}} = 1.18$ nm. The TMC of 661% is the largest value ever reported for MTJs. The calculation results of TMC fit to the experimental data well. Fig. 2 shows the MgO thickness dependence of capacitance $C_{\text{P(AP)}}$ in the parallel (antiparallel) magnetization state at 1 MHz. $C_{\text{P(AP)}}$ increases exponentially with decreasing the MgO thickness, and a significant difference between C_{P} and C_{AP} is observed. The experiment data provide an excellent fit to the calculated results in the entire MgO thickness range. These experimental and theoretical findings contribute to a deeper understanding on the exact mechanism of the TMC effect, and the prospect of an increasingly large TMC at higher frequencies opens exciting opportunities for novel spintronic applications. This work was partly supported by JSPS KAKENHI Nos. 24K00948 and 24H00408, MEXT Program: Data Creation and Utilization-Type Material Research and Development Project Grant Number JPMXP1122715503.

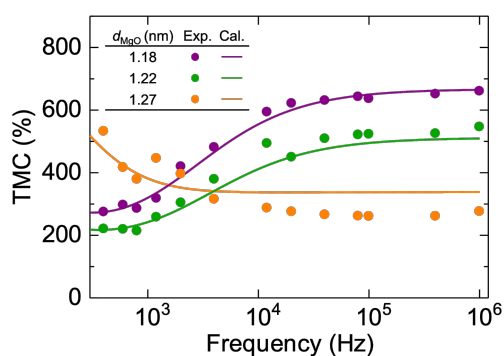


Fig. 1 Frequency characteristics of TMC.

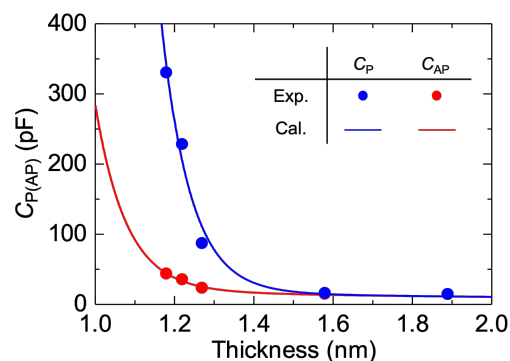


Fig. 2 MgO thickness dependence of $C_{\text{P(AP)}}$.

[1] H. Kaiju *et al.*, *Appl. Phys. Lett.* **107**, 132405 (2015).

[2] Y. Shibata, K. Sato, H. Sukegawa, and H. Kaiju, *Appl. Phys. Express* **16**, 113003 (2023).

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A Comparison of Electrical 1/f Noise in Magnetic Tunnel Junctions with MgO and Mg-Al-O Barriers

Shintarou Nii¹, Chaoliang Zhang¹, Haoxiang He¹, Yupeng Wang¹, Takayuki Hojo¹, Takafumi Nakano^{1,2}, Mikihiro Oogane^{1,3}

Department of Applied Physics, Tohoku Univ.¹, Green X-tech, Tohoku Univ.² CSIS, Tohoku Univ.³

E-mail: Chaoliang.zhang.e8@tohoku.ac.jp

Magnetic tunnel junction (MTJ)-based tunnel magnetoresistance (TMR) sensors offer high magnetic field sensitivity, compact size, and operation capability above room temperature, making them suitable for biomedical applications.¹ Many such applications involve sensing weak magnetic fields in the sub-100 Hz frequency range, where electrical 1/f noise becomes a significant limiting factor. This noise primarily originates from charge trapping and detrapping at the tunnel barrier or its interfaces.² Although MgO is one of the most widely used tunnel barriers in MTJs, its lattice mismatch with Fe-based electrodes often introduces interfacial defects, leading to elevated 1/f noise.³ In contrast, magnesium aluminum oxide (MAO) offers a better lattice match to Fe, making it a potential low-noise alternative.⁴ Although previous studies have focused on the TMR properties of these barriers, detailed comparison of their 1/f noise behavior is still required to fully understand the noise mechanism. Here we address this gap by performing a direct comparison of the electrical 1/f noise characteristics of MgO- and MAO-based MTJs fabricated under similar processing conditions.

The MTJ stack in this study is MgO(001) substrate / Cr(60) / Fe(50) / Mg(0.2) / MgO or MAO(2) / Fe(5) / IrMn(10) / Cr(5) (thickness in nm). The barrier layers (MgO or MAO) are deposited via electron beam evaporation, while the remaining layers are formed using DC magnetron sputtering. Device patterning is carried out using standard photolithography and ion milling techniques, and TMR measurements are performed using a four-probe setup. Devices with MgO barriers (MgO-MTJs) exhibited TMR ratios ranging from 140% to 180%, whereas those with MAO barriers (MAO-MTJs) showed TMR ratios between 60% and 100%. The power spectra density of MgO and MAO-MTJs is measured to assess their noise electrical 1/f noise, which is quantified with the Hooge parameter.⁵ MgO-MTJs shows a value of $5.74 \times 10^{-8} \mu\text{m}^2$, while MAO-MTJs showed a substantially lower value of $5.69 \times 10^{-9} \mu\text{m}^2$, confirming the noise suppression capability of MAO. To further investigate the underlying cause, scanning transmission electron microscopy was utilized to examine interfacial defect densities. The analysis revealed that the MAO/Fe interface had approximately 1% defect density, significantly lower than the 4% observed at the MgO/Fe interface, pointing to the superior lattice compatibility and structural quality of MAO, which is considered to contribute to the noise suppression. These results offer valuable guidance for selecting tunnel barrier materials in the design of low-noise TMR sensors, especially for sensitive applications in biomedical and low-frequency detection environments.

This work was partially supported by the X-nics project and CSIS, and CIES at Tohoku University, SIP project and BRIDGE project of Cabinet Office, JSPS KAKENHI 24K17316, and research grants of Hirose Foundation.

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強化学習を援用したスピントルクによる高速磁化反転方法の模索

A theoretical study of precessional magnetization reversal via spin torque assisted by reinforcement learning

埼玉大理工 ○(M2) 五十嵐優太, 藤本純治

Saitama Univ. °Yuta Igarashi, Junji Fujimoto

E-mail: yigarashi@spin.eeap.saitama-u.ac.jp

近年注目されている磁気抵抗メモリ (MRAM) は, 磁化の向きによって情報を記録する不揮発性メモリである. MRAM の性能向上には, 磁化を高速かつ低消費電力で反転させる技術が不可欠である. 磁化を高速に反転させる方法の一つとしてスピン軌道トルク [1]を利用したものがあるが, 反転に必要な電流量の低減や, さらなる反転速度の向上が求められている.

そこで我々は機械学習の一種である強化学習を導入し, 磁化反転の高速化と最適な電流波形の自律推定を試みた. 強化学習はシステム自身が試行錯誤して最適な行動戦略を学ぶ手法であるため, 教師データを必要とせず, 未知の環境にも適用可能である. この強化学習を, 磁化の運動を記述する LLG 方程式に組み込むことにより, 磁化反転軌道を最小化するための電流波形の推定を行った.

強化学習シミュレーションを行った結果, $3 \times 10^{10} \text{ A/m}^2$ という低電流かつ外部磁場を印加しない条件下で, 300 ps 以内の磁化反転を可能にする電流波形を推定することに成功した. 本発表では, 強化学習アルゴリズムの詳細や, 最適方策における電流波形と磁化反転の物理的メカニズムについての考察を示す.

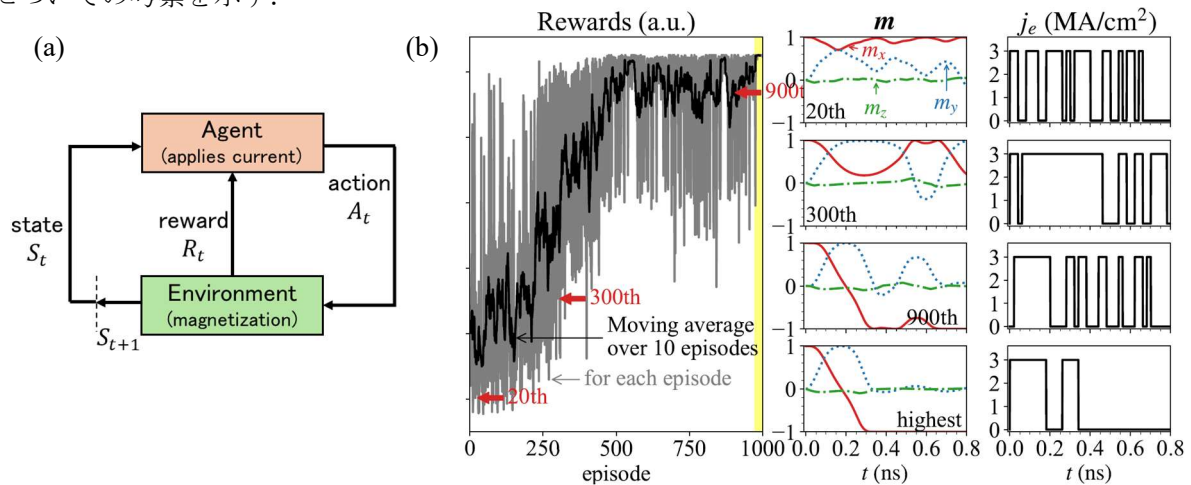


FIG.1. (a) Reinforcement learning framework for magnetization reversal. (b) (Left) Episode dependence of the total rewards. (Center) Magnetization dynamics for the 20th, 300th, and 900th episodes and the episode yielding the highest total reward. (Right) The corresponding current waveforms. The simulation is performed for $\alpha_G = 0.01$ and $M_S = 750 \text{ kA/m}$ (i.e., $\mu_0 M_S = 0.94 \text{ T}$) at zero temperature $T = 0$.

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電流誘起磁壁駆動におけるインピーダンスの影響

Impedance effects in current-induced magnetic domain wall motion

豊田工業大学¹ ○(B) 船江貴大¹, 栗野博之¹, 田辺賢士¹

Toyota Technological Institute¹, °T. Funae¹, H. Awano¹, K. Tanabe¹

E-mail: sd22083@toyota-ti.ac.jp

近年、データ消費量の飛躍的な増大に伴い、省電力、高速動作可能な磁壁駆動型磁気メモリが期待されている。特に、磁壁駆動速度はメモリの動作速度に直結しており、重要な評価パラメータになっている。ごく最近、10 ns 以下(中には1 ns 以下)の短パルス電流印加によって高速動作が実現しており、非常に注目されている。[1,2]。しかし、このような短パルス領域は、マイクロ波領域に突入しているものの、これまで、細線のインピーダンスを考慮した実験は行われていない。そこで我々は、電流誘起磁壁駆動のインピーダンスの影響について調査を行った。

Fig. 1 に示すように、熱酸化膜(SiO₂) を持つ Si 基板上に、特性インピーダンス 50 Ω になるように設計されたコプレーナ型電極: Cr(50 nm)/Au(150 nm) を作製し、その上に磁性細線: Pt(10 nm)/Gd₂₅Fe₇₅(30 nm)/SiN_x(10 nm) の構造を持つ試料を、マグネトロンスパッタ装置、電子線リソグラフィを用いて作製した。このとき、細線幅を一定に固定しながら細線長(L)を変調することでインピーダンス(抵抗)を変調した。細線のインピーダンスにおける、パルス幅と磁壁速度の関係を Fig. 2 に示す。60 ns 以上の長パルス幅領域では、どのサンプルにおいても 50 m/s 程度の一定の磁壁速度を記録した。一方で、30 ns 以下の短パルス領域では、磁壁速度が変化し始め、細線ごとに磁壁速度にばらつきが生じた。試料はすべて、同一幅、同一膜厚、同一材料であるため、これまでの解析では同一の値をとるべきものである。今回の結果は、短パルス領域において、細線のインピーダンスを考慮する必要があることを示唆している。

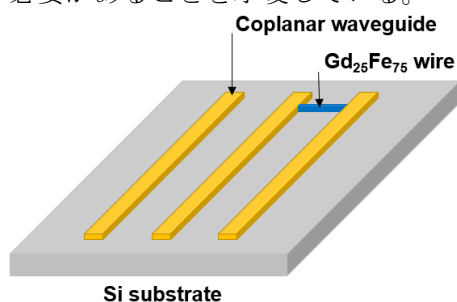


Fig. 1 Schematic sample structure

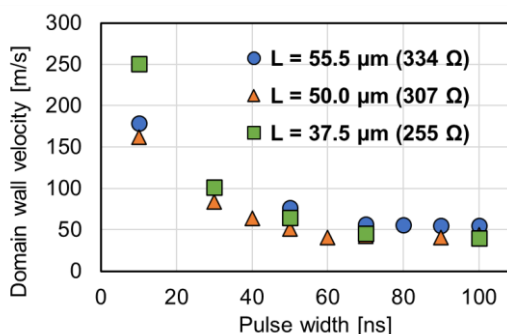


Fig. 2 Relationship between pulse width and domain wall velocity

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- [1] S. Ranjbar et al., *Materials Advances*, **3**, 7028 (2022).
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垂直方向の組成勾配を有する Gd-Fe 細線における電流誘起磁壁移動 Current-induced domain wall motion in Gd-Fe wires with vertical composition gradient

豊田工業大学, °水野 淳平, 栗野博之, 田辺賢士

Toyota Tech. Inst., °Jumpei Mizuno, Hiroyuki Awano and Kenji Tanabe

E-mail: sd24447@toyota-ti.ac.jp

ジャロシンスキー・守谷相互作用 (DMI) やラシュバ効果は、非対称な系でのみ発現する反対称相互作用であり、磁壁の運動制御において重要な役割を果たしている。近年のスピン트로ニクス分野では、厚さ 1 nm 以下の磁性超薄膜を重金属層と絶縁層で挟んだ人工的な非対称構造[1]を用いて、DMI やラシュバ効果を制御する研究が進められている。しかし、磁性超薄膜は磁氣的に不安定であることに加え、重金属層には貴金属である Pt などが使用されるため、実用化には課題が残されている。ごく最近、垂直方向に組成勾配を持つ磁性体薄膜が注目されている。このような組成勾配は自発的な反転対称性の破れを引き起こし、反対称相互作用を誘起する可能性がある。実際に、磁性超薄膜や重金属を使用せずに、組成勾配を有する単層で DMI[2-3]とラシュバ効果[3]が誘起されたことが報告されている。本研究では、垂直方向の組成勾配を有する GdFe 細線において電流誘起磁壁移動実験を行い、組成勾配が磁壁移動に及ぼす影響について調査した。

熱酸化膜 (SiO₂) を持つ Si 基板上に Pt (5 nm)/ g-GdFe(20 nm)/SiN (10 nm)の構造を持つ磁性細線を、マグネトロンスパッタ装置で作製した。g-GdFe は面直方向に組成勾配 (gradient) を持つ GdFe 膜を表し (Fig. 1)、カソードパワーをリモート制御したコスパッタ法を用いて作製された。Gd₂₁Fe₇₉ から Gd₂₅Fe₇₅ までの線形的な組成勾配を適用し、エネルギー分散型 X 線分光法により平均組成 Gd₂₃Fe₇₇ が測定された。参照試料として Gd₂₃Fe₇₇ の均一組成を有する磁性細線も同様に作製した。電極にパルス電流 (100 ns) を流して磁壁移動を誘起し、組成勾配を持つ細線と均一組成の細線の磁壁移動速度を比較した。Fig. 2 は注入されたパルス電流の電流密度に対する磁壁移動速度を示す。Fig. 2 に示すように、組成勾配を有する磁性細線では均一な組成を有する磁性細線よりも高速な磁壁移動が観察された。磁壁移動速度向上の原因として、勾配誘起 DMI による影響や g-GdFe 層・重金属層界面の影響が考えられる。

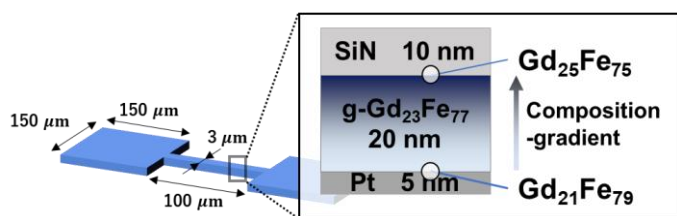


Fig. 1 Schematic illustration of the g-GdFe films.

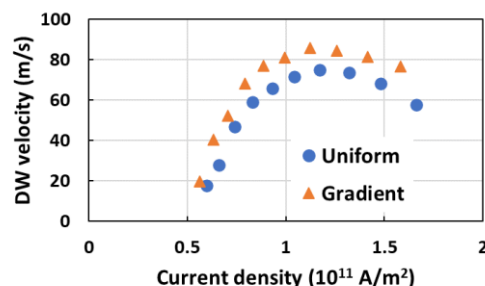


Fig. 2 Comparison of the DW velocity. ○ indicates wire with uniform composition, and △ indicates wire with composition gradient.

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電析法と細孔テンプレートを用いて作製した Ni-Pt 合金ナノ細線の構造と磁気特性

Characterization of structure and magnetic properties for Ni-Pt alloy nanowires
fabricated by electrodeposition and nanoporous templates

岐阜大学, (M1)[○]小田裕介, (M2)川名梨央, 嶋睦宏, 山田啓介

Gifu Univ., [○]Yusuke Oda, Rio Kawana, Mutsuhiro Shima¹, Keisuke Yamada¹

E-mail: oda.yusuke.z8@s.gifu-u.ac.jp, yamada.keisuke.p6@f.gifu-u.ac.jp

[概要] 次世代の不揮発性かつ高速動作が可能な磁気メモリとして、三次元磁壁移動型抵抗メモリが注目されている^[1]。この磁気メモリは、人工強磁性体と呼ばれる強磁性体の記録層と磁壁層が積層された構造をもち、細線内の磁壁位置を電子スピンにより制御することでメモリとして実装させる。現在までの研究において Co-Pt 合金を用いた人工強磁性体細線の作製には成功しているが^[2,3]、細線内の磁壁移動にはまだ課題がある。そこで、より軟磁性材特性を有する Ni-Pt 合金を用いて人工強磁性体の作製し、電流による磁壁移動の観測を目指した。本研究では、初めに基盤研究として、単層 Ni-Pt 合金薄膜及び細線の作製を行い、試料の構造と磁気特性を調べた。

[方法] 初めに Ni-Pt 合金ナノ細線を作製するために、溶液組成比 (Ni:Pt = 25:8, 50:8, 100:8 [mM]) や電析電位を変化させ、Ni-Pt 合金薄膜の作製条件を調査した。次に、ナノ細線は、ポリカーボネート(PT)の細孔内に電析法を用いて作製した。作製した薄膜及び細線の結晶構造、磁気特性、微細構造を XRD, VSM, SEM-EDX, TEM を用いて評価した。

[結果] Fig.1(a)は、Ni-Pt 合金薄膜の各 Ni-Pt 溶液組成比における電析電位の Ni 組成比依存性の結果を示す。各 Ni-Pt 溶液組成比において高電位であるほど Ni 組成比が増加することが確認できた。Ni-Pt 合金薄膜の XRD 測定結果より、Ni fcc (111), (311)の多結晶体の Ni-Pt 合金が確認でき、VSM 測定結果から、[Ni:Pt = 100:8]溶液, 電析電位 $E = -1050$ mV vs. Ag/AgCl において、強磁性の特性を示した。以上の結果から、[Ni:Pt = 100:8]溶液, 電析電位 $E = -1050$ mV vs. Ag/AgCl 条件を用いて、PT 内に Ni-Pt 合金を電析させたところ、Fig.1(b,c)に示すように、Ni-Pt 合金ナノ細線を作製できたことを確認できた。

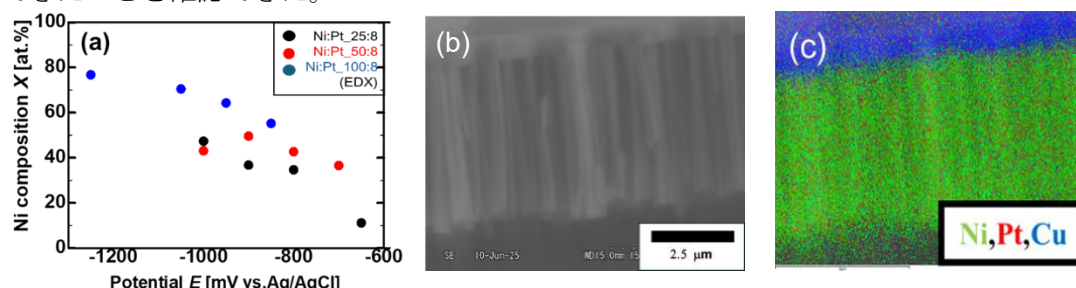


Fig. 1 (a) Electrodeposition potential E vs Ni composition X in Ni-Pt alloy films. (b) Cross-sectional view of SEM image and (c) SEM-EDX analysis for Ni-Pt alloy nanowires.

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謝辞: 本研究は、CREST「3次元磁気メモリの開発」の助成を受けて行われた。

Characterization of structure and magnetic properties for $\text{Co}_x\text{Pd}_{100-x}$ alloy nanowires fabricated by electrodeposition and nanoporous template

Gifu Univ., (M2) Afifah Nur Chairinnisa*, Shunpei Matsuoka, (M2) Rio Kawana, Mutsuhiro Shima,
and Keisuke Yamada**

E-mail: *afifah.nur.chairinnisa.g1@s.gifu-u.ac.jp, **yamada.keisuke.p6@f.gifu-u.ac.jp

Recently, three-dimensional magnetic memory technology that utilizes domain wall motion has attracted attention due to its ability to enhance memory performance characteristics^[1]. These devices operate by manipulating magnetic domain walls (DWs) within nanowires, which consist of magnetic domains and DW-pinning layers. For the development of magnetic nanowire devices, Co-Pt and Co-Pd alloys are as optimal materials for their high magnetocrystalline anisotropy (K_u) and for construction of multilayer structures. Our research group has previously published findings on the characterization of Co-Pt alloy nanowires produced through electrodeposition and nanoporous membranes^[2,3]. However, the optimization of preparation conditions for Co-Pd alloy nanowires and their characterization has not been investigated. In this report, we focus on examining the structure and magnetic properties of Co-Pd alloy nanowires.

Co-Pd alloy nanowires were fabricated in the nanopores of a polycarbonate template (PT) through the process of electrodeposition. We investigated the conditions necessary for the formation of these Co-Pd alloy nanowires by modifying the characteristics of the polycarbonate template and adjusting the electrodeposition potential. The microstructure, alloy composition, crystal structure, and magnetic properties of the nanowires were analyzed using SEM, TEM, EDX, ED, XRD, and VSM, respectively.

$\text{Co}_x\text{Pd}_{100-x}$ alloy nanowires with Co compositions x ranging from 35 to 98 could be fabricated when the samples were prepared using a solution composition ratio of $(\text{Co}^{2+}:\text{Pd}^{2+}) = (100:1)$ as shown in Fig. 1(a). The templates used are PT 1%, 8%, and 31% in the same electrodeposition potential (-850, -800, -750, -700 mV vs. Ag/AgCl). Figure 1(b) shows the cross-sectional SEM-EDX view for the sample of PT 8% at -850 mV vs. Ag/AgCl, the wire length was approximately 8 μm and atomic percent of Co: Pd was 87:12. Figure 1(c) shows that the K_u value does not depend exactly on Co composition because the wire length and saturation magnetization (M_s) also affected K_u value. By applying these three PT conditions, $\text{Co}_x\text{Pd}_{100-x}$ alloy single nanowires were successfully fabricated, with lengths ranging from 2 to 20 μm and a face-centered cubic (fcc) structure. PT 1% and PT 31% were found to be the best electrodeposition templates for estimating K_u and M_s .

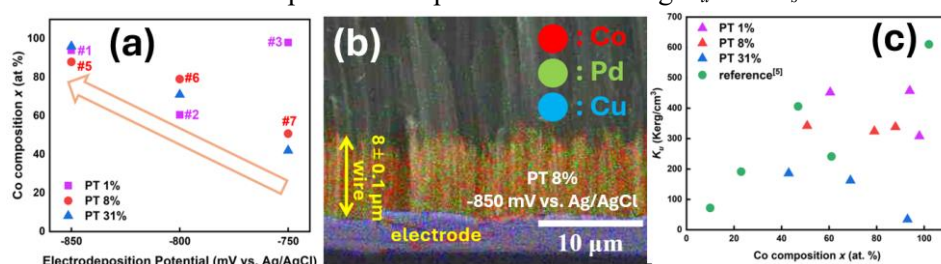


Figure 1. (a) Correlation between the electrodeposition potential and Co composition for Co-Pd nanowires fabricated in each PT's porosity. (b) Cross-section SEM-EDX view of the samples. (c) Correlation between K_u value with Co composition^[4]

References: [1] Y. M. Hung, et. al., *J. Magn. Soc. Jpn*, **45**, 6 (2021). [2] N. Oguchi, et. al., *J. Magn. Magn. Mater.* **601**, 172159 (2024). [3] R. Kawana, et al., *Appl. Phys. Express* **18**, 033002 (2025). [4] N. Nozawa, et al. *J. Phys. D: Appl. Phys.*, **46**, 172001 (2013).

Acknowledgment: This research was supported by the CREST program, "Development of Three-Dimensional Magnetic Memory."

Fabrication and evaluation of Co electrodes for the creation of novel molecular nanodevices

[○]Koki Terai¹, Mizuki Matsuzaka¹, Takumi Ueda¹, and Hideo Kaiju^{1,2}

¹Keio Univ. and ²CSRN, Keio Univ.

E-mail: kokitera13@keio.jp

Molecular spintronics has attracted much attention due to long spin-relaxation times in devices. Notably, a large magnetoresistance (MR) effect has been reported in molecular spintronic devices with nanosized junction area¹. Recently, we have observed a positive MR effect in Ni₇₈Fe₂₂ (Py)/2, 7-dioctyl[1]benzothieno[3, 2-*b*][1]benzothiophene (C8-BTBT)/Py nanodevices using magnetic thin-film edges². Here, toward the creation of novel molecular nanodevices, we focus on Co electrodes as magnetic layers and fullerene (C₆₀) as a molecular layer. Previous studies have demonstrated a high spin polarization at the interface between Co and C₆₀³, which is attractive for the application of MR devices. In this study, we fabricate Co electrodes for molecular nanodevices, and investigate their structural, electrical, and magnetic properties.

A schematic of Co/C₆₀/Co nanodevices is shown in Fig. 1. Co electrodes were fabricated by following procedure. Co thin films were deposited on glass substrates by sputtering. Glass/Co/glass (S-Co) was fabricated by thermal pressing and mechanical cutting. The cut surfaces of S-Co were polished by mechanical polishing and chemical mechanical polishing procedure. The structural, electrical, and magnetic properties of the Co electrodes were measured by scanning electron microscopy (SEM), atomic force microscopy (AFM), conductive AFM (c-AFM), and magneto-optical Kerr effect.

The magnetic properties of S-Co can be controlled by changing the pressure P during the thermal pressing and deposition time t of Co films. Fig. 2 shows the magnetization curves of S-Co (sample A; $P = 1.0$ MPa, $t = 6$ min, sample B; $P = 0.25$ MPa, $t = 4$ min). The coercivities in samples A and B are different from each other, which suggests that the parallel and anti-parallel magnetization states can be realized in nanodevices. The SEM study reveals that the edge width of Co thin films in polished samples A and B, d_A and d_B , are 48 nm and 31 nm, respectively. Therefore, when we use the polished S-Co of samples A and B as the top and bottom electrodes, the nanodevices with a junction area S of $48 \text{ nm} \times 31 \text{ nm}$ can be produced, leading to the observation of MR effect. Fig. 3 shows the c-AFM image of the surface of polished S-Co of sample A. A uniform electrical conduction is observed along the Co edges. Additionally, the AFM measurement shows that the surface roughness of the polished S-Co of sample A is lower than 1.0 nm. These results indicate that the Co electrodes can be used in Co/C₆₀/Co nanodevices from the viewpoints of structural, electrical, and magnetic properties.

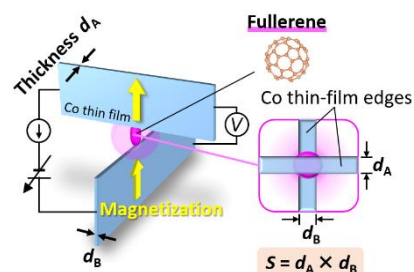


Fig. 1 Schematic of Co/C₆₀/Co nanodevices.

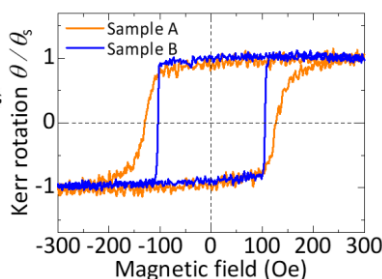


Fig. 2 Magnetization curves of S-Co (samples A and B).

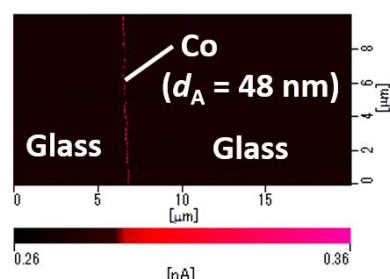


Fig. 3 c-AFM image of the surface of polished S-Co (sample A).

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ナノインプリントによる三次元磁性デバイス作製技術研究

Investigation of fabrication process for three-dimensional magnetic microstructure using nano-imprint technique

九大シス情¹, 豊田工大², 岐阜大³, ○黒川 雄一郎¹, 田辺 賢士², 山田 啓介³,

鷲見 聡², 栗野 博之², 湯浅 裕美¹

Kyushu Univ.¹, Toyota Tech. Inst.², Gifu Univ.³

○Yuichiro Kurokawa¹, Kenji Tanabe², Keisuke Yamada³, Satoshi Sumi²,

Hiroyuki Awano², Hiromi Yuasa¹

E-mail: ykurokawa@ed.kyushu-u.ac.jp

[Introduction] Controlling a magnetic domain wall (DW) using electric current has been widely studied as one of the most active research topics in the spintronics because it can be applied to magnetic memories [1]. For practical application, a three-dimensional (3D) magnetic wire is required to obtain sufficient recording density. In this study, we suggest a fabrication process for the 3D magnetic microstructure using nano-imprint technique.

[Experiment] We fabricated the thin polyimide (PI) sheet on a thermally oxidized Si substrate using polyimide vanish and spin coating method. The perpendicular magnetized Co/Ni magnetic film was deposited on the PI sheet using magnetron sputtering method. After deposition, the PI sheet was peeled off from the Si substrate. The PI sheet with the magnetic film was put on a cyclo olefin polymer (COP) sheet and a Si mold was pressed on the PI sheet with the COP sheet under vacuum and temperature $T = 180\text{ }^{\circ}\text{C}$. After the Si mold was released, the 3D patterned magnetic film was obtained, that is so-called as a nano-imprint method, as shown in Fig. 1(a).

[Results] Fig. 1(b) shows a scanning electron microscopy (SEM) image of surface of the 3D patterned magnetic film. The PI sheet is successfully patterned by the nano-imprint method. Next, we observed DW motion controlled by an external magnetic field using a Kerr microscope. We successfully observed DW motion on 3D patterning step.

[Acknowledgements] This study was supported in part by the JSPS KAKENHI Grant No. JP25K00039, the JST, ACT-X Grant Number JPMJAX21K5, Murata Science and Education Foundation, and Iketani Science and Technology Foundation. A part of this work was supported by ARIM of the MEXT. Proposal Number JPMXP1224TT0034.

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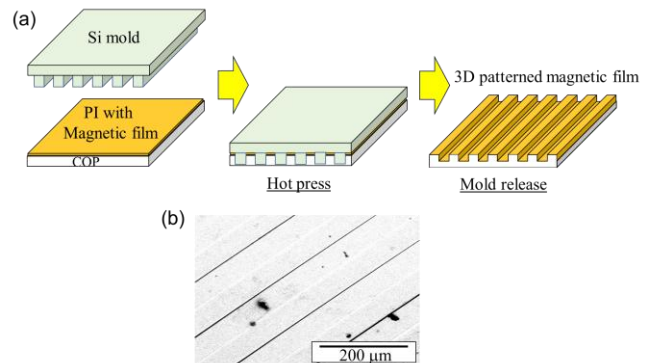


Fig. 1 (a) Schematic illustration of fabrication process for 3D patterned magnetic film and (b) SEM image of surface of patterned magnetic film.

First-principles prediction of nitride and fluoride compounds modification at the Fe/MgO interface for perpendicular magnetic anisotropy and voltage-controlled magnetic anisotropy

Mie Univ., °Masato Tsuchida, Yosephine N. Apriati, Kohji Nakamura

E-mail: 424m229@m.mie-u.ac.jp

In the development of spin-transfer torque magneto-resistive random-access memory (STT-MRAM), the material design for magnetic tunnel junctions (MTJs) becomes a critical issue in addressing the grand challenges in spintronic memory, achieving perpendicular magnetic anisotropy (PMA) exceeding 2 mJ/m² and voltage-controlled magnetic anisotropy (VCMA) efficiency over 1000 fJ/Vm [1, 2]. For MTJ structure of Fe/MgO, the Fe-O p-d coupling at the interface is a key factor for PMA. The interface modification is a promising approach to tuning both PMA and VCMA[3]. Previous work, involving the interface insertion of light elements (LiF) [4] and inserting heavy metal (Ir and W) [5], successfully enhances PMA and VCMA from its pristine structure. Although the guidelines for overcoming the grand challenge are still unclear. This work, implementing a first-principles study based on density functional theory (DFT) by the full-potential linearized augmented plane wave method (FLAPW) [6], examines the Fe/MgO interface modification using nitride and fluoride compounds on the PMA and VCMA. The fluoride and nitride, those with one more or one less electron compared to the oxides at the periodic table. The pristine Fe/MgO is modelled by considering 10 atomic monolayers (ML) of Fe (001) and 5 ML of MgO (001). We consider the interface modification model by substituting one ML of MgO at the interface with the MX, namely, the Fe (10 ML)/MX (1 ML)/MgO (4 ML) model. The MXs from the nitride group are MgN, BN, AlN, GaN, InN, ScN, and TiN, and from the fluoride group are MgF, LiF, and NaF. The results for PMA and VCMA for the pristine Fe/MgO model are 0.1755 meV and 32.3 ε fJ/Vm respectively. Here ε is the dielectric constant of the insulator. From the nitride group, MgN and BN modifications model, and LiF from the fluoride group show significantly improved PMA, by approximately 413.2%, 296.8% and 314.5% compared to that on the pristine Fe/MgO model. As for the VCMA, only the AlN modification model is enhanced from the pristine Fe/MgO, by 139.9%. Detailed insight into the origin of nitride and fluoride compound modifications at the Fe/MgO interface on the PMA and VCMA will be presented.

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10 Spintronics and Magnetism | Oral presentation : 10.1 Emerging materials in spintronics and magnetism
(including fabrication and characterization methodologies)

[8a-N304-1~10] 10.1 Emerging materials in spintronics and magnetism (including fabrication and characterization methodologies)

[8a-N304-1]

Giant Enhancement of the Anomalous Nernst Coefficient in $\text{Co}_{1-x}\text{Pt}_x$ Thin Films

○(PC)Mojtaba Mohammadi¹, Satoshi Sumi¹, Hiroyuki Awano¹, Kenji Tanabe¹ (1.Spintronics Laboratory, Toyota Technological Institute, Nagoya 468-8511, Japan)

[8a-N304-2]

Anomalous Nernst effect in amorphous Gd-Co-Pt films

○(M2)Tomohiro Koizumi¹, Mojtaba Mohammadi¹, Hiroto Imaeda¹, Hiroyuki Awano¹, Kenji Tanabe¹ (1.Toyota Tech Inst.)

[8a-N304-3]

Systematic studies of anomalous Nernst effect in amorphous $\text{Tb}_x(\text{Fe}_y\text{Co}_{100-y})_{100-x}$

○Hiroto Imaeda¹, Tsunehiro Takeuchi¹, Hiroyuki Awano¹, Kenji Tanabe¹ (1.Toyota Tech. Inst.)

[8a-N304-4]

Large anomalous Nernst conductivity in Pt_2CoNi permanent magnet films with high in-plane and out-of-plane coercivities

○(PC)Rajkumar Modak^{1,2}, Hossein Sepehri-Amin¹, Yuya Sakuraba¹, Weinan Zhou¹, Ken-ichi Uchida^{1,2} (1.NIMS, 2.GSFS, U Tokyo)

[8a-N304-5]

Influence of Fermi energy tuning on anomalous Nernst effect in $(\text{Co}_{1-x}\text{Ni}_x)_2\text{MnGa}$ composition spread epitaxial film

○(D)Benugopal Bairagya^{1,2,3}, G Xing², Nanhe Kumar Gupta², Vineet Barwal², Keisuke Masuda², Weinan Zhou², Sanjay Singh³, Yuya Sakuraba^{2,1} (1.Uni. of Tsukuba, 2.NIMS, 3.IITBHU)

[8a-N304-6]

Giant sensitivity of amorphous Fe-Sn films for anomalous-Nernst-type heat flux sensors

○Kenji Tanabe¹, Kohei Fujiwara^{2,3}, Ko Mibu⁴, Atsushi Tsukazaki^{3,5} (1.Toyota Tech. Inst., 2.Rikkyo Univ., 3.Tohoku Univ., 4.Nagoya Inst. of Tech., 5.Univ. of Tokyo)

[8a-N304-7]

A kagome-magnet Co_3Mo films : room-temperature ferrimagnet with perpendicular magnetic anisotropy

○Keiki Ishida¹, Kohei Fujiwara², Kazuki Nakazawa^{3,4}, Jun Okabayashi⁵, Takumi Yamazaki⁶, Takeshi Seki^{6,7,8}, Yukitoshi Motome¹, Atsushi Tsukazaki^{1,6} (1.Dep. Appl. Phys. UTokyo, 2.Dep. Chem. Rikkyo U., 3.RIKEN CEMS, 4.RIKEN RQC, 5.Dep. Chem. UTokyo, 6.IMR, Tohoku U., 7.CSIS, Tohoku U., 8.SRIS, Tohoku U.)

[8a-N304-8]

Preparation of Mn_2PtSn thin films and characterization of their structure/magnetic/transport properties

○(M2)Koya Saijo^{1,2}, Takaaki Dohi¹, Takeshi Tasaki^{1,2}, Tomohiro Uchimura^{1,2}, K. Vihanga De Zoysa¹, Hideo Ohno^{1,3,4,5}, Shunsuke Fukami^{1,2,3,4,5,6} (1.RIEC, Tohoku Univ., 2.Tohoku Univ., 3.WPI-AIMR, 4.CSIS, Tohoku Univ., 5.CIES, Tohoku Univ., 6.InaRIS)

[8a-N304-9]

Reconsideration of the magnetic compensation in $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ epitaxial films

○Yuki Sobukawa¹, Tomohiro Yasuda¹, Soshi Akita¹, Kenta Amemiya², Takashi Suemasu¹ (1.Univ. of Tsukuba, 2.KEK)

[8a-N304-10]

Deposition temperature dependence of magnetic properties of ferrimagnetic Mn_4N epitaxial thin films on $\text{Pt/Fe/SrTiO}_3(001)$

○Soushi Akita¹, Tomohiro Yasuda¹, Daisuke Ogawa², Amemiya Kenta³, Takashi Suemasu¹ (1.Tsukuba Univ., 2.NIMS, 3.KEK)

Giant Enhancement of the Anomalous Nernst Coefficient in $\text{Co}_{1-x}\text{Pt}_x$ Thin Films

Toyota Technological Institute, Nagoya, Japan.

°Mojtaba Mohammadi, Satoshi Sumi, Hiroyuki Awano, Kenji Tanabe

°E-mail: mojtaba_mohammadi@toyota-ti.ac.jp



In recent years, the anomalous Nernst effect (ANE) has attracted significant attention due to its potential applications in energy harvesting and heat flux sensing [1,2]. The unique transverse geometry of ANE offers distinct advantages over the conventional longitudinal Seebeck effect in converting waste heat into electricity. Despite these advantages, the exploration of materials that exhibit large ANE remains limited. In this study, we focus on the thermoelectric properties of $\text{Co}_{1-x}\text{Pt}_x$ thin films with a thickness of 20 nm, systematically varying the Pt content from 0 to 95 at.%. The films were deposited on quartz glass substrates. Through comprehensive measurements, we characterized the electrical and thermoelectric properties of these samples, including resistivity (ρ_{xx}), Seebeck coefficient (S_{SE}), Hall resistivity (ρ_{yx}), and the anomalous Nernst coefficient (S_{ANE}). Based on thermoelectric transport theories, S_{ANE} can be expressed as $S_{ANE} = \alpha_{yx}\rho_{xx} + \alpha_{xx}\rho_{yx}$, where α_{xx} and α_{yx} represent the longitudinal and transverse thermoelectric constants, respectively. The terms $\alpha_{yx}\rho_{xx}$ and $\alpha_{xx}\rho_{yx}$ correspond to $S1$ and $S2$, respectively, with $S1$ being an intrinsic mechanism where the transverse electric current is generated directly from the temperature gradient, independent of the Seebeck effect. Our results showed a systematic increase in S_{ANE} with increasing Pt content, reaching a peak at around $x=50\%$ before experiencing a decline at higher concentrations. Notably, the S_{ANE} magnitude exhibited a significant enhancement, increasing from 0.33 $\mu\text{V/K}$ for the Pt-free sample ($x=0$) to around 3.2 $\mu\text{V/K}$ at $x=50\%$. Figure 1 shows S_{ANE} , $S1$, and $S2$ as a function of the Co-Pt composition. Our findings indicate that $S1$ is significantly larger than $S2$, highlighting the importance of enhancing the transverse thermoelectric constant α_{yx} and the resistivity ρ_{xx} in enhancing S_{ANE} . Our calculations showed that the magnitude of α_{yx} is significantly enhanced with increasing Pt content up to 50%. It is notable that a previous theoretical calculation study suggested that a large α_{yx} could be achieved in $L1_0$ -CoPt by adjusting the electron doping [3].

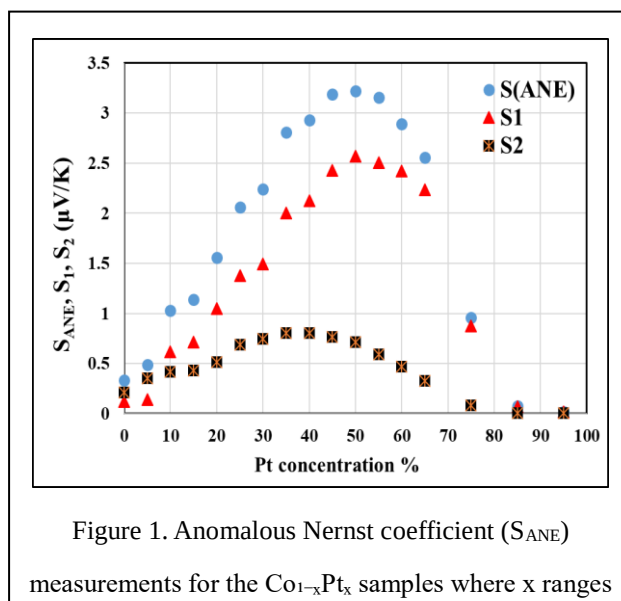


Figure 1 shows S_{ANE} , $S1$, and $S2$ as a function of the Co-Pt composition. Our findings indicate that $S1$ is significantly larger than $S2$, highlighting the importance of enhancing the transverse thermoelectric constant α_{yx} and the resistivity ρ_{xx} in enhancing S_{ANE} . Our calculations showed that the magnitude of α_{yx} is significantly enhanced with increasing Pt content up to 50%. It is notable that a previous theoretical calculation study suggested that a large α_{yx} could be achieved in $L1_0$ -CoPt by adjusting the electron doping [3].

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アモルファス Gd-Co-Pt 薄膜における異常ネルンスト効果

Anomalous Nernst effect in amorphous Gd-Co-Pt films

豊田工業大学, °(M2) 小泉朋寛, M. Mohammadi, 今枝寛人, 栗野博之, 田辺賢士

Toyota Technological Institute., °T. Koizumi, M. Mohammadi, H. Imaeda, H. Awano and K. Tanabe

E-mail: sd24425@toyota-ti.ac.jp

近年、廃熱マネジメント社会の要素技術の観点から異常ネルンスト効果（ANE）に基づく熱流センサが注目されている[1]。ANE の大きさに関する指標である、異常ネルンスト係数（ S_{ANE} ）は次式で表すことができる。

$$S_{ANE} = \alpha_{yx}\rho_{xx}(=S_1) + \alpha_{xx}\rho_{yx}(=S_2)$$

ここで、 α_{yx} は横熱電係数、 ρ_{xx} は縦抵抗率、 α_{xx} は縦熱伝導率、 ρ_{yx} はホール抵抗率である。 α_{yx} は結晶構造に基づく Berry 曲率によって著しく増大することが明らかにされて以来、ANE は様々な結晶材料系で広く研究されてきた。近年、Fujiwara らはアモルファス構造を持つ Fe-Sn 薄膜において大きな Berry 曲率の寄与を実証し、“アモルファス-トポロジカル磁性体”の可能性を示唆している[2]。さらに我々は、アモルファス Gd-Co において、大きな S_{ANE} および、低い熱伝導率、そしてその結果である大きな ANE 型熱流センサの感度を実現できることを示した[3]。このような結晶性の失われたアモルファス材料は、一見 Berry 曲率がゼロになることが予想されるものの、大きな ANE を生み出す可能性があり、非常に注目されている。しかし、アモルファス材料における ANE の報告は少なく、どの程度物性制御（ S_{ANE} や熱伝導率の制御）が可能なのか明らかになっていない。本研究では、大きな ANE を示す Co-Pt 合金に Gd をドーピングし、物性制御した結果を報告する。

作製した試料構造は、 $\text{Si}_3\text{N}_4(10\text{ nm})/\text{Gd}_x(\text{Co}_{0.5}\text{Pt}_{0.5})_{1-x}(20\text{ nm})/\text{Si}_3\text{N}_4(3\text{ nm})/\text{SiO}_2\text{ glass sub.}$ である。Gd-Co-Pt 層はコスパッタ法を用いて成膜された。各試料における S_{ANE} や抵抗率等の輸送係数を測定した。その結果、Gd-Co-Pt 膜の S_{ANE} 、熱伝導率、 α_{yx} はすべて Gd の増加に伴い減少した。これは、Gd ドープによって、アモルファス Gd-Co 合金に近づく、結晶性の崩壊が進むことを示唆している。一方、アモルファス Gd-Co 合金に比べて急激な減少をしており、Gd-Co-Pt 合金と Gd-Co 合金のミクロな電子状態は大きく異なっていることを示唆している。

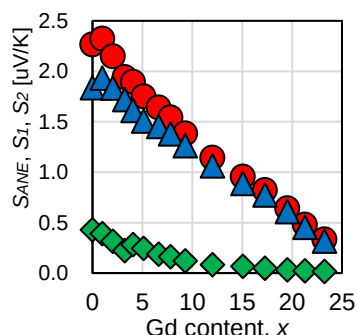


Fig. 1 Composition dependence of S_{ANE} , S_1 , S_2

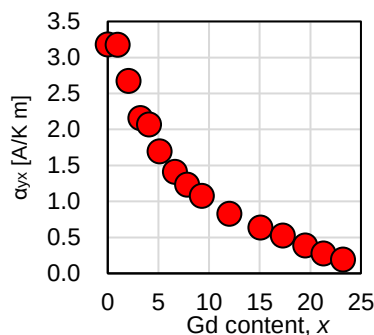


Fig. 2 Composition dependence of α_{yx}

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アモルファス $\text{Tb}_x(\text{Fe}_y\text{Co}_{100-y})_{100-x}$ における 異常ネルンスト効果の系統的な研究

Systematic studies of anomalous Nernst effect in amorphous $\text{Tb}_x(\text{Fe}_y\text{Co}_{100-y})_{100-x}$

豊田工業大学, °今枝 寛人, 竹内 恒博, 栗野 博之, 田辺 賢士

Toyota Tech. Inst., °Hiroto Imaeda, Tsunehiro Takeuchi, Hiroyuki Awano and Kenji Tanabe

E-mail: sd25501@toyota-ti.ac.jp

磁性体中の温度勾配と磁化の両方に垂直な方向に起電力が発生する異常ネルンスト効果 (ANE) は、その特性上薄膜化が容易であり、フレキシブルな熱流センサや熱電発電デバイスへの応用が期待されている[1, 2]。しかし、温度勾配に対して発生する起電力が小さく、デバイス応用への大きな障壁となっている。近年、アモルファス (amo.) でありながら比較的大きな ANE を示す amo. Tb-Fe-Co 合金の様々な研究が報告されている[3-5]が、組成やキャップ層、バッファ層の種類が異なり、系統的でない。そこで本研究では amo. Tb-Fe-Co 合金の組成を系統的に変化させたときの ANE 発生要因について詳しく調査した。

マグネトロンスパッタ装置を用いて SiO_2 基板上に成膜した SiN_z (10 nm)/ amo. $\text{Tb}_x(\text{Fe}_y\text{Co}_{100-y})_{100-x}$ (20 nm)/ SiN_z (3 nm) 構造の試料の、電気抵抗率 ρ_{xx} 、異常ホール抵抗率 ρ_{xy} 、ゼーベック係数 S_{xx} および異常ネルンスト係数 S_{xy} を測定した。Fig. 1 に $y = 0, 25, 50, 75, 100$ のときの S_{xy} と x の関係を示す。Fe-Co の組成によって S_{xy} の値が大きく異なり、最大で amo. $\text{Tb}_{10}(\text{Fe}_{50}\text{Co}_{50})_{90}$ のとき $1.8 \mu\text{V/K}$ と amo. $\text{Fe}_{87}\text{Sn}_{13}$ の $2.0 \mu\text{V/K}$ [6] に匹敵する非常に大きな値を示した。Fig. 2 に $y = 50$ の、 x に対する S_{xy} とその内因性寄与 $S_1 (= \rho_{xx}\alpha_{yx})$ 、外因性寄与 $S_2 (= S_{xx}\frac{\rho_{yx}}{\rho_{xx}})$ の結果を示す。 $x \sim 10$ のとき、 S_1 と S_2 がともに最大になっているため S_{xy} が非常に大きな値を示した。このように大きな S_{xy} の実現には、 S_1 と S_2 の両寄与が重要である。

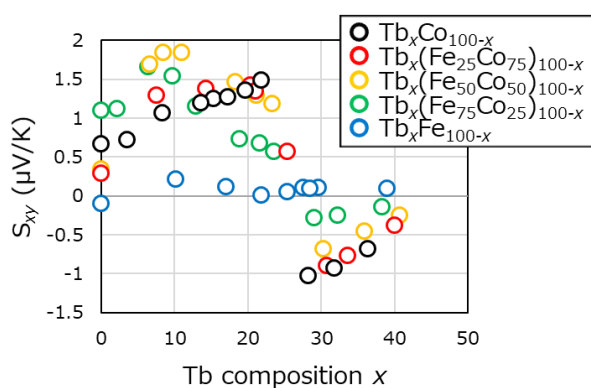


Fig. 1 Composition dependence of S_{xy} of $\text{Tb}_x(\text{Fe}_y\text{Co}_{100-y})_{100-x}$

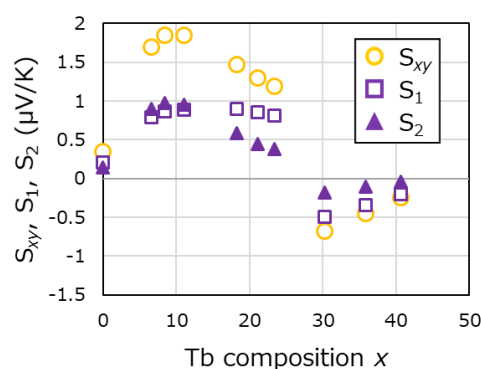


Fig. 2 Composition dependence of S_{xy} , S_1 , S_2 of $\text{Tb}_x(\text{Fe}_{50}\text{Co}_{50})_{100-x}$

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Large anomalous Nernst conductivity in Pt₂CoNi permanent magnet films with high in-plane and out-of-plane coercivities

NIMS¹, GSFS, U Tokyo²

°Rajkumar Modak^{1,2}, Hossein Sepehri-Amin¹, Yuya Sakuraba¹, Weinan Zhou¹, Ken-ichi Uchida^{1,2}

E-mail: r.modak@edu.k.u-tokyo.ac.jp

The anomalous Nernst effect (ANE) has recently attracted significant interest for its ability to generate a transverse electric field, enabling the development of advanced thermoelectric devices with simplified structures, such as ANE thermopiles and heat flux sensors [1, 2]. However, most promising materials exhibit weak magnetic anisotropy and small coercivity, necessitating external magnetic fields, which can be impractical for device applications. This highlights the critical need for permanent magnet materials with excellent ANE properties. While recently explored ferromagnet (FM)-Pt-based alloys can exhibit either large coercivity or ANE [3, 4], achieving both simultaneously remains a challenge. To address these challenges, we explore the Pt₂CoNi alloy, which shows significant promise due to a combination of factors: its FM-Pt-type composition, which suggests the potential for large coercivity [3], and theoretical predictions of large anomalous Nernst (α_{xy}) and Hall conductivities—key factors for achieving a large anomalous Nernst thermopower (S_{ANE}) [5].

In this study, we evaluated the Pt₂CoNi alloy film for its transverse thermoelectric conversion properties and magnetization behavior. For this evaluation, 50-nm-thick single-crystalline Pt₂CoNi films were deposited on MgO substrates using magnetron sputtering. Direct measurement of the ANE-induced electric field for both in-plane and out-of-plane magnetization configurations revealed a square-type hysteresis loop with a coercive field greater than 1 T. The film exhibited a large room-temperature S_{ANE} of $\sim 1.8 \mu\text{VK}^{-1}$, which is significantly higher than those of Co, Ni, Co-Pt, and Ni-Pt alloys. Furthermore, both the coercivity and S_{ANE} for present Pt₂CoNi film are substantially greater than those recently reported for Sm-Co-based thermoelectric permanent magnet films [6]. Detailed analysis reveals that the major contribution to this large S_{ANE} is due to the robust α_{xy} of $\sim 4.1 \text{ Am}^{-1}\text{K}^{-1}$ for the Pt₂CoNi alloy film, a value among the best reported at room temperature for Heusler alloys and permanent magnet films. Furthermore, through systematic evaluation using composition-gradient Pt_{2-x-y}Co_{1+x}Ni_{1+y} films, we identified a wide range of compositions with excellent ANE properties and coercivity behavior. This systematic study reveals Pt_{2-x-y}Co_{1+x}Ni_{1+y} alloys as highly promising thermoelectric permanent magnets, offering an exceptional balance of S_{ANE} , coercivity, and remanence, making them suitable for applications like heat-flux sensing. This study will significantly contribute to advancing efficient and sustainable ANE-based thermoelectric technologies.

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Influence of Fermi energy tuning on anomalous Nernst effect in $(\text{Co}_{1-x}\text{Ni}_x)_2\text{MnGa}$ composition spread epitaxial film

B. Bairagya^{1,2,3}, G. Xing³, Nanhe K Gupta³, Vineet Barwal³, K. Masuda³, W. Zhou³, S. Singh², Y. Sakuraba^{1,3}

¹University of Tsukuba, Tsukuba, Japan

²Indian Institute of Technology (BHU), Varanasi, India

³National Institute for Materials Science (NIMS), Tsukuba, 305-0047, Japan

E-mail: BAIRAGYA.Benugopal@nims.go.jp

Co_2MnGa , a well-known nodal line semimetal with a Heusler $L2_1$ structure, exhibits both a giant anomalous Hall effect (AHE) and a significant anomalous Nernst effect (ANE). However, the theoretically studies predict that maximum positive value of anomalous Nernst conductivity (α_{xy}) appears at an energy slightly above the Fermi level. Therefore tuning the Fermi level via electron doping can be a promising strategy to increase the ANE in Co_2MnGa [1]. Substitution of Co with Ni is a suitable approach for electron doping while keeping the $L2_1$ -ordered structure as Ni_2MnGa is also known to form a well-ordered $L2_1$ structure. The purpose of this study is to investigate the effect of Ni substitution at the Co-site in Co_2MnGa on the ANE.

To systematically investigate the Co:Ni composition ratio dependence on α_{xy} , we fabricated a composition-spread epitaxial thin film of $(\text{Co}_{1-x}\text{Ni}_x)_2\text{MnGa}$, which allows for a range of Ni concentrations within a single film ($0 \leq x \leq 1$). We measured the anomalous Hall resistivity (ρ_{yx}), anomalous Nernst thermopower (S_{ANE}), Seebeck thermopower (S_{SE}), and longitudinal resistivity (ρ_{xx}) across the composition range to accurately evaluate α_{xy} from S_{ANE} . Contrary to the theoretical prediction, we observed neither the enhancement in S_{ANE} nor in α_{xy} . Instead, both continuously decrease with increasing Ni concentration.

To confirm the shift in Fermi energy we measured the anisotropic magnetoresistance (AMR) for various Ni concentrations. The change of AMR ratio from large negative to positive values suggests the shifting of Fermi energy.

Further to confirm preferred occupation of Ni atoms intended to Co sites, we performed anomalous X-ray diffraction measurements and compared them with theoretical simulations. The quantitative agreement between experiment and simulation confirms that Ni atoms are indeed substituting at the Co sites, as expected. Finally, we recalculated α_{xy} for Co_2MnGa by incorporating on-site Coulomb interaction (U) at the Co site in the first-principles calculation, as the presence or absence of U_{Co} can significantly impact anomalous transverse transport properties [2]. We found that the calculated α_{xy} show closer agreement with the experimental data for a specific value of U_{Co} (see Fig. 1(b)). This result highlights the importance of including on-site Coulomb interaction at the Co site to accurately reproduce the experimentally observed α_{xy} .

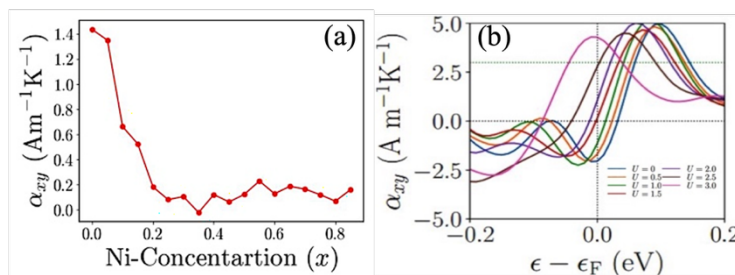


Figure 1 (a) Ni concentration dependence of experimental α_{xy} in $(\text{Co}_{1-x}\text{Ni}_x)_2\text{MnGa}$ varying Ni concentration. (b) Theoretically calculated α_{xy} for different U at Co site for Co_2MnGa .

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Giant sensitivity of amorphous Fe-Sn films for anomalous-Nernst-type heat flux sensors

Toyota Tech. Inst.¹, Rikkyo Univ.², Tohoku Univ.³, Nagoya Inst. of Tech.⁴, and Univ. of Tokyo⁵

○Kenji Tanabe¹, Kohei Fujiwara^{2,3}, Ko Mibu⁴, and Atsushi Tsukazaki^{3,5}

E-mail: tanabe@toyota-ti.ac.jp

Heat flux sensors (HFSs) detect the flow of heat and are anticipated to become a key component technology for next-generation thermal management systems. In particular, recently, HFSs utilizing the anomalous Nernst effect (ANE) have attracted significant attention[1]. The sensitivity of the ANE-HFSs is evaluated as the ratio of the generated ANE electric field to the heat flux density $E_{\text{ANE}}/j_Q^{\text{Perp}}$, which is proportional to the ANE thermopower S_{ANE} and inversely proportional to the thermal conductivity. Recently reported amorphous Fe-Sn films have the potential to be an optimal material with low thermal conductivity and Berry curvature that produces large S_{ANE} [2]. In this study, we investigated the composition and thickness dependence of ANE in amorphous Fe-Sn films to improve the sensitivity.

We fabricated Si-O(15 nm)/amo. $\text{Fe}_x\text{Sn}_{1-x}(d)$ films on glass substrates at room temperature by using a magnetron sputtering system. Amorphous Fe-Sn films were deposited by co-sputtering. The composition and thickness of the Fe-Sn films are $x = 0.5 - 0.84$ and 3.3-170 nm, respectively. The sensitivity of ANE-HFSs was measured by applying the heat flux in the out-of-plane direction and the magnetic field in the in-plane direction (Fig. (a)). By investigating the composition dependence of sensitivity, we found that at $x = 0.74$, an exceptionally high sensitivity of $+0.37 \mu\text{m}/\text{A}$ was achieved (Fig. (b)). This value is much larger than the reported values (Fig. (c)). This may be attributed to the low thermal conductivity of the amorphous phase and the presence of kagome-lattice fragments of Fe_3Sn , which produces a large Berry curvature. We confirmed by Mössbauer spectroscopy that about 30% of Fe in the $\text{Fe}_{0.74}\text{Sn}_{0.26}$ film is incorporated into kagome-lattice Fe_3Sn structure. This study shows the importance of amorphous materials in spin caloritronics.

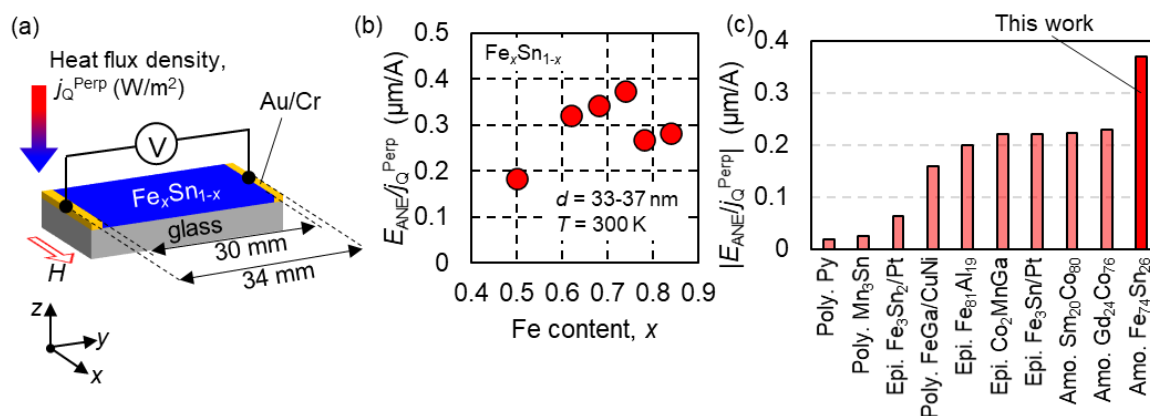


Figure: (a) Schematic illustrations of measurement setup. (b) Composition dependence of sensitivity in amorphous Fe-Sn films. (c) Summary of sensitivity of ANE-HFSs.

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室温で垂直磁気異方性のフェリ磁性を示す カゴメ格子磁性体 Co_3Mo 薄膜の合成と評価

A kagome-magnet Co_3Mo films : room-temperature ferrimagnet with perpendicular magnetic anisotropy

東大工¹, 立教大理², 理研 CEMS³, 理研 RQC⁴,

東大理⁵, 東北大金研⁶, 東北大 CSIS⁷, 東北大 SRIS⁸

◦石田圭輝¹, 藤原宏平², 仲澤一輝^{3,4}, 岡林潤⁵, 山崎匠⁶, 関剛斎^{6,7,8}, 求幸年¹, 塚崎敦^{1,6}

Dep. Appl. Phys. UTokyo¹, Dep. Chem. Rikkyo U.², RIKEN CEMS³, RIKEN RQC⁴,

Dep. Chem. UTokyo⁵, IMR, Tohoku U.⁶, CSIS, Tohoku U.⁷, SRIS, Tohoku U.⁸

◦Keiki Ishida¹, Kohei Fujiwara², Kazuki Nakazawa^{3,4}, Jun Okabayashi⁵, Takumi Yamazaki⁶,

Takeshi Seki^{6,7,8}, Yukitoshi Motome¹, Atsushi Tsukazaki^{1,6}

E-mail: hitagi-keiki443@g.ecc.u-tokyo.ac.jp

Recent studies on 3d-transition-metal-based kagome-lattice materials have discovered rich emergent phenomena resulting from interactions between magnetism, nontrivial topological band structure, and electronic correlation [1]. Especially, Co-kagome materials such as CoSn [2] and $\text{Co}_3\text{Sn}_2\text{S}_2$ [3] are typical examples exhibiting flat-band-induced anisotropic charge transport and Weyl-point-mediated large anomalous Hall conductivity, respectively. In this study, we report on a Co-kagome ferrimagnet Co_3Mo films with perpendicular magnetic anisotropy (PMA) at room temperature.

We fabricated Co_3Mo thin films on Al_2O_3 (0001) substrates by magnetron sputtering. The crystal structure of the films was characterized as D0_{19} structure by out-of-plane and in-plane x-ray diffractions. The electronic band structure of Co_3Mo was investigated by ab initio calculation, which reveals that the large density of states near Fermi level derived from flat band coming from Co-kagome lattice at paramagnetic condition. In addition, the ferrimagnetic state with PMA is preferable owing to large gain of exchange-splitting. We experimentally elucidated the magnetic properties of Co_3Mo films using vibrating sample magnetometer (VSM) and magnetic properties measurement system (MPMS). Judging from these experimental results, the perpendicular magnetic anisotropy was obtained in ferrimagnetic state. The Curie temperature of the film was estimated to be about 440 K. Since the magnetization value was consistent to the theoretically-estimated one, we conclude that anti-parallel alignment between Co and Mo moment is stabilized. This Co_3Mo film is an interesting platform to reveal flat-band physics by further physical measurements and to be applied for magnetic devices with PMA.

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Preparation of Mn₂PtSn thin films and characterization of their structure/magnetic/transport properties

K. Saijo^{1,2}, T. Dohi¹, T. Tasaki^{1,2}, T. Uchimura^{1,2}, K. V. De Zoysa¹, H. Ohno^{1,3,4,5}, and S. Fukami^{1,2,3,4,5,6}

RIEC, Tohoku Univ.¹, Graduate School of Engineering, Tohoku Univ.²,

WPI-AIMR, Tohoku Univ.³, CSIS, Tohoku Univ.⁴, CIES, Tohoku Univ.⁵, InaRIS⁶

E-mail: saijo.koya.r1@dc.tohoku.ac.jp

Skyrmion, a topological spin texture, holds promise for applications such as information storage owing to its topological stability and low currents required for its manipulation [1]. The skyrmion Hall effect [2,3], a transverse motion relative to the driving force, remains a critical obstacle to device implementation. An antiskyrmion, a topological antiparticle of the skyrmion, can be a solution, as its Hall angle can be zero due to its distinct domain wall chirality [4]. Up to now, antiskyrmion has been observed in bulk Heusler compounds such as Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn and Mn_{1.4}PtSn on the [001] crystallographic orientation above room temperature [5]. In contrast, (001)-oriented thin films of such Heusler family that can host the antiskyrmion have not yet been realized. Here, we report the successful epitaxial growth of (001)-orientated Mn₂PtSn thin films by tailoring buffer layers. We also investigate their magnetic and transport properties, which are different from those of well-studied (110)-oriented Mn₂PtSn [6].

We deposit two stacks of Mn₂PtSn on MgO (001) single-crystal substrates using DC/RF magnetron sputtering; one is directly grown on the substrate, resulting in (110)-orientation [6], while the other has specific buffer layers to promote the (001)-oriented epitaxial growth. As shown in Fig. 1, magnetization measurements suggest a perpendicular magnetic easy axis with a possible formation of a perpendicular multi-domain state at room temperature for the latter stack. In the presentation, we will discuss the correlation between magnetic/transport properties and crystalline orientation of these Mn₂PtSn thin films.

This work is partly supported by JSPS Kakenhi, JST-ASPIRE, and MEXT X-NICS.

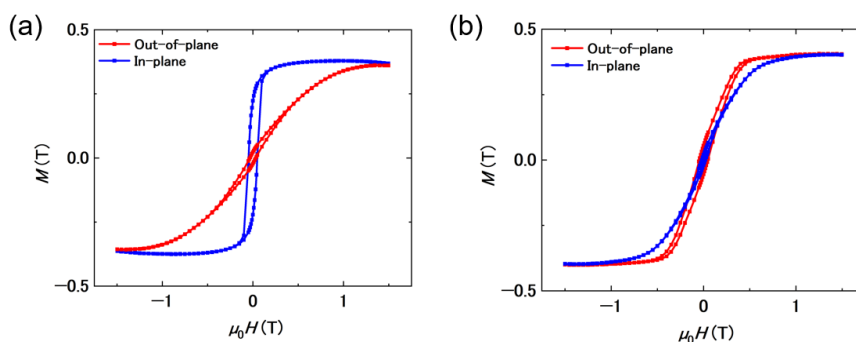


Fig. 1: Magnetization measurements for (a) (110)-oriented and (b) (001)-oriented Mn₂PtSn.

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Reconsideration of the magnetic compensation in $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ epitaxial films

1. Univ. of Tsukuba, 2. KEK

Yuki Sobukawa¹, Tomohiro Yasuda¹, Soshi Akita¹, Kenta Amemiya² and Takashi Suemasu¹

E-mail: sbforstudy.st@gmail.com

[Introduction] Ferrimagnetic Mn_4N films with antiperovskite structure (Fig. 1) have attracted attention as a candidate for magnetic switching devices because of their small magnetization and perpendicular magnetic anisotropy. Previously, we discovered a magnetic compensation (MC) composition by incorporating Ni¹⁾, which enabled ultra-fast current-induced domain motion²⁾. In another study, we successfully grew $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ thin films as a potential MC material. However, due to the distinct XMCD spectral features differing from those of known MC materials³⁾, it was difficult to confirm the presence of MC composition. In this work, we deposited $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ films and bilayers with Mn_4N to re-evaluate the magnetic properties and the existence of the MC composition.

[Experiment] 20-nm-thick $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ ($x = 0, 0.6$) films and $\text{Mn}_{3.4}\text{Ga}_{0.6}\text{N}$ (10 nm)/ Mn_4N (10 nm) bilayer were formed on $\text{SrTiO}_3(001)$, and XMCD measurements were conducted at Mn- $L_{2,3}$ edges at BL-16A of KEK-PF.

[Result] Fig. 2 (a) and (b) show the XMCD spectra of the Mn- $L_{2,3}$ edges in $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ films. Peaks α and β are mainly attributed to corner and face-centered Mn atoms, respectively.⁴⁾ We confirmed a magnetic field dependence of magnetic structure by comparing the spectra. At 0 T, they showed completely sign-reversed spectra indicative of the MC between $x = 0.0$ and $x = 0.6$. These results were consistent with the reports by L. Predeville *et al.*⁵⁾. On the other hand, the shape of the spectra at 5 T changed with the composition, suggesting a change in the magnetic structure of $\text{Mn}_{3.4}\text{Ga}_{0.6}\text{N}$ with the field. This behavior was the same as our previous experiments. Therefore, we concluded that the $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ film has an MC composition at RT, and the magnetic structure of $\text{Mn}_{3.4}\text{Ga}_{0.6}\text{N}$ should be canted by a large field. Fig. 3 (a) illustrates the structure of the bilayer, and Fig. 3 (b) shows the corresponding XMCD spectra at the Mn- $L_{2,3}$ edge. The magnetic field dependence was also observed in the bilayer. Furthermore, we identified the presence of antiferromagnetic coupling by comparing the XMCD spectra of $\text{Mn}_{3.4}\text{Ga}_{0.6}\text{N}$ and the bilayer at 0 T. We conclude that this antiferromagnetic coupling originates from the magnetization sign reversal associated with MC and exchange interaction between the layers.

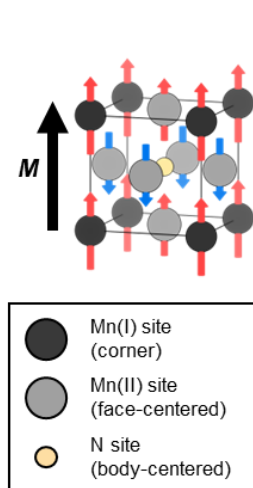


Fig. 1. Magnetic Structure of Mn_4N films

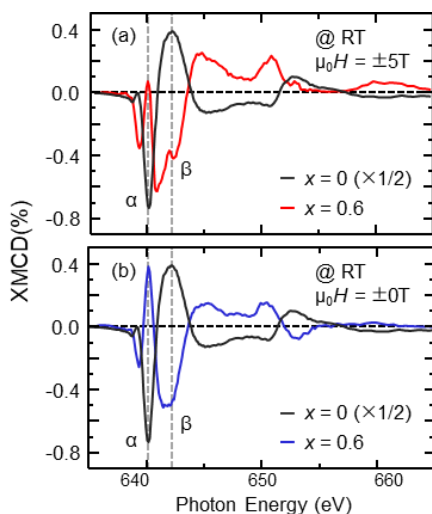


Fig. 2. XMCD spectra at the Mn $L_{2,3}$ edge of $\text{Mn}_{4-x}\text{Ga}_x\text{N}$ films at (a) $\pm 5\text{T}$ and (b) $\pm 0\text{T}$

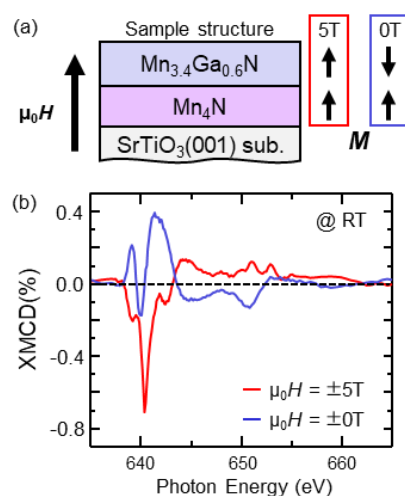


Fig. 3. (a) Magnetic structure and (b) XMCD spectra at the Mn $L_{2,3}$ edge of the bilayer

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Deposition temperature dependence of magnetic properties of ferrimagnetic Mn₄N epitaxial thin films on Pt/Fe/SrTiO₃(001)

¹ Univ. of Tsukuba, ²NIMS, ³ KEK

S. Akita¹, T. Yasuda¹, D. Ogawa², K. Amemiya³, and T. Suemasu¹

Email: s2520274@u.tsukuba.ac.jp

Ferrimagnetic Mn₄N thin film with an anti-perovskite structure exhibits a small magnetization ($M_s = 80 \text{ kA m}^{-1}$) and perpendicular magnetic anisotropy ($K_u = 0.1 \text{ MJ m}^{-3}$),¹⁾ characteristics that enable high-speed domain wall motion driven by spin transfer torque.²⁾ Therefore, we have focused on Mn₄N for high-speed magnetization control using spin torques. In this study, Mn₄N films on a heavy metal underlayer are prepared. We selected Pt as an underlayer because it is a proven source of spin injection³⁾ and has a low lattice mismatch of -0.8% with Mn₄N. The bilayer structure enables us to control the magnetization of Mn₄N with spin-orbit torques in spin oscillating or switching devices. However in a previous study,⁴⁾ Mn₄N/Pt/MgO(001) showed large surface roughness that was inherited from the Pt underlayer. Thus, we used Pt/Fe underlayer to obtain flat surface in this work. In addition, we evaluated the properties depending on the substrate temperature during Mn₄N deposition.

20-nm-thick Mn₄N films were deposited on Pt(4.5 nm)/Fe(0.5nm)/SrTiO₃(001) at temperatures $T_{\text{Mn4N}} = 250\text{--}450^\circ\text{C}$ using molecular beam epitaxy with radio-frequency nitrogen plasma. The crystallinity and surface roughness of these films were evaluated by X-ray diffraction (out-of-plane XRD) and atomic force microscopy (AFM), respectively. Additionally, we conducted anomalous Hall effect (AHE), X-ray absorption spectroscopy (XAS) and X-ray magnetic circular dichroism (XMCD) measurements to examine the magnetic properties of the thin film.

Fig. 1(a) shows the out-of-plane XRD profiles. Diffraction peaks of Pt and Mn₄N oriented perpendicular to the surface were observed. In addition, streak patterns were confirmed in the reflection high-energy electron diffraction images. These results indicate the epitaxial growth was successfully achieved. Additionally, AFM measurements showed a root-mean-square surface roughness below 0.3 nm for all films, confirming smooth surfaces comparable to previous studies on Mn₄N/STO(001).²⁾ Fig. 1(b) presents the results of AHE measurements at room temperature, showing the summed signal with a positive contribution from the Fe underlayer and a negative contribution from Mn₄N. Notably, for samples formed at $T_{\text{Mn4N}} \geq 350^\circ\text{C}$, a strong Mn₄N-derived signal was observed. Furthermore, Fig. 1(c) shows the results of XAS and XMCD, with the profiles normalized by XAS at the L_3 absorption edge. The XAS and XMCD profiles showed no significant differences among samples, with clear positive and negative peaks in the XMCD at the L_3 edge, attributable to the ferrimagnetism of Mn₄N. These results suggest high-quality Mn₄N layers can be formed at $T_{\text{Mn4N}} \geq 350^\circ\text{C}$. We will also discuss atomic diffusion across the interface and other magnetic properties in our presentation.

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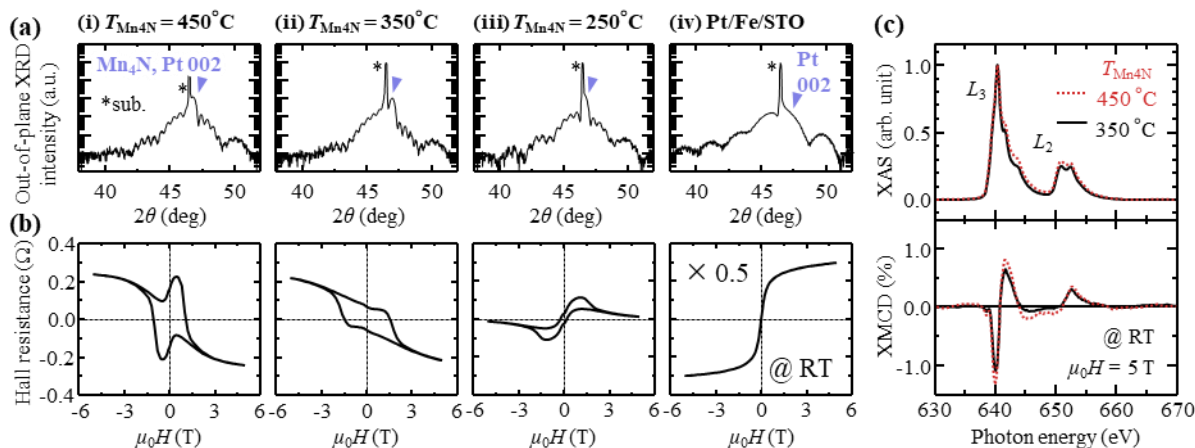


Figure 1. (a) Out-of-plane XRD profiles and (b) AHE profiles of Mn₄N/Pt/Fe/STO and Pt/Fe/STO samples. (c) XAS and XMCD spectra of Mn₄N fabricated on Pt/Fe/STO with $T_{\text{Mn4N}} = 450^\circ\text{C}$ and 350°C .

10 Spintronics and Magnetism | Oral presentation : 10.1 Emerging materials in spintronics and magnetism
(including fabrication and characterization methodologies)

[8p-N304-1~9] 10.1 Emerging materials in spintronics and magnetism (including fabrication and characterization methodologies)

[8p-N304-1]

Enhanced field-free current-induced magnetization switching by two-dimensional metastable MXene

Prabhat Kumar¹, Hitoshi Abe², Oshinji Isogami¹ (1.NIMS, 2.KEK)

[8p-N304-2]

Orbital Torque and Field-Free Magnetization Switching in a Light-Element-Based SOT Device

O(P)GAURAV KUMAR SHUKLA¹, SHINJI ISOGAMI¹ (1.National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan)

[8p-N304-3]

(001)-textured $\text{Co}_2\text{Fe}_{0.4}\text{Mn}_{0.6}\text{Si}$ full-Heusler alloy electrodes formed by solid-phase epitaxy in MgO-based magnetic tunnel junctions

O(DC)Kenta Watanabe¹, Takafumi Nakano^{1,2}, Mikihiro Oogane^{1,3} (1.Tohoku Univ., 2.Tohoku Univ. Green X-tech, 3.Tohoku Univ. CSIS)

[8p-N304-4]

Reducing critical current for spin-transfer-torque-induced magnetization reversal in CPP-GMR devices: effect of low damping and enhanced spin scattering asymmetry in $\text{Co}_2\text{FeGa}_{0.5}\text{Ge}_{0.5}$ Heusler alloy

O(P)Vineet Barwal¹, Hirofumi Suto¹, Yuya Sakuraba¹ (1.National Institute for Materials Science)

[8p-N304-5]

Low-Temperature Characterization of the Circular Complex Permeability in Single-Crystal YIG

OJunta Igarashi¹, Shota Norimoto¹, Hiroyuki Kayano¹, Noriyoshi Hashimoto¹, Makoto Minohara¹, Nobu-Hisa Kaneko¹, Tomonori Arakawa¹ (1.AIST)

[8p-N304-6]

Modulation of antiferromagnetic domain structure of epitaxial NiO(001) films by inserting Pt underlayer

OTakumi Yamazaki¹, Keita Ito¹, Weida Yin¹, Theo Balland¹, Likun Chen¹, Rie Y. Umetsu¹, Takuo Ohkouchi^{2,3}, Takeshi Seki^{1,4,5} (1.IMR, Tohoku Univ., 2.JASRI, 3.Univ. of Hyogo, 4.CSIS, Tohoku Univ., 5.SRIS, Tohoku Univ.)

[8p-N304-7]

Electric-field control of magnetic signatures in ferromagnetic Rashba 2DEGs

OBibes Manuel¹ (1.Lab. Albert Fert)

[8p-N304-8]

Perpendicular and In-plane Magnetic Anisotropy in Co/h-BN Heterostructure: a First-principles Calculation

ODian Putri Hastuti¹, Yukie Kitaoka¹, Hiroshi Imamura¹ (1.AIST)

[8p-N304-9]

DFT study on atomic structures and conduction properties of the NiFe/graphene interface

O(M2)Naohiro Matsumoto¹, Mitsuharu Uemoto¹, Tomoya Ono¹ (1.Kobe Univ.)

Enhanced field-free current-induced magnetization switching efficiency by two-dimensional metastable MXene

Prabhat Kumar ¹, Hitoshi Abe ², and Shinji Isogami ¹

¹ NIMS, ² KEK

E-mails: isogami.shinji@nims.go.jp

Magnetic memory devices using two-dimensional (2D) materials as spin current channel layers have been proposed in recent years¹⁾. However, large-area synthesis remains a bottleneck, making practical implementation difficult. In contrast, we have successfully synthesized a large-area film of a novel 2D material discovered in 2011, that is, chromium nitride (Cr₂N) MXene ($M_{n+1}X_nT_x$)^{2,3)}, by sputtering, and demonstrated field-free magnetization switching in a magnetic memory device⁴⁾. In transition metal compounds, the influence of light $2p$ elements has been reported to enhance anomalous Hall conductivity and modulate spin structures as observed in magnetic materials with inverse perovskite structures⁵⁾. A similar mechanism is considered to contribute to our results. In this study, we aimed to enhance the spin-orbit torque and achieve field-free magnetization reversal by intentionally introducing nitrogen atoms into nonequilibrium metastable sites in Cr₂N-MXene, thereby breaking local spatial symmetry.

We fabricated a multilayer stacking: C-plane Al₂O₃ substrate // Cr₂N(5) / [Co(0.35) / Pt(0.3)]×3 / MgO(3) (thickness unit in nm), using a magnetron sputtering system. The Cr₂N-MXene layer was deposited at 500 °C, with N₂ partial pressure ($N_2/(Ar+N_2)$) ranging from 0 to 15% (Fig. 1(a, b)). To investigate the local structure with varying nitrogen content, X-ray absorption fine structure (XAFS) measurements were performed using beamline BL07C at KEK-PF.

Figure 1(c) shows the XAFS spectra at the Cr K-edge. Clear differences in the absorption shape and edge intensity suggest significant variations in local atomic structure. Figure 1(d) presents the magnetization reversal efficiency under zero field, quantified as the amplitude ratio of current-induced switching relative to fully saturated magnetization. As the nitrogen composition increases, a clear enhancement in reversal efficiency is observed, implying that nitrogen atoms at nonequilibrium metastable sites play a crucial role in facilitating magnetization switching.

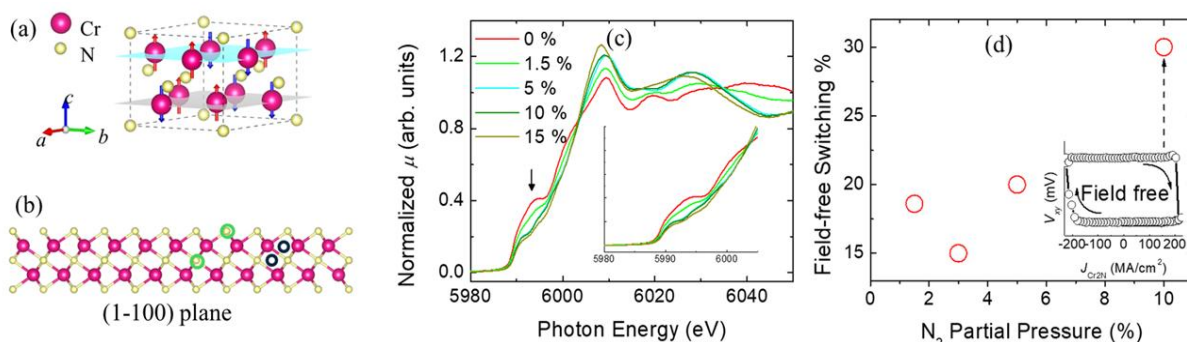


Fig. 1 (a) Crystal structure of Cr₂N MXene with (b) (1-100) plane view which includes illustration of stable (green circle) and metastable (black circle) interstitial sites. (c) The x-ray absorption spectra at the Cr K-edge. (d) Variation of field-free magnetization switching % which is defined as switching amplitude/amplitude of AHE against the N₂ partial pressure.

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Orbital Torque and Field-Free Magnetization Switching in a Light-Element-Based SOT Device

Gaurav K. Shukla and Shinji Isogami

National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan

Orbital torque arising from the orbital Hall effect (OHE) has recently garnered significant attention for its potential in next-generation orbitronic devices [1,2]. While heavy metals are commonly employed in spin-orbit torque (SOT) devices [3], their scarcity and environmental impact necessitate the development of SOT devices based on light metals. Recent theoretical and experimental studies suggest that the OHE in light metals can generate a significant orbital current even in the absence of strong spin-orbit coupling (SOC) [4], which, upon entering a ferromagnet, is converted into a spin current. To date, the OHE has been experimentally verified in only three systems: Cr [2], Ti [5], and Zr [6]. Another major challenge in SOT devices is achieving deterministic magnetization switching without an external in-plane magnetic field, field-free switching (FFS) [7], which is demonstrated using low-symmetry materials, asymmetric structures, oblique deposition, and other techniques [8]. In this study, we aim to fabricate light-element-based SOT-devices for energy-efficient magnetization switching by harnessing orbital torque, while also achieving FFS.

Recently, an SOT device with the 2D-MXene of Cr_2N was discovered and exhibits FFS, which is associated with the OHE identified by the intrinsic band structures as the primary mechanism [9]. These results suggest that 2D layered materials have a great impact on the FFS due to OHE. Inspired by this discovery, we investigate the FFS for a VN-based SOT-device, Al_2O_3 substrate // VN(5) / $[\text{Co}(0.35) / \text{Pt}(0.3)]_3$ / $\text{MgO}(3)$ (in nm), aiming to harness the OHE from VN. Here, the VN layer has (111) orientation of face-centered cubic structure, where the V and N atomic layers are alternately stacked similar to the layered structure of 2D-MXene. Figure 1(a) shows the magnetization switching under different in-plane magnetic fields. Full switching was observed with in-plane field, while FFS was also observed, suggesting the high switching efficiency. The analysis of second harmonic Hall data for three different ferromagnetic layers on $[\text{Co}(0.35) / \text{Pt}(0.3)]_3$, $\text{CoFeB}(1.5)$, and $\text{Py}(4)$ (Fig. 1(b)) suggests that the $[\text{Co}/\text{Pt}]_3$ device exhibits a damping-like torque efficiency, which is twice that of CoFeB . Notably, the second harmonic Hall signal for the Py device does not exhibit damping-like behavior, due to its negligible orbital-to-spin conversion efficiency. FFS is also observed in the studied device, which is attributed to broken mirror symmetry at the interface arising from the existence of small in-plane magnetic anisotropy.

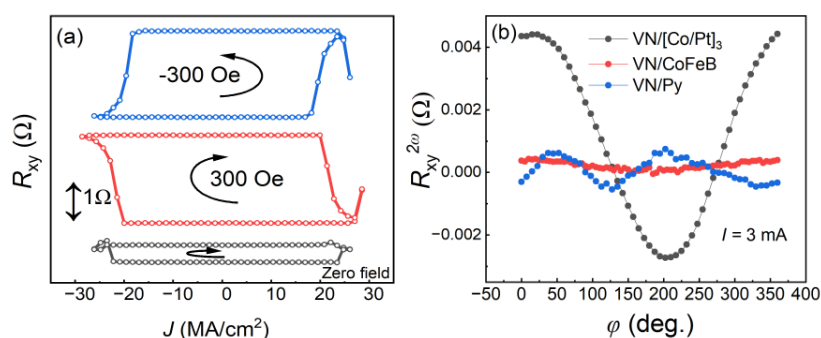


Fig.1. (a) Current-induced magnetization switching in the multilayer stack of Al_2O_3 substrate//VN(5)/ $[\text{Co}(0.35)/\text{Pt}(0.3)]_3/\text{MgO}(3)$ (in nm) under zero, 300 Oe and -300 Oe of in-plane external magnetic fields. (b) Dependence of the second harmonic Hall resistance $R_{xy}^{2\omega}$ on the in-plane angle ϕ between the magnetic field and current direction for $[\text{Co}(0.35\text{nm})/\text{Pt}(0.3\text{nm})]_3$, CoFeB (1.5nm), and Permalloy (Py, 4 nm) ferromagnetic layers.

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(001)-textured $\text{Co}_2\text{Fe}_{0.4}\text{Mn}_{0.6}\text{Si}$ full-Heusler alloy electrodes formed by solid-phase epitaxy in MgO-based magnetic tunnel junctions

Tohoku Univ.¹, Tohoku Univ. Green X-tech², Tohoku Univ. CSIS³,

[○](DC)Kenta Watanabe¹, Takafumi Nakano^{1,2}, Mikihiro Oogane^{1,3}

E-mail: watanabe.kenta.s6@dc.tohoku.ac.jp

Co-based full-Heusler alloys, such as $\text{Co}_2(\text{Fe,Mn})\text{Si}$ (CFMS), are promising spintronic materials due to their predicted half-metallicity and coherent tunneling compatibility with MgO barriers, as demonstrated by a 429% TMR at room temperature in fully epitaxial CFMS/MgO/CFMS MTJs [1]. While most studies have focused on single-crystalline MTJs, we aim to fabricate CFMS-based MTJs on Si/SiO₂ substrates using polycrystalline films for practical applications. Following the solid-phase epitaxy approach established in CoFeB/MgO systems [2], we applied a similar method to a CFMS/MgO system and investigated the resulting TMR effect.

All samples were prepared by ultra-high vacuum DC magnetron sputtering. MTJ stacks were fabricated with the following structure: Si/SiO₂ subs./bottom electrode/ TaB (5 nm)/Co₂Fe_{0.4}Mn_{0.6}Si (3 nm)/MgO/CoFeB-based pinned layer/capping layer. Post-deposition annealing was performed at 300–425 °C under a magnetic field of 1 T using an in-field annealing furnace. Microstructural analysis was performed by scanning transmission electron microscopy (STEM). TMR properties were measured by DC four-probe method after microfabrication.

Figure 1 shows bright-field STEM images of the MTJ stacks. In the as-deposited state, both CoFeB and CFMS layers adjacent to the MgO barrier appear amorphous. After annealing at 400 °C, both layers exhibit lattice fringes, indicating crystallization via solid-phase epitaxy from the MgO(001) interface. Figure 2 presents a TMR curve of a microfabricated MTJ annealed at 400 °C. A TMR ratio of ~154% was obtained, suggesting that the crystallized CFMS layer supports coherent tunneling through the MgO barrier. These results confirm that solid-phase epitaxy enables the crystallization of (001)-textured CFMS in polycrystalline MgO-based MTJs. Further details on the crystalline structure and the TMR properties as a function of annealing temperature will be discussed at the conference.

This work was supported by SIP project, BRIDGE project, SCOPE project, NEDO leading project, CSIS, CIES, the AIE-WISE Program, and MEXT Initiative to Establish Next-generation Novel Integrated Circuits Centers (X-nics) Grant Number JPJ011438.

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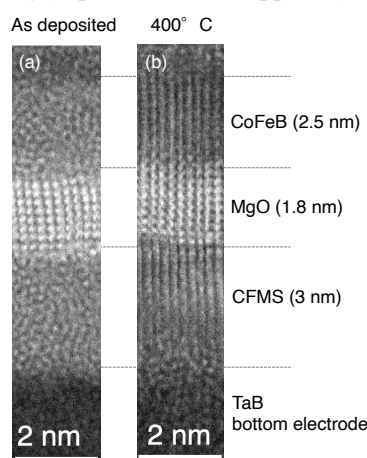


Figure 1. Bright-field STEM images of MTJ stacks (a) before and (b) after post-annealing at 400 °C.

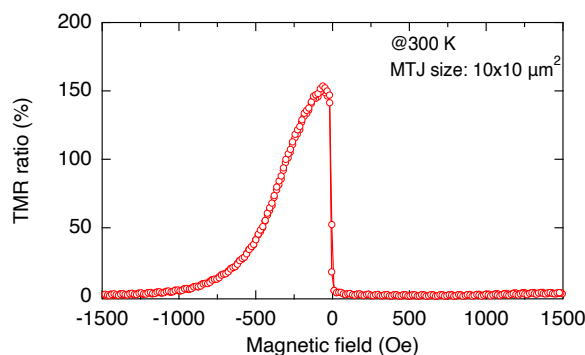


Figure 2. TMR curve of microfabricated MTJ annealed at 400 °C.

Reducing critical current for spin-transfer-torque-induced magnetization reversal in CPP-GMR devices: effect of low damping and enhanced spin scattering asymmetry in $\text{Co}_2\text{FeGa}_{0.5}\text{Ge}_{0.5}$ Heusler alloy

Vineet Barwal, Hirofumi Suto, and Yuya Sakuraba

Research Center for Magnetic and Spintronic Materials, National Institute for Materials Science (NIMS), Tsukuba, 305-0047, Japan

E-mail: BARWAL.Vineet@nims.go.jp

Spin-transfer torque (STT) in magnetoresistive devices has enabled key applications such as STT-magnetoresistive random access memory, spin torque oscillators, and energy-assisted magnetic recording¹. In device structures, where a free layer (FL) magnetization is manipulated by spin injection from a spin injection layer (SIL), the critical current density required for operation is directly proportional to the damping constant of FL and inversely proportional to the STT efficiency, which depends on the spin polarization of the materials². We investigated the effect of low Gilbert damping (α) and high spin polarization (P) of $\text{Co}_2\text{FeGa}_{0.5}\text{Ge}_{0.5}$ (CFGG) Heusler alloy on the operation current required for STT-induced magnetization reversal in current perpendicular-to-plane giant magnetoresistance (CPP-GMR) devices.

magnetization was reversed against the field by applying a bias current. The current value corresponding to the FL magnetization reversal was defined as critical current (I_c). The details of the measurement method can be found in Ref.[4]⁴.

Figure (b) shows the MR ratio distribution for the devices. In comparison between Type-I and II devices, the average MR ratio is higher in Type-II because CFGG has high P and the good electronic band matching with the Ag spacer^{5,6}. The distribution of MR ratios is broader in Type-II due to device-to-device quality inhomogeneities in the two CFGG layers. In type-III devices, MR ratio increases with annealing temperature up to 450°C, where the MR property was similar to that of Type-II samples. Figure (c) shows I_c at a perpendicular field of 2.4 T plotted against the MR ratios. Type-I devices show clear correlation between MR ratio and I_c because MR ratio and STT efficiency both depend on the quality of CFGG layer. Type-II devices achieved a large reduction in I_c , as compared Type-I devices owing to very low α of CFGG, demonstrating its advantage as a FL material. However, scattering in I_c was large, as discussed later. Type-III device ($T_p = 450^\circ\text{C}$) employing CoFe/CFGG-SIL exhibited the lowest I_c , indicating enhanced STT efficiency by spin scattering asymmetry at the CoFe/CFGG interface. Moreover, the device-to-device distribution in I_c was smaller in Type-III devices. This suppression in the I_c distribution is interesting considering that the MR ratio distribution is similarly broad in both Type-II and III devices, and one possible reason is that the magnetization of the CoFe/CFGG-SIL is stable against counter spin injection from the CFGG-FL because CoFe has high saturation magnetization and higher α than CFGG. These findings highlight the potential of CFGG Heusler alloy and CoFe/CFGG bilayer structures as key components for the development of efficient and stable STT-based spintronic devices.

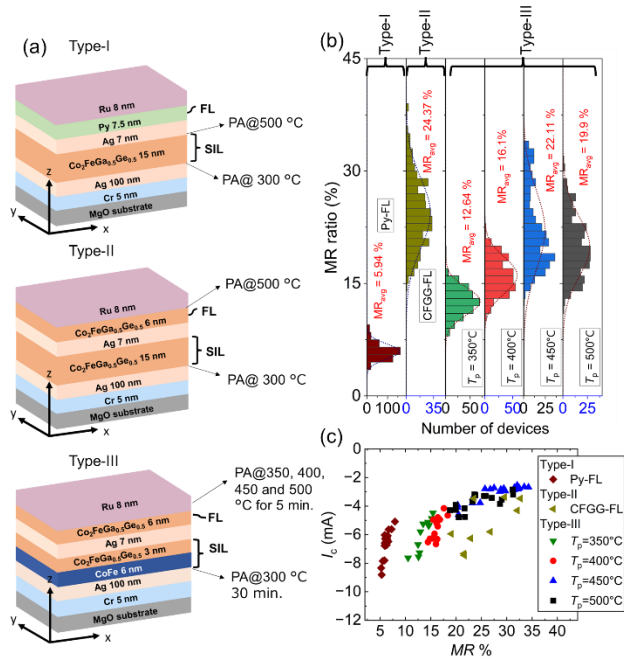


FIG. (a) Three types of CPP-GMR stack configurations. Arrows indicates the position and temperature of the in-situ annealing. (b) Distribution of MR ratio in the CPP-GMR devices. (c) Critical current (I_c) required for magnetization reversal of the FL against the perpendicular magnetic field at $\mu_0 H_z = 2.4$ T versus MR ratios.

Three types of epitaxial GMR stacks, as shown in the Fig. (a), were fabricated on MgO (001) substrates. Type-I consists of CFGG-SIL and $\text{Ni}_{80}\text{Fe}_{20}$ - (Py-) FL. Type-II utilizes CFGG-FL with lower α than Py. Type-III utilizes CoFe/CFGG bilayer-SIL with enhanced interfacial spin scattering asymmetry³. Arrows represent the position and temperature of in-situ annealing. The CPP-GMR device were fabricated from these stacks and systematically analyzed through magnetoresistance (MR) and STT measurements. In the STT measurement, both SIL and FL were first aligned to the perpendicular direction by a strong perpendicular field, and then the FL

Acknowledgement

This work was partially supported by the Advanced Storage Research Consortium (ASRC), JSPS KAKENHI (grant numbers 23K03934).

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Low-Temperature Characterization of the Circular Complex Permeability in Single-Crystal YIG

National Institute of Advanced Industrial Science and Technology (AIST)¹

°Junta Igarashi¹, Shota Norimoto¹, Hiroyuki Kayano¹, Noriyoshi Hashimoto¹, Makoto Minohara¹,
Nobu-Hisa Kaneko¹, and Tomonori Arakawa¹

E-mail: junta.igarashi@aist.go.jp

The development of superconducting quantum devices has increased demand for cryogenic non-reciprocal microwave components such as circulators. In the development of such components, it is crucial to evaluate the temperature dependence of ferrite magnetic properties. However, evaluating ferrite materials at cryogenic temperatures remains challenging without specialized measurement systems.

In this study, we establish a method to characterize ferrite materials down to 2 K without requiring device fabrication. We select single-crystal YIG for this study because of its intrinsically low loss and the absence of magnetization compensation even at cryogenic temperatures. By employing a circularly polarized TE_{11n} cavity mode, we selectively excite a circularly polarized mode, which allows us to evaluate the circular complex permeability of YIG and extract key magnetic parameters such as saturation magnetization and damping constant [1,2]. This approach offers a powerful tool for evaluating ferrite materials under cryogenic conditions and contributes to the development of cryogenic circulators and isolators.

This work was supported by New Energy and Industrial Technology Development Organization of Japan (NEDO) Grant (No. JPNP14004), Cross-ministerial Strategic Innovation Promotion Program (SIP), “Promoting Application of Advanced Quantum Technologies to Social Challenges” and JSPS KAKENHI24K22964 and 24K21737.

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Modulation of antiferromagnetic domain structure of epitaxial NiO(001) films by inserting Pt underlayer

IMR, Tohoku Univ.¹, JASRI², Univ. of Hyogo³, CSIS, Tohoku Univ.⁴, SRIS, Tohoku Univ.⁵

°Takumi Yamazaki¹, Keita Ito¹, Weida Yin¹, Theo Balland¹, Likun Chen¹, Rie Y. Umetsu¹,

Takuo Ohkochi^{2,3}, and Takeshi Seki^{1,4,5}

E-mail: takumi.yamazaki.d5@tohoku.ac.jp

Antiferromagnetic materials have attracted growing interest in spintronics due to their features such as negligible magnetic stray fields and terahertz-scale magnetic resonance [1]. These materials enable efficient spin injection, propagation, and conversion, making them candidates for next-generation spintronic devices. NiO is a prototypical antiferromagnetic insulator, and its spin current transmission has been extensively studied using various transport measurement techniques [2-4]. In many studies, Pt/NiO heterostructures are widely used as a typical platform because Pt not only serves as a spin current injector via the spin Hall effect, but also enables the epitaxial growth of NiO on top of it [5-7]. However, the influence of Pt layer positioning, *i.e.*, whether as an underlayer or overlayer for the NiO layer, on the magnetic structure and spin current transmission properties of NiO is yet to be understood.

In this study, we investigate how the insertion of Pt layer affects the antiferromagnetic domain structure in epitaxial NiO(001) films. NiO films were grown on MgO(001) substrates using radio-frequency magnetron sputtering. For samples with Pt underlayers, an ultrathin Fe seed layer was introduced to facilitate epitaxial growth. Structural characterization was conducted using reflection high-energy electron diffraction (RHEED), x-ray diffraction (XRD), and reciprocal space mapping (RSM). The antiferromagnetic domain structures were visualized via x-ray magnetic linear dichroism-photoemission electron microscopy (XMLD-PEEM) in BL17SU RIKEN beamline at SPring-8 [8]. The RHEED and XRD patterns showed that the epitaxial growth of NiO(001) was achieved both with and without the Pt underlayer. The RSM of (113) reflection revealed that the NiO film without the Pt layer was remarkably strained to the MgO substrate, whereas the NiO film with the Pt layer was relaxed. XMLD-PEEM images at Ni-L₂ edge showed distinct antiferromagnetic domains of NiO with μm-scale sizes for without Pt. In contrast, for with Pt, the domain contrast disappeared, likely due to a reduction in domain size below the spatial resolution of PEEM. These findings highlight that even in identically oriented epitaxial NiO films, the Pt underlayer induces notable changes in the antiferromagnetic domain configurations, which may lead to modulation of the spin current transmission characteristics.

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Electric-field control of magnetic signatures in ferromagnetic Rashba 2DEGs

Gabriel Lazrak¹, Luis M. Vicente-Arche¹, R. Abrudan², Borge Göbel³, D. Hrabovsky⁴, C. Luo², V. Ukleev², Srijani Mallik^{1,5}, F. Radu², Sergio Valencia², Annika Johansson^{6*}, Agnès Barthélémy¹ and Manuel Bibes^{1*}

¹ Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91797 Palaiseau, France

² Helmholtz-Zentrum Berlin, Albert-Einstein-Strasse 15, 10405 Berlin, Germany

³ Institut für Physik, Martin-Luther-Universität, Halle-Wittenberg, 06099 Halle (Saale), Germany

⁴ Sorbonne Université, Campus Pierre et Marie Curie, 4 place Jussieu, 75005 Paris, France

⁵ Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Kolkata 700 064, India

⁶ Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle (Saale), Germany

The breaking of inversion symmetry at complex oxide interfaces gives rise to a rich landscape of emergent phenomena, including ferromagnetism and Rashba spin-orbit coupling (SOC), which entangle spin and momentum and reshape the electronic band structure^{1,2}. While the coexistence of Rashba SOC and ferromagnetism opens up exciting theoretical possibilities, experimental demonstrations have remained limited.

Here, we explore the magnetotransport behavior of a two-dimensional electron gas (2DEG) formed at the interface between EuO and SrTiO₃ (STO), a system where ferromagnetism and interfacial inversion symmetry breaking are both present. Using Hall effect measurements and their field derivatives as a diagnostic tool, we uncover signatures of a gate-tunable anomalous Hall effect (AHE) superimposed on the ordinary Hall response. These features are markedly distinct from those observed in nonmagnetic 2DEGs such as AlO_x/STO, where the Hall resistance and its derivative can be entirely understood by two-band transport models.

Figure 1 compares these two systems. In AlO_x/STO, the Hall resistance shows a nonlinear field dependence with a derivative that dips near zero field – a characteristic of two-band conduction in a nonmagnetic system. In contrast, the EuO/STO sample exhibits a dramatically different behavior at low temperature: the Hall resistance is also nonlinear but the Hall derivative becomes U-shaped rather than V-shaped, consistent with the presence of an AHE superimposed on the ordinary Hall effect. The effect is absent at 24 K, reflecting the onset of magnetic order in the 2DEG (at 18 K).

These observations confirm the presence of ferromagnetism in the 2DEG and support the interpretation of the system as a Rashba ferromagnet. Importantly, the AHE is found to be tunable by gate voltage, not only in magnitude but also in sign – highlighting a possible form of magnetoelectric coupling where the Berry curvature, rather than the net magnetic moment, is controlled via electrostatic gating. In parallel, the system displays spontaneous nonreciprocal transport effects³ even in the absence of an external magnetic field, further reinforcing the role of spin-orbit and exchange interactions in shaping transport. Taken together, these findings establish ferromagnetic oxide 2DEGs as a robust and tunable platform for exploring the physics of broken time-reversal and inversion symmetries, and for engineering magnetoelectric functionalities based on Berry-phase physics.

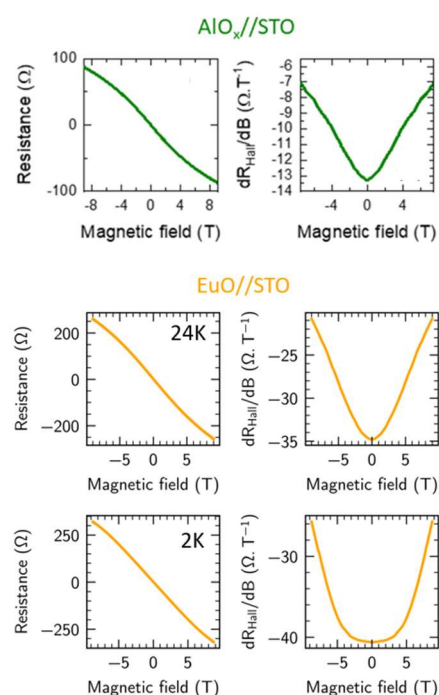


Figure 1. Hall resistance and its derivative in oxide 2DEGs. Top: AlO_x/STO (nonmagnetic) shows a nearly linear Hall resistance and a peaked derivative, consistent with two-band transport. Bottom: EuO/STO exhibits a nonlinear Hall signal and a broad U-shaped derivative at low temperature (2 K), indicating the emergence of an anomalous Hall contribution associated with interfacial

Perpendicular and In-plane Magnetic Anisotropy in Co/h-BN Heterostructure: a First-principles Calculation

National Institute of Advanced Industrial Science and Technology (AIST)¹

Dian Putri Hastuti¹, Yukie Kitaoka¹, Hiroshi Imamura¹

E-mail: dian.hastuti@aist.go.jp

Magnetic anisotropy (MA) is an essential characteristic of magnetic films for spintronic devices. Perpendicular MA (PMA) is more suitable for magnetoresistive random access memory (MRAM), while in-plane MA is better for magnetic field sensor applications. Traditionally, PMA enhancement has relied on ferromagnet/oxide interfaces, which are based on cubic symmetry, a strategy that has successfully boosted the stability and performance of magnetic storage systems. However, with the expected shift from three-dimensional to two-dimensional (2D) channel materials, it is important to explore tunnel barriers compatible with 2D materials that possess hexagonal symmetry. To develop 2D-based spintronic devices with hexagonal symmetry, it is important to investigate the MA of a ferromagnetic film deposited on a material with hexagonal symmetry. Recent studies have shown that Co/h-BN heterostructures can exhibit tunnel magnetoresistance ratios comparable to those of Fe/MgO structures¹⁾. Despite this promise, the study of magnetocrystalline anisotropy (MCA), along with its underlying mechanisms in Co/h-BN heterostructures, has not yet been thoroughly explored.

In this work, we theoretically investigated magnetic anisotropy of Co/h-BN heterostructures using first-principles calculations based on the full-potential linearized augmented plane wave (FLAPW) method. Buckled structure of h-BN is stable and exhibits larger MCA energy (MCAE). We investigated the dependence of MCAE on the thickness of the Co film by varying the number of Co layers up to 5 layers and found a PMA of 1.68 mJ/m² in monolayer Co heterostructure, comparable to that of a single Fe layer on MgO²⁾. To explore the voltage control, we applied an external electric field to the monolayer Co heterostructure, resulting in a voltage-controlled magnetic anisotropy (VCMA) of −175 fJ/Vm, as shown in Fig. 1. Thicker films (2 to 5 Co layers) which is in-plane magnetized is potential for the highly sensitive magnetic field sensors. To realize this, the magnetization must change very smoothly as the signal magnetic field varies. We calculated the angular dependence of total MAE for in-plane angle (ϕ_m) up to 120°. The total MAE remains constant for all values of ϕ_m within the numerical accuracy of 0.1 μ eV (Fig. 2), which is a desirable characteristic for sensor applications. These findings offer key insights into the magnetic anisotropy behavior of Co/h-BN heterostructures for developing voltage-controlled MRAM and magnetic field sensors based on this material system.

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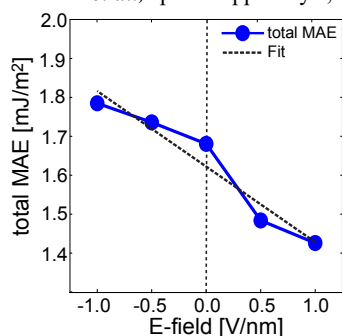


Fig 1. Electric field dependence of total MA energy (MAE) in a monoatomic Co film. Dashed line shows linear fit for VCMA coefficient.

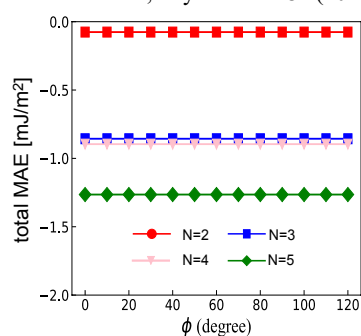


Fig 2. in-plane angle of magnetization, ϕ_m , dependence MCAE of in-plane magnetized films consisting of N Co atomic layers.

第一原理計算を用いた NiFe/グラフェン界面の原子構造及び伝導特性の解明

DFT study on atomic structures and conduction properties of the NiFe/graphene interface

神戸大工¹ ○(M2)松本 尚弥¹, 植本 光治¹, 小野 倫也¹

Kobe Univ.¹, °Naohiro Matsumoto¹, Mitsuharu Uemoto¹, Tomoya Ono¹

E-mail: 246t257t@stu.kobe-u.ac.jp

磁気トンネル接合 (MTJ) は強磁性金属の間に絶縁体を挟んだ構造であり、強磁性体層の磁化方向を制御することで、素子全体の伝導特性を制御できる。従来、絶縁体層には酸化マグネシウムが用いられてきたが、界面酸化や酸素欠陥、特定の金属材料との格子不整合によるデバイス性能低下の問題があり、近年では絶縁体層に 2 次元材料を応用する検討が進められている。また、強磁性金属材料には高い垂直磁気異方性や低い Gilbert 緩和定数を持つ材料が求められ、FeCoNi 系の合金や鉄パラジウム合金 (FePd) が広く用いられている。このような、強磁性金属と 2 次元材料のヘテロ界面に関する先行研究として、FePd/グラフェン界面の作成実験とその理論予測[1]、NiFe 表面への六方晶窒化ホウ素 (hBN) の作成[2]あるいは hBN 薄膜への NiFe 電極蒸着実験[3]が報告されている。

本研究では MTJ に向けた応用を想定し、強磁性金属 NiFe と 2 次元材料グラフェンの界面原子構造の詳細を明らかにするため、第一原理計算を用いて安定な原子構造を探索した。[4] 計算モデルとして Fig. 1 のような構造を用意した。基板表面層の組成比、基板バルク層の組成比、ベア表面・吸着サイトそれぞれの条件を変えたモデルを構築し、NiFe ベア表面の形成エネルギー・グラフェンの吸着エネルギーを調べ、界面の安定性について評価した。その結果、ベアな NiFe 表面においては Ni-rich 表面、吸着界面では Fe-rich 表面が安定することが分かった。これは Fe-C 間の軌道混成によるものである。また、NiFe の top サイト上に C 原子が位置する構造が安定であった。top サイトに吸着することで金属の d 軌道にグラフェン側から電子移動が電子状態密度の解析から明らかとなった。本研究ではさらに伝導特性計算を行い、デバイスの性能予測についても議論する予定である。

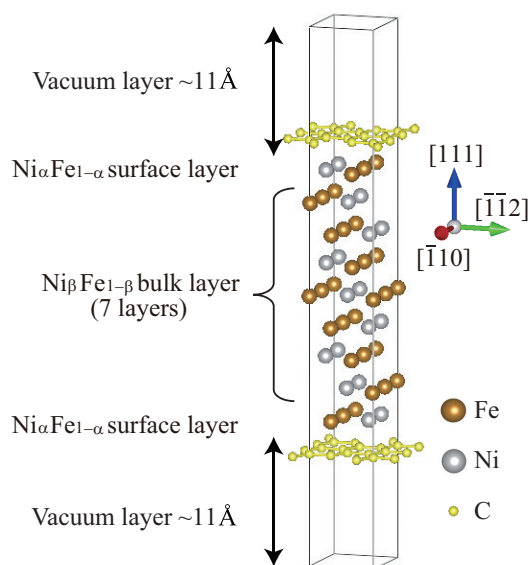


Fig. 1 Overall view of computational model of NiFe/graphene.

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10 Spintronics and Magnetism | Oral presentation : 10.2 Fundamental and exploratory device technologies for spin

[7a-N302-1~9] 10.2 Fundamental and exploratory device technologies for spin

[7a-N302-1]

Anisotropic Gilbert damping in the V/Fe/MgO multilayer

O(D)Jieyi Chen¹, Shoya Sakamoto¹, Ivan Kurniawan², Hidetoshi Kosaki¹, Erkang Wei¹, Tempei Hatajiri¹, Keisuke Masuda², Shinji Miwa^{1,3} (1.ISSP-UTokyo, 2.NIMS, 3.TSQS-UTokyo)

[7a-N302-2]

Engineering THz Magnon Frequencies via Stacking in 2D Ferromagnetic van der Waals CrI₃/As Bilayer: a First-Principles Study

O(D)Andi Gumarilang Ahmadi¹, Kohji Nakamura¹ (1.Mie Univ.)

[7a-N302-3]

Ultrafast spin dynamics characterization of ferromagnetic YIG/GGG and spin-glass YIG/YAG measured by time-resolved magneto-optic Faraday effect(TR-MOFE)

O(P)Dongxun Yang¹, Md Shamim Sarker¹, Hiroyasu Yamahara¹, Munetoshi Seki¹, Hitoshi Tabata¹ (1.Univ. of Tokyo)

[7a-N302-4]

Effect of Spin-Wave Mode on Physical Reservoir Computing using Synthetic Antiferromagnet

O(M1)Takumu Shinkai¹, Satoshi Iihama¹, Kensuke Hayashi¹, Takahiro Moriyama¹ (1.Nagoya Univ.)

[7a-N302-5]

Dimension-dependent magnon-magnon interactions

O(P)Huanhuan Yang¹, Gerrit E. W. Bauer^{1,2} (1.Tohoku University, 2.University of the Chinese Academy of Sciences)

[7a-N302-6]

Geometric structure dependence of RF oscillation properties of spin Hall nano-oscillators

O(M1)Hitoshi Iida^{1,2}, Karunathilaka Vihanga De Zoysa¹, Yuzu Yoshida^{1,2}, Aakanksha Sud^{1,3}, Aurelien Lagarrigue¹, Takaaki Dohi¹, Akash Kumar^{1,4,7}, Ahmad Awad^{1,4,7}, Shun Kanai^{1,2,5,6,7,8,9}, Johan Akerman^{1,4,7}, Shunsuke Fukami^{1,2,7,8,10,11}, Hideo Ohno^{1,7,8,10} (1.LNS RIEC Tohoku Univ., 2.Tohoku Univ. Engineering, 3.FRIS Tohoku Univ., 4.Univ. of Gothenburg, 5.JST-PRESTO, 6.DEFS Tohoku Univ., 7.CSIS Tohoku Univ., 8.WPI-AIMR Tohoku Univ., 9.QST, 10.CIES Tohoku Univ., 11.InaRIS)

[7a-N302-7]

Electric field control of spin wave propagation in strained iron oxide garnet thin films with unquenched orbital moments

O(D)EMK IKBALL AHAMED¹, Md Shamim Sarker¹, Hiroyasu Yamahara¹, Munetoshi Seki¹, Hitoshi Tabata¹ (1.University of Tokyo)

[7a-N302-8]

Investigating the atomic origin of room temperature spin glass behavior in non-substituted yttrium iron garnet thin films towards brain mimetic computing

○(PC)shamim sarker¹, E M K Ikball Ahamed¹, Zhiqiang Liao¹, Ritsui Sonetaka¹, Ryoken Nako¹, Yang Dongxun¹, Haining Li¹, Hiroyasu Yamahara¹, Munetoshi Seki¹, Hitoshi Tabata¹ (1.Tokyo Univ)

[7a-N302-9]

Two-stage Formation of an Anomalously Large Nuclear Field in Bulk *n*-AlGaAs

○Andong Shen¹, Reina Kaji¹, Sota Yamamoto², Tetsuya Uemura³, Satoru Adachi¹ (1.Eng, Hokkaido Univ., 2.Eng, Tohoku Univ., 3.IST, Hokkaido Univ.)

Anisotropic Gilbert damping in the V/Fe/MgO multilayer

ISSP-UTokyo¹, NIMS², TSQS-Utokyo³

°Jieyi Chen¹, Shoya Sakamoto¹, Ivan Kurniawan², Hidetoshi Kosaki¹, Erkang Wei¹,

Tempei Hatajiri¹, Keisuke Masuda², and Shinji Miwa^{1,3}

E-mail: jieyi@issp.u-tokyo.ac.jp

The intrinsic Gilbert damping constant in magnetic multilayers is a fundamental parameter that characterizes the dynamic behavior of ferromagnetic materials. In most studies of magnetic materials, the intrinsic Gilbert damping constant is considered an isotropic parameter. Recently, several studies have discovered the anisotropic Gilbert damping with respect to the in-plane magnetization direction in the epitaxial Fe film grown on GaAs substrates [1, 2]. In the previous JSAP meeting, we have reported that the intrinsic Gilbert damping in the V/Fe/MgO multilayer is also influenced by the magnetization direction [3]. In this study, we systematically investigate the anisotropy of the Gilbert damping in the V/Fe/MgO system, focusing on its dependence on the out-of-plane magnetization direction.

We fabricated epitaxial V/Fe/MgO multilayers using molecular beam epitaxy [Fig. 1(a)]. The Gilbert damping constant was characterized by the time-resolved magneto-optical Kerr effect (TR-MOKE). The setup of the TR-MOKE system and the magnetization direction dependence of intrinsic Gilbert damping in the V (8 nm)/Fe (0.6-1.2 nm)/MgO (0.5 nm) multilayers are shown in Fig. 1(b) and 1(c). We found that the Gilbert damping depends on the magnetization direction and increases when the direction of the magnetic field angle is changed from in-plane to out-of-plane. We have also conducted a first principles calculation of the intrinsic Gilbert damping and compared with the experimental results in detail. Specifically, bulk and interfacial effects on the anisotropic Gilbert damping will be discussed.

This work was partly supported by JSPS KAKENHI (Nos. JP22H04964, JP23H01833, 24H02234, and 25H00414), Spin-RNJ, JST-Mirai Program (JPMJMI20A1), JST-ASPIRE (No. JPMJAP2317), X-NICS (No. JPJ011438), and JST-SPRING (No. JPMJSP2108).

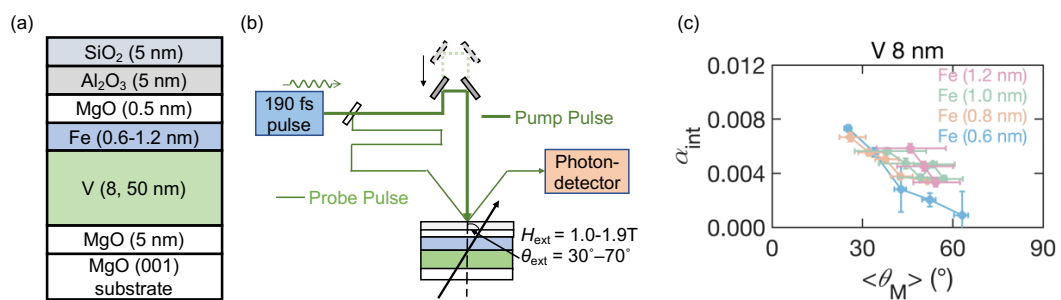


Fig. 1. (a) Schematic of the multilayers. (b) Setup of the TR-MOKE. (c) Magnetization direction dependence of intrinsic Gilbert damping in the V (8 nm)/Fe (0.6-1.2 nm)/MgO (0.5 nm) multilayers.

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Engineering THz Magnon Frequencies via Stacking in 2D Ferromagnetic van der Waals CrI₃/As Bilayer: First-Principles Study



Mie Univ.¹, °Andi Gumarilang¹, Kohji Nakamura¹

E-mail: 423db01@m.mie-u.ac.jp

Discovery of 2D ferromagnetic van der Waals CrI₃ opens new avenues for tunable THz magnon excitation by harnessing the possibility of multiple stacking orders in one multi-layer system. Monolayer Weyl semi-metals As/Sb/Bi have small lattice mismatch to CrI₃^[1], and the triangular lattice structure of As/Sb/Bi allows different types of symmetry breaking to be applied on the honeycomb lattice CrI₃ depending on the stacking order. While the As displayed topological phase transition from quantum anomalous Hall state into metallic state under CrI₃ magnetization re-orientation in one CrI₃/As stacking order^[1], the effect of As on THz magnon excitation of CrI₃ at multiple stacking orders remain unaddressed, which serves for establishing a guide of tunability of THz magnon excitation in the CrI₃ via stacking control. Here, we demonstrated the THz magnon frequencies modulation in multiple CrI₃/As stacking orders via spin-exchange and Kitaev interactions modulation by employing first-principles calculation based on full-potential linearized augmented plane-wave^[2] and linear spin-wave theory^[3]. In each stacking order, interaction between I and As atoms weakens the crystalline electric field that splits the unoccupied and occupied Cr *d* states and provide an additional *d* state at the gap in the stacking orders with broken *C*_{3z} symmetry, leading to a significant enhancement of the spin-exchange constants by more than 100%. The hybridization between I and As *p* states narrow the energy gap between occupied I *p*_z states and unoccupied *p*_x/*p*_y states, which gives rise to enhanced Kitaev interactions by two times of magnitude. In the magnon dispersion, the degeneracy between optic and acoustic modes can be lifted by the enhanced Kitaev interaction, inversion symmetry breaking, and *C*_{3z} rotational symmetry breaking with the gap induced by the *C*_{3z} rotational symmetry breaking being the highest and that by enhanced Kitaev interaction being the lowest. By taking the magnon frequencies at zero wave-vector as the ferromagnetic resonance (FMR) frequencies, the enhancement of optic mode FMR frequencies ranges from 14% to 60% from 5.14 THz, which depends on the spin-exchange constants enhancement, while the modulation of acoustic mode FMR frequencies ranges from weakening of 15% to enhancement of 100%, from 0.12 THz which depends on the magnetic anisotropy energy modulation driven by the Kitaev interactions.

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Ultrafast spin dynamics characterization of ferromagnetic YIG/GGG and spin-glass YIG/YAG measured by time-resolved magneto-optic Faraday effect(TR-MOFE)

Dongxun Yang¹, Md Shamim Sarker², Hiroyasu Yamahara¹, Munetoshi Seki^{1,2}, Hitoshi Tabata^{1,2}

¹ Department of Bioengineering, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

² Department of Electrical Engineering and Information Systems, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

E-mail: yang-dx@bioxide.t.u-tokyo.ac.jp

1. Introduction

Ultrafast spin dynamics reveal critical information about magnetic materials, including ultrafast demagnetization, spin precession, and damping parameters[1]. These properties are essential for understanding spin excitations and standing spin wave transport, which are crucial for various spintronic applications. Yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, or YIG) is a remarkable magnetic material that has attracted significant attention due to its excellent magnetization characteristics. Through intentional doping or interface strain engineering, YIG thin films can exhibit spin glass behavior at room temperature, making them promising candidates for future neuromorphic computing devices. Therefore, characterizing the spin dynamics of YIG is of great importance. To gain deeper insight into its ultrafast magnetization behavior, a rapid and sensitive characterization method is required. In this work, we implemented a time-resolved magneto-optic Faraday effect (TR-MOFE) system to investigate the spin dynamics of YIG thin films grown on GGG and YAG substrates under varying external magnetic fields[2]. We successfully detected spin precession signals and analyzed the mechanism underlying their observation using tr-MOFE. Finally, key dynamic parameters of YIG were extracted and discussed.

2. Experiment and results

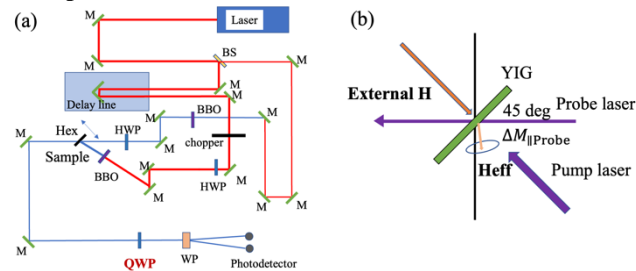


Fig.1 (a)The diagram of the Tr-MOFE system with 45° incident probe and vertical pump. (b) The setting configuration of the external magnetic field.

In this study, a time-resolved magneto-optic Faraday effect (tr-MOFE) system was performed to measure the spin dynamics of YIG thin films with the external magnetic field in the range of 10 mT to 160 mT. A Ti-sapphire coherent laser was used to provide a 35-fs 800 nm pulse laser source and was turned to 400 nm by using non-linear crystal BBO for both pump and probe laser. The spin variation was detected by the linearly polarized probe laser with an incident angle of 45° and the polarization of the transmission were detected by a balanced detector after a quarter wave plane and an analyzing Wollaston prism. The samples were illuminated by a 405-nm CW laser source at an incident angle of 45° and the polarization rotation of the reflections were detected by a balanced detector after an

analyzing Wollaston prism, as shown in Fig.1(a). The setting configuration of external magnetic field is shown in Fig.1(b).

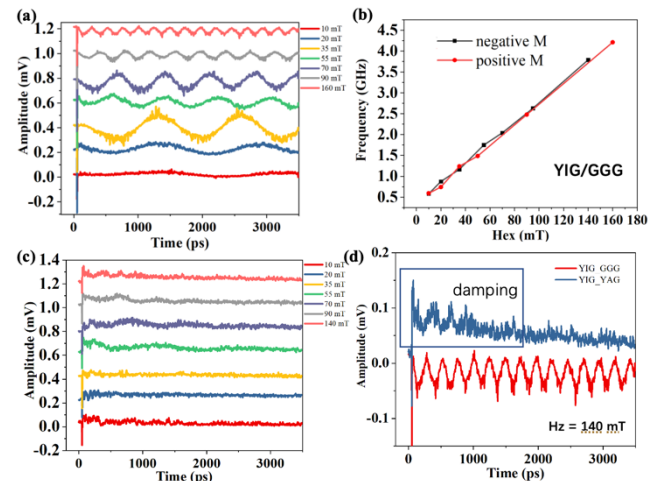


Fig.2 The tr-MOFE spin precession of (a) YIG/GGG and (c) YIG/YAG. (b)The FMR vs. Hex in YIG/GGG (d) Comparison of tr-MOFE between YIG/GGG and YIG/YAG under 140 mT.

Figures 2(a) and 2(c) present the experimental TR-MOFE signals of YIG/GGG and YIG/YAG under various external magnetic fields. Figure 2(b) shows the dependence of the ferromagnetic resonance (FMR) frequency on the external magnetic field for YIG/GGG under both positive and negative field directions. The results indicate that the application of an external magnetic field induces FMR in both YIG/GGG and YIG/YAG samples. However, as illustrated in Figure 2(d), the damping parameter of spin precession in YIG/YAG is 0.0186, which is significantly larger than that in YIG/GGG (0.0072). This difference is attributed to the larger lattice mismatch in YIG/YAG, which induces spin glass-like behavior—characterized by magnetic disorder. Under high magnetic fields, the disordered magnetic domains in YIG/YAG tend to partially align, enabling transient spin excitations; however, the excitations decay rapidly due to the strong damping effects[3].

This research was supported by Institute for AI and Beyond for the University of Tokyo, JST, CREST Grant Number JPMJCR2202, Japan, AMED under Grant Number JP22zf0127006, JSPS KAKENHI Grant Number JP20H05651, 25H00730, 25H02602.

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積層反強磁性体を用いた物理リザーバー計算における スピン波モードの影響

Effect of Spin-Wave Mode on Physical Reservoir Computing using Synthetic Antiferromagnet

名古屋大工¹ ○(M)新海拓夢¹, 飯浜賢志¹, 林兼輔¹, 森山貴広¹

Nagoya Univ.¹, Takumu Shinkai¹, Satoshi Iihama¹, Kensuke Hayashi¹, Takahiro Moriyama¹

E-mail: shinkai.takumu.b6@s.mail.nagoya-u.ac.jp

Artificial intelligence (AI), driven by neural networks, has become an essential technology in modern society. Nevertheless, traditional AI architecture depends heavily on CPUs and GPUs, leading to considerable power consumption. To tackle this limitation, physical reservoir computing (PRC)—a hardware-based realization of neural networks—has gained attention as a promising method for achieving energy-efficient and high-speed information processing. Among various physical platforms explored for PRC, spin-wave-based systems, which exploit the non-local dynamics of magnetization, offer notable advantages such as nanoscale scalability and low energy consumption [1]. In particular, Synthetic Antiferromagnets (SAFs)—structures consisting of two ferromagnetic layers antiferromagnetically coupled through a non-magnetic spacer—display spin-wave dispersion relations that differ significantly from those of single-layer ferromagnets. Due to the interlayer exchange interaction, SAFs support two distinct spin-wave modes: an in-phase acoustic mode and an out-of-phase optical mode, each exhibiting unique propagation characteristics. This research investigates whether the selective excitation of these spin-wave modes can be used to modulate the memory characteristics of the reservoir, specifically focusing on linear memory capacity (MC) and nonlinear information processing capacity (IPC). The ability to utilize this modal degree of freedom, absent in single ferromagnetic layers, may open up new pathways to enhance the functionality of spin-wave-based PRC. To explore this, we conducted micromagnetic simulations using Mumax³. As depicted in Fig. 1(a), physical nodes were introduced on the SAF structure, and spin-transfer torque was applied to the first ferromagnetic layer to initiate spin-wave propagation. Figure 1(b) shows the dispersion analysis, where wavevector–frequency mappings reveal the differences in propagation behavior between the acoustic and optical modes. In our presentation, we will examine how the excitation of each mode influences performance of PRC.

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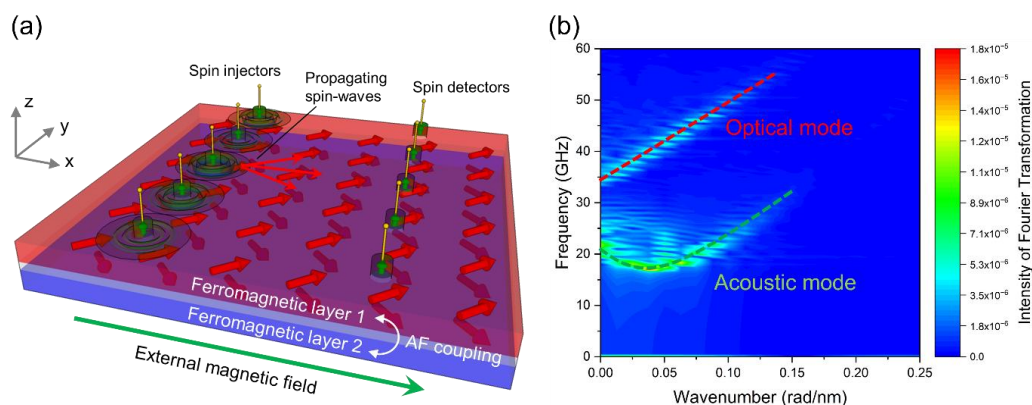


Figure 1 (a) Schematic illustration of PRC based on propagating spin-waves in SAF. (b) Spin-wave dispersion relation obtained by calculating Fourier transformation of propagating spin-waves.

Dimension-dependent magnon-magnon interactions

WPI-AIMR, Tohoku Univ.¹, IMR, Tohoku Univ.², CSRN, Tohoku Univ.³, KITS, UCAS⁴

Huanhuan Yang¹, Gerrit E. W. Bauer^{1,2,3,4}

E-mail: yang.huanhuan.b6@tohoku.ac.jp

We investigate magnon-magnon interactions in ferromagnetic systems across different dimensionalities, emphasizing their sensitivity to geometric confinement. In the long-wavelength limit, dipolar interactions dominate and lead to a suppression of three-magnon processes in reduced dimensions, while four-magnon interactions display distinct scaling behaviors from 1D to 3D. At larger wave vectors, the exchange interaction becomes important, but the corresponding four-magnon interactions are independent of the dimensions. By analyzing the threshold fields for first- and second-order Suhl instabilities, we uncover their dependence on wavevector orientation and dimensionality. Our findings highlight the crucial role of geometric confinement in shaping nonlinear magnon dynamics and provide a route to control spin-wave instabilities in magnets of various dimensions.

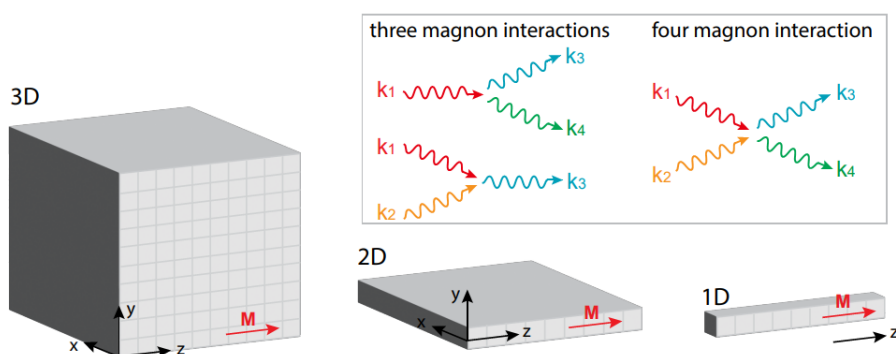


Figure: Sketch of the 3D, 2D, and 1D magnetic lattices. The magnetization is set to align z direction. Insets: (left) the sketch of three magnon splitting and confluence processes and (right) four magnon interactions.

Geometric structure dependence of RF oscillation properties of spin Hall nano-oscillators

○(M1)Hitoshi Iida^{1,2}, Karunathilaka Vihanga De Zoysa¹, (B4)Yuzu Yoshida^{1,2}, Aakanksha Sud^{1,3},
Aurélien Lagarrigue¹, Takaaki Dohi¹, Akash Kumar^{1,4,7}, Ahmad Awad^{1,4,7}, Shun Kanai^{1,2,5-9},
Johan Åkerman^{1,4,7}, Shunsuke Fukami^{1,2,7,8,10,11}, and Hideo Ohno^{1,7,8,10}
¹LNS, RIEC, Tohoku Univ., ²Graduate School of Engineering, Tohoku Univ., ³FRIS, Tohoku Univ.
⁴Physics department, Univ. of Gothenburg, ⁵JST-PRESTO, ⁶DEFS, Tohoku Univ., ⁷CSIS, Tohoku
Univ., ⁸WPI-AIMR Tohoku Univ., ⁹QST, ¹⁰CIES Tohoku Univ., ¹¹InaRIS

E-mail: iida.hitoshi.s6@dc.tohoku.ac.jp

Nanoconstriction-based spin Hall nano-oscillators (SHNOs), made of heavy metal/ferromagnet layers and utilizing spin Hall effect in heavy metal to drive auto-oscillation in ferromagnet layer [1], have attracted significant attention as next-generation information devices, such as broadband RF field generators and neuromorphic devices[2]. Although studies focusing on the material systems and array structures for efficient and stable operations have been extensively performed, guidelines for geometric design of the nanoconstriction remain unclear. In this study, we investigate the auto-oscillation properties of the SHNO with different nanoconstriction structures.

We use stacks of Si substrate/Pt(5)/Py(4,5,6)/MgO(2)/Ta(1) (thickness in nm) with different constriction widths (w) ranging from 80 - 300 nm. Oscillations are excited by applying DC under an in-plane external magnetic field ($\mu_0 H_{\text{ext}}$) of 80 mT with an angle of 80 degrees (with respect to the direction of the applied current) and detected by a spectrum analyzer. The maximum oscillation power (P_{max}) is defined as the peak amplitude of the Lorentzian fit to the power spectral density. As shown in Fig. 1, P_{max} increases as w decreases down to 100 nm, which can be explained by the separate edge-localized modes that overlap as w decreases.[3] Further decrease of w decreases P_{max} , which may be due to the increase of the constriction resistance and decrease of the detection and/or conversion efficiency of the auto-oscillation. The present finding establishes the basics of designing an efficient SHNO device.

We thank F. Shibata, R. Nomura, I. Morita, M. Musya, and R. Ono for their technical support. This work was supported by JSPS Kakenhi, JST PRESTO, JST ASPIRE. H. Iida acknowledges financial support from GP-Spin at Tohoku University.

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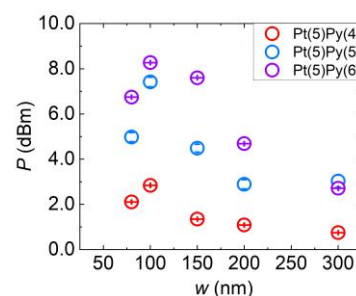


Fig. 1 Constriction width w dependence of maximum output power P_{max} of SHNO.

Electric field control of spin wave propagation in strained iron oxide garnet thin films with unquenched orbital moments

Univ. Tokyo¹, ^o (D) EMK Ikbāl Ahamed^{1*}, Md Shamim Sarker¹, Hiroyasu Yamahara¹, Munetoshi Seki¹, Hitoshi Tabata¹

*E-mail: ahamedikball@g.ecc.u-tokyo.ac.jp

This study aims to control spin wave propagation in rare-earth iron garnet (RIG) thin films by the electric field. Traditional garnet materials, such as yttrium iron garnet (YIG) and related RIGs, possess a highly symmetric cubic crystal structure and exhibit negligible spontaneous polarization and inherently weak coupling between electric and magnetic order parameters. To overcome this limitation, this research proposes a novel strategy: reducing the high centrosymmetry of garnet films by introducing strain or strain gradients, thereby enabling symmetry-breaking mechanisms that can enhance electric-magnetic coupling.^[1-2] YIG thin films were grown on lattice-matched GGG (12.38 Å) and ~1% mismatched SGGG (12.50 Å) substrates using pulsed laser deposition (PLD). Likewise, lutetium iron garnet (LuIG) thin films were grown on SGGG (~1.8% mismatch) substrates. X-ray absorption spectroscopy (XAS) and X-ray magnetic circular dichroism (XMCD) were measured at room temperature, and the orbital and spin moments (m_{orb} and m_{spin}) were calculated as in Fig. 1(a)-(b). Lattice-matched YIG/GGG exhibits quenched m_{orb} , whereas the unquenched m_{orb} in YIG (120 nm)/SGGG and LuIG (80 nm)/SGGG films indicates that the m_{orb} is alleviated by the reduction of crystal symmetry from cubic to tetragonal.^[2] Epitaxial strain lifts orbital degeneracy in Fe–O octahedra, enabling partial unquenching of orbital angular momentum. Fig. 1(d) exhibits the schematic of a voltage-controlled spin wave device using RIG thin films, where interdigital electrodes (IDE) were analogous to the control gate used to apply an in-plane electric field. Fig. 1(e) summarizes the shift in spin wave transmission resonance frequency (Δf) as a function of the electric field (E). Electric fields induced notable frequency shifts in strained films, whereas lattice-matched YIG/GGG films showed minimal response even at 800 kV/cm. This modulation arises from electric-field-induced changes in magnetization, altering spin wave behavior. An applied electric field causes surface electron accumulation (Fig. 1(e)), preferentially filling specific low-energy d -orbitals in strained FeO₆ octahedra (Fig. 1(f)), leading to orbital polarization. This change in orbital occupancy alters the magnetic moment balance between the Fe sites (antiferromagnetic coupling between the tetrahedral and octahedral sites), thereby increasing the net magnetization. This electric-field-driven dynamic magnon control marks a significant step in magnonics, enabling low-power spin wave-based logic devices.

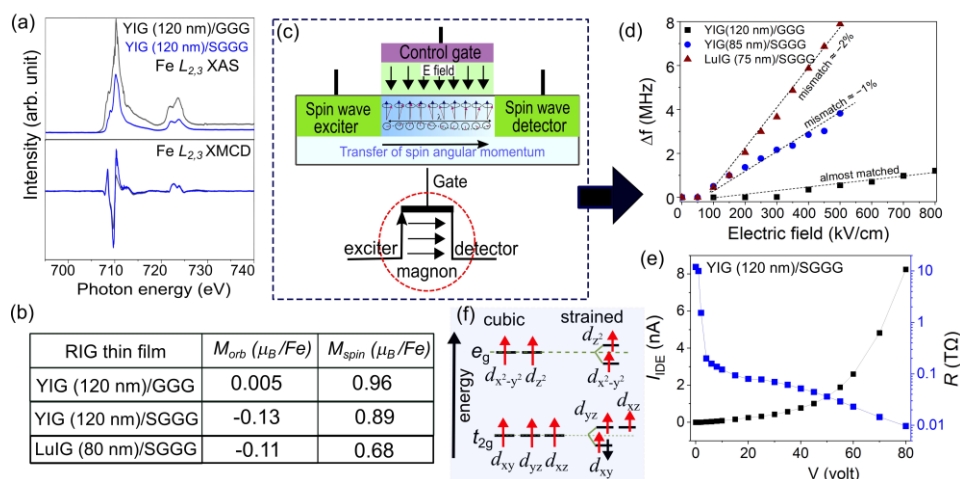


Fig. 1. (a)-(b) XAS and XMCD spectra, and corresponding orbital moments of YIG/GGG, YIG/SGGG and LuIG/SGGG thin films, (c) schematic of voltage-controlled spin wave devices using RIG thin films (d) spin wave transmission resonance frequency shift [$\Delta f(E) = f_{\text{res}}(E) - f_{\text{res}}(E=0)$] versus applied electric field (E), (e) IDE current versus voltage characteristics in YIG/SGGG and (f) microscopic origin of magnetization modulation in strained RIG thin films by electric field from the viewpoint of crystal field splitting in strained octahedron.

This research was supported by the Institute for AI and Beyond for the University of Tokyo, JST, CREST Grant Number JPMJCR22O2, Japan, AMED under Grant Number JP22zf0127006, and JSPS KAKENHI Grant Number JP20H05651, 25H00730, 25H02602, 202513995 (DC2).

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Investigating the atomic origin of room temperature spin glass behavior in non-substituted yttrium iron garnet thin films towards brain mimetic computing

Univ. Tokyo, ° Md Shamim Sarker*, E M K Ikbali Ahamed, Zhiqiang Liao, Ritsui Sonetaka, Ryoken Nako, Yang Dongxun, Haining Li, Hiroyasu Yamahara, Munetoshi Seki, and Hitoshi Tabata

*E-mail : sarker@g.ecc.u-tokyo.ac.jp

Systems with disordered magnetic configurations can enter a frozen spin state at low temperatures, driven by the coexistence of frustration and randomness in their exchange interactions. Such states inherently exhibit non-equilibrium behaviors like memory retention and history dependence, making them attractive for brain-inspired computational models. This work investigates the dynamics of low-power spin excitations within such disordered regimes to enable neuromorphic reservoir computing. However, the need for cryogenic temperatures restricts their applicability. To address this, we explore the emergence of glassy spin states near ambient conditions by tailoring oxygen non-stoichiometry in garnet-based ferrimagnets. Yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) serves as our initial platform due to its minimal intrinsic damping and robust magnetic order.

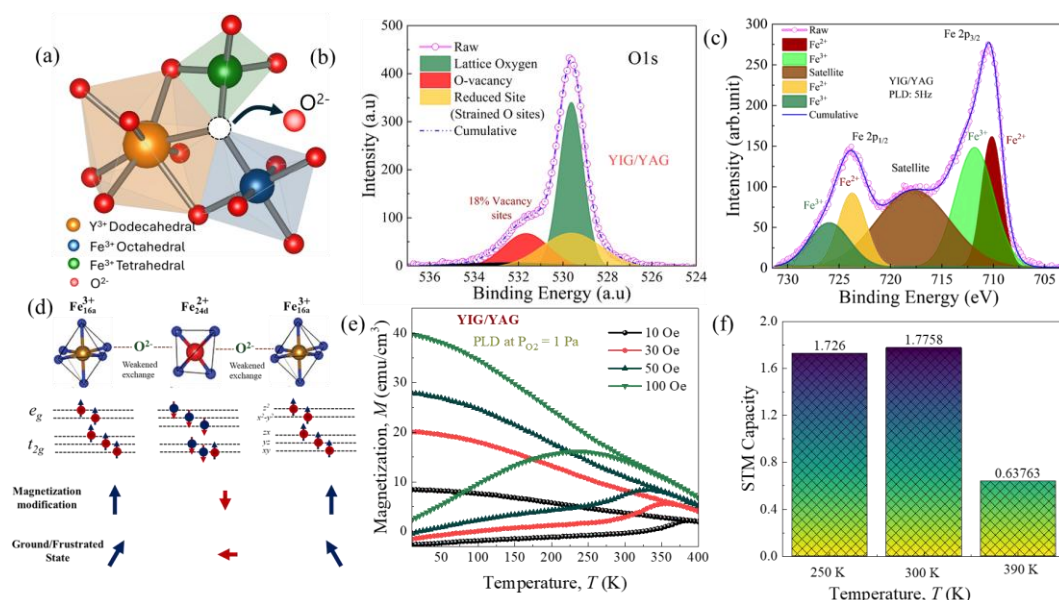


Figure 1. Structural, spectroscopic, and magnetic signatures of oxygen-vacancy-induced spin frustration in YIG/YAG thin films. (a) Crystal structure showing oxygen coordination. (b–c) XPS spectra indicating oxygen vacancies and Fe^{2+} formation. (d) Orbital distortion and asymmetric exchange pathways. (e) FC–ZFC bifurcation behavior. (f) Memory capacity across distinct glassy states.

We fabricated 80 nm-thick oxygen non-stoichiometric YIG films on 2.96% lattice-mismatched YAG (001) substrates using PLD (Fig. 1a). Oxygen vacancies were confirmed by lattice expansion to 12.54 Å. XPS analysis of O 1s and Fe 2p spectra (Fig. 1b–c) reveals lattice oxygen at 529.8 eV and additional components at 531.0 and 529.3 eV, indicating 18% of oxygen vacancies and reduced metal sites, respectively. The coexistence of Fe^{3+} and Fe^{2+} confirms mixed valency ($\text{Fe}^{2+}/\text{Fe}^{3+} \sim 0.15\text{--}0.2$) driven by oxygen deficiency, which disrupts spin alignment and exchange interactions, leading to a frustrated magnetic ground state (Fig. 1d). The assumption of Fe^{2+} occupancy in the tetrahedral sites supports the reduction of magnetization from the bulk value. Spin glass behavior is evidenced by FC–ZFC bifurcation (Fig. 1e), along with enhanced short-term memory below the glass transition temperature (Fig. 1f) [1].

Acknowledgement

This research was supported by Institute for AI and Beyond for the University of Tokyo, JST, CREST Grant Number JPMJCR22O2, Japan, AMED under Grant Number JP22zf0127006, JSPS KAKENHI Grant Number JP20H05651, 25H00730, 25H02602.

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Two-stage Formation of an Anomalously Large Nuclear Field in Bulk n -AlGaAs

バルク n -AlGaAs における異常に大きい核磁場の 2 段階生成

Grad. Sch. Eng., Hokkaido Univ.¹, Grad. Sch. Eng., Tohoku Univ.², Grad. Sch. IST, Hokkaido Univ.³

○Andong Shen¹, Reina Kaji¹, Sota Yamamoto², Tetsuya Uemura³, Satoru Adachi¹

北大院工¹, 東大院工², 北大院情報³

○(D2) 沈 安東¹, 鍛治 怜奈¹, 山本 壮太², 植村 哲也³, 足立 智¹

E-mail: andong.shen.w5@elms.hokudai.ac.jp

Introduction: Dynamic nuclear polarization in bulk semiconductors is often constrained by electron delocalization, typically resulting in smaller nuclear fields than in nanostructures. However, in bulk n -AlGaAs samples, a large nuclear magnetic field (B_N) up to 1.1 T can be formed slowly under an oblique magnetic field (B_{ext}). Further experiments revealed a two-stage formation of this large field. We investigated this phenomenon across three samples with varying Al concentrations to reveal the underlying mechanisms, including the roles of electron localization, nuclear quadrupole interactions, and spin diffusion.

Sample & Experiment: Two bulk n -Al _{x} Ga _{$1-x$} As ($x=0.05$ and 0.15) and a n -GaAs ($x=0$) with a doping density of $N_c \sim 1 \times 10^{16} \text{ cm}^{-3}$ were used. Electron and nuclear spin dynamics were investigated by time-resolved Kerr rotation (TRKR) measurement. “pre-pump” and “dark-time” were introduced before the TRKR measurement to observe the formation and relaxation dynamics of B_N [1].

Results & Discussion: The observed formation and relaxation dynamics of the B_N , indicated in Fig. 1 (a), clearly exhibit a two-stage behavior in all samples. An initial rapid rise of B_N is observed even at zero pre-pump time, attributed to hyperfine interaction at electron localization sites. The initial B_N is larger in AlGaAs, possibly due to the higher localization density caused by the alloy disorder from Al incorporation. Following is a significantly slower increase towards saturation, which we associate with slow nuclear spin transfer from localization sites into surrounding areas. Further, we compared the relaxation dynamics of B_N under 560 mT and 6 mT. By comparing the data of relaxation experiments under strong and weak B_{ext} , further suggest that the slow formation is caused by two key factors: the suppression of quadrupole-induced nuclear spin relaxation by strong B_{ext} , and slow nuclear spin diffusion processes.

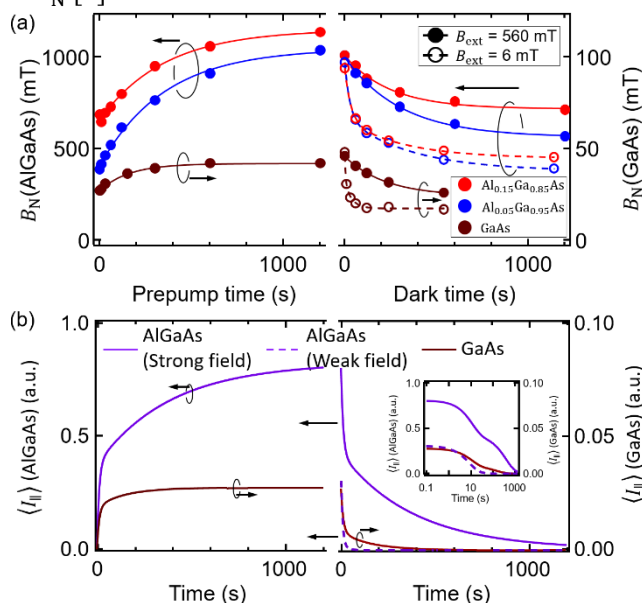


Fig.1. (a) Formation (left) and relaxation (right) of B_N of the three samples. (b) Model calculations of the formation (left) and relaxation (right) processes of NSP. In the relaxation dynamics, the fast re-polarized NSP in the pump/probe stage makes the offset. Also, the initial fast decay due to HFI is beyond our time resolution.

The conventional model of nuclear spin polarization (NSP) formation [2] has successfully explained various experiments in single QDs, but the observed two-stage NSP formation, as shown in Fig. 1(a), cannot be reproduced. So, we modified the model by dividing the nuclear spins into the ones near the electron localization sites ($\langle I_{\text{Loc}} \rangle$) and the ones in the surrounding region ($\langle I_{\text{Sur}} \rangle$). The calculated results are summarized in Fig. 1(b). As clearly shown, the model calculation reproduced the two-stage NSP formation well. The details of our model and the physical origin of large nuclear magnetic fields will be discussed.

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10 Spintronics and Magnetism | Oral presentation : 10.2 Fundamental and exploratory device technologies for spin

[8p-N303-1~16] 10.2 Fundamental and exploratory device technologies for spin

[8p-N303-1]

[The 58th Young Scientist Presentation Award Speech] Observation of the orbital Hall effect in Silicon

○Ryoga Matsumoto¹, Ryo Ohshima^{1,2}, Yuichiro Ando³, Masashi Shiraishi^{1,2} (1.Kyoto Univ., 2.CSRN Kyoto Univ., 3.Osaka Metropolitan Univ.)

[8p-N303-2]

Nernst effect in ferromagnetic Fe_{2-x}Pd_xMo₃N thin films skyrmions

○Kanchi Yamamoto¹, Hirofumi Kyou¹, Hidehumi Asano², Toshio Miyamachi¹, Masaki Mizuguchi¹ (1.Nagoya Univ., 2.Nagoya Industrial Science Institute)

[8p-N303-3]

Electric field effect on anomalous Nernst effect in an FePt thin film

○Soki Yoshida¹, Shimpei Ono², Bowen Qiang¹, Toshio Miyamachi¹, Masaki Mizuguchi¹ (1.Nagoya Univ., 2.Tohoku Univ.)

[8p-N303-4]

Tuning of the anomalous Nernst effect in Co-based maze-like structures

○Takuya Tsujimoto¹, Takeshi Fujita², Toshio Miyamachi¹, Masaki Mizuguchi¹ (1.Nagoya Univ., 2.Kochi Univ. Tech.)

[8p-N303-5]

Ultrafast thermomagnetic effects in FePt thin films

○(M1C)Naoto Fukushima¹, Satoshi Iihama¹, Takahiro Moriyama¹, Toshio Miyamachi¹, Masaki Mizuguchi¹ (1.Nagoya Univ.)

[8p-N303-6]

Observation of Nonlinear Thermoelectric Effect at room temperature

○(D)Yuya Hirata¹, Takashi Kikkawa^{1,2}, Hiroki Arisawa^{1,3}, Eiji Saitoh^{1,3,4,5} (1.Dept. Appl. Phys., Univ. Tokyo, 2.JAEA ASRC, 3.RIKEN CEMS, 4.BAI Univ. Tokyo, 5.AIMR Tohoku Univ.)

[8p-N303-7]

Observation of Unconventional Spin Current Transmission in Epitaxial NiO(001) Films Probed by Thermo-spin Effects

○JUNWEI GU^{1,2}, Takumi Yamazaki¹, Takeshi Seki^{1,3,4} (1.IMR, Tohoku Univ., 2.Tongji Univ., 3.CSIS, Tohoku Univ., 4.SRIS, Tohoku Univ.)

[8p-N303-8]

Tungsten-Mediated Interlayer Exchange Coupling System Revisited

○(P)Xueyao HOU¹, Keita ITO¹, Varun Kumar KUSHWAHA¹, Takumi YAMAZAKI¹, Junwei GU¹, Shoya SAKAMOTO^{1,2}, Zhenchao WEN³, Keisuke MASUDA³, Jun OKABAYASHI⁴, Takeshi SEKI^{1,2,5} (1.IMR, Tohoku Univ., 2.CSIS, Tohoku Univ., 3.CMSM, NIMS, 4.RCS, Univ. Tokyo, 5.SRIS, Tohoku Univ.)

[8p-N303-9]

Spin current measurement using ST-FMR in epitaxial multilayer Fe/Ru/Co

○Yota Suzuki¹, Toma Hattori¹, Kensuke Hayashi¹, Satoshi Iihama¹, Takahiro Moriyama¹
(1.Nagoya Univ.)

[8p-N303-10]

Spin-orbit torque in sputtered W-Te/Ru/CoFeB thin film

○Yukihiro Marui¹, Hideo Ohno^{1,2,3,4}, Shunsuke Fukami^{1,2,3,4,5,6} (1.RIEC, Tohoku Univ., 2.WPI-AIMR, Tohoku Univ., 3.CSIS, Tohoku Univ., 4.CIES, Tohoku Univ., 5.Grad. Sch. Sci. Eng. Tohoku Univ., 6.InaRIS)

[8p-N303-11]

Large spin Hall effect in BiSb topological insulator and perpendicularly magnetized CoFeB heterojunctions with oxide buffer and interfacial layers

○(D)Thuan Van Pham¹, Hoang Huy Ho¹, Wentao Li¹, S. Takahashi², Y. Kato², S. Hirayama², Nam Hai Pham¹ (1.Science Tokyo, 2.Samsung Japan Corp)

[8p-N303-12]

Evaluation of Spin-Orbit Torque-Driven Magnetization Switching Using Phosphorus-Ion-Implanted Platinum

○Kazuki Shintaku¹, Arun Jacob Mathew¹, Akihisa Iwamoto¹, Mojtaba Mohammadi², Hiroyuki Awano², Hironori Asada³, Yasuhiro Fukuma¹ (1.Kyushu Inst. Tech., 2.Toyota Tech. Inst., 3.Yamaguchi Univ.)

[8p-N303-13]

Electrical mutual switching in a noncollinear-antiferromagnetic-ferromagnetic heterostructure

Ju-Young Yoon^{1,2}, Yutaro Takeuchi^{1,3}, Ryota Takechi^{1,2}, OJiahao Han^{1,4}, Tomohiro Uchimura^{1,2}, Yuta Yamane^{1,5}, Shun Kanai^{1,2,4,6,7,8,9}, Junichi Ieda¹⁰, Hideo Ohno^{1,2,4,8,11}, Shunsuke Fukami^{1,2,4,8,11,12} (1.RIEC, Tohoku Univ., 2.Grad School of Eng., Tohoku Univ., 3.RCMSM, NIMS, 4.AIMR, Tohoku Univ., 5.FRIS, Tohoku Univ., 6.PRESTO, JST, 7.DEFS, Tohoku Univ., 8.CSIS, Tohoku Univ., 9.QST, 10.ASRC, JAEA, 11.CIES, Tohoku Univ., 12.InaRIS)

[8p-N303-14]

Current-induced switching in epitaxial Mn₃Sn thin films: A temperature dependent study

○Kota Nihei^{1,2}, Tomohiro Uchimura^{1,2}, Jiahao Han^{1,3}, Shun Kanai^{1,2,3,4,5,6,7}, Hideo Ohno^{1,2,3,4,8}, Shunsuke Fukami^{1,2,3,4,8,9} (1.RIEC, Tohoku Univ., 2.Grad. Sch. Eng., Tohoku Univ., 3.AIMR, Tohoku Univ., 4.CSIS, Tohoku Univ., 5.PRESTO, JST, 6.DEFS, Tohoku Univ., 7.QST, 8.CIES, Tohoku Univ., 9.InaRIS)

[8p-N303-15]

Pulse width dependence of spin-orbit torque switching in noncollinear antiferromagnetic Mn₃Sn nanodot

○(DC)Yuma Sato^{1,2}, Yutaro Takeuchi^{3,4}, Yuta Yamane^{1,5}, Shun Kanai^{1,2,4,6,8,9}, Hideo Ohno^{1,4,6,7}, Shunsuke Fukami^{1,2,4,6,7,10} (1.Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku Univ., 2.Graduate School of Engineering, Tohoku Univ., 3.CMSM, NIMS, 4.WPI-AIMR, Tohoku Univ., 5.FRIS, Tohoku Univ., 6.CSIS, Tohoku Univ., 7.CIES, Tohoku Univ., 8.EFS, Tohoku Univ., 9.QST, 10.InaRIS)

[8p-N303-16]

Unconventional spin Hall magnetoresistance in a non-collinear antiferromagnet/heavy metal heterostructure

OTomohiro Uchimura^{1,2}, Jiahao Han^{1,3}, Ping Tang³, Ju-Young Yoon¹, Yutaro Takeuchi³, Yuta Yamane^{1,4}, Shun Kanai^{1,2,3,5,6,7,8}, Gerrit E. W. Bauer^{3,7,9,10}, Hideo Ohno^{1,2,3,7,11}, Shunsuke Fukami^{1,2,3,7,11,12} (1.RIEC, Tohoku Univ., 2.Graduate School of Engineering, Tohoku Univ., 3.WPI-AIMR, Tohoku Univ., 4.FRIS, Tohoku Univ., 5.PRESTO, JST, 6.DEFS, Tohoku Univ., 7.CSIS, Tohoku Univ., 8.QST, 9.IMR, Tohoku Univ., 10.Kavli ITS, UCAS, 11.CIES, Tohoku Univ., 12.InaRIS)

Observation of the orbital Hall effect in Silicon

Kyoto Univ.¹, CSRN Kyoto Univ.², Osaka Metropolitan Univ.³,

[○]Ryoga Matsumoto¹, Ryo Ohshima^{1,2}, Yuichiro Ando³, Masashi Shiraishi^{1,2}

E-mail: matsumoto.ryoga.25a@st.kyoto-u.ac.jp

In recent years, the orbital Hall effect (OHE) has emerged as a new mechanism of angular momentum transport and attracted tremendous attention in the field of condensed matter physics and spintronics. The OHE is a phenomenon in which an application of an electric field gives rise to the transverse flow of orbital angular momentum (orbital current) (see Fig. 1). Unlike the spin Hall effect, which typically requires heavy elements with strong spin-orbit coupling, the OHE takes place even in light elements, offering a significant advantage in terms of material flexibility for spin-orbit torque (SOT) devices. Although the OHE is observable in a wide variety of materials with orbital hybridization, the previous study on OHE has mainly focused on light transition metals such as Ti and Zr, where s - d orbital hybridization plays a crucial role in generating orbital currents. In this study, the OHE in Si, which is semiconductor and has s - p orbital hybridization, is investigated by using spin-torque ferromagnetic resonance measurement.

Figure 2 illustrates the device structure and the measurement setup. A (001) silicon-on-insulator substrate is used to fabricate Ni/Si bilayer devices. The Si layer is doped with Phosphorus, and Si is n-type and degenerated. All measurements were carried out at room temperature. Figure 3 shows a DC voltage (V_{DC}) measured under the ferromagnetic resonance condition of the Ni in the Ni/Si bilayer device as a function of an external magnetic field (B_{ext}). The frequency of the rf current was 5 GHz, where B_{ext} was applied along $\varphi = 45^\circ$ for the rf current direction. The damping-like torque efficiency per unit electric field (ξ_{DL}^E), which represents the magnitude of OHE in Si, was calculated to be $75 \Omega^{-1} \text{cm}^{-1}$ using the amplitude of the V_{sym} component exhibiting the $\sin 2\varphi \cos \varphi$ dependence. Si thickness (t_{Si}) dependence of ξ_{DL}^E was measured (see Fig. 4) and the orbital decay length in Si was estimated to be 17.8 nm. Monotonic increase of ξ_{DL}^E as a function of the Ni thickness supports our assertion of successful creation of the orbital current in Si.

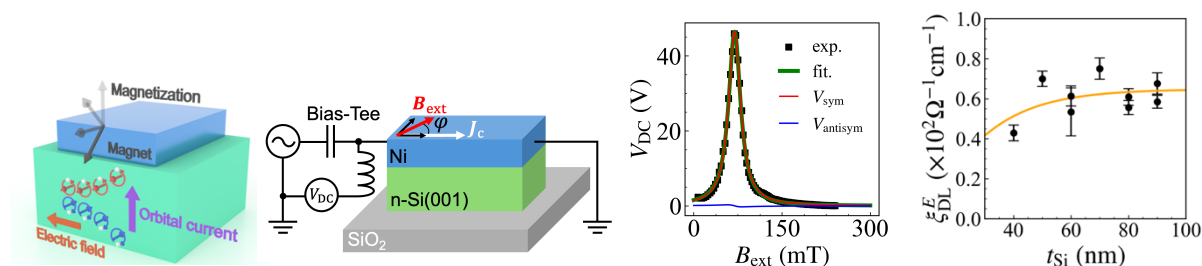


Fig. 1 Schematic.

Fig. 2 Measurement setup.

Fig. 3 B_{ext} dependence of V_{DC} .

Fig. 4 t_{Si} dependence.

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Nernst effect in ferromagnetic $\text{Fe}_{2-x}\text{Pd}_x\text{Mo}_3\text{N}$ thin films with skyrmions

K. Yamamoto¹, B.W. Qiang¹, H. Asano², T. Miyamachi¹, M. Mizuguchi¹
(¹Nagoya Univ, ²Nagoya Industrial Science Institute)

【Background】

Magnetic skyrmions, characterized by their topologically protected spin textures, have attracted significant interest for applications in thermoelectric devices and heat-flow sensing technologies due to their unique transport signatures. Recent studies have revealed that, in addition to the conventional anomalous Nernst effect (ANE) governed by Berry curvature from intrinsic magnetization [1], the presence of skyrmions induces a distinct topological Nernst effect (TNE) arising from the emergent electromagnetic field associated with their spin structure [2–4]. This effect enables enhanced transverse thermoelectric responses that are highly sensitive to skyrmion density and configuration.

Various materials such as MnSi [2], Co-Zn-Mn alloys [3], and multilayered systems [4] have demonstrated TNE associated with skyrmions, particularly in the low-temperature or narrow-field regimes. In this study, we focus on $\text{Fe}_{2-x}\text{Pd}_x\text{Mo}_3\text{N}$ (FPMN) thin films, which are notable for hosting small-size skyrmions stable over a wide temperature and magnetic field range [5]. These films offer a promising platform for room-temperature thermoelectric applications due to their chemically tunable Dzyaloshinskii–Moriya interaction (DMI) and robust skyrmion phase stability. We investigate the Nernst response of FPMN thin films and their correlation with the magnetic phase diagram, emphasizing the particle-like behavior of skyrmions under thermal gradients.

【Results】

FPMN thin film material was prepared on a sapphire (001) substrate by magnetron sputtering at a substrate temperature of 580°C in a nitrogen atmosphere of 6.4 Pa. Nernst measurements were performed using a PPMS with a temperature gradient of several kelvin at a wide temperature range from room temperature down to 80 K. The analysis of TNE was carried out by subtracting the ordinary and anomalous terms from the overall Nernst signal. In the FPMN ($x=0.3$), TNE of ~ 30 nV/K was observed at room temperature, which is comparable to the value reported for Gd_2SiPd_3 that exhibits giant topological Nernst signals.[6] In the presentation, we will discuss the comparison between the skyrmion phase diagram and the TNE phase diagram, incorporating both theoretical considerations and experimental validation.

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Electric field effect on anomalous Nernst effect in an FePt thin film

°S. Yoshida¹, S. Ono², B. Qiang¹, T. Miyamachi¹, M. Mizuguchi¹

¹ Nagoya Univ., ² Tohoku Univ.

E-mail: mizuguchi.masaki@material.nagoya-u.ac.jp

Recently, the anomalous Nernst effect (ANE) has attracted attention as an alternative thermoelectric conversion phenomenon to the Seebeck effect. The ANE generates an electric field in the direction perpendicular to both the temperature gradient and the magnetization. Since the Nernst voltage increases with the length between two electrodes of voltage output in principle, the ANE can be applied to thermoelectric devices with various shapes, such as two-dimensional sheets, and it enables low manufacturing costs and high durability of devices. By controlling the ANE, its potential for diverse applications can be expanded, for example, it leads to switching devices driven only by the temperature gradient. In this study, we focused on the electric field effect as a means of controlling it, which is a way to modulate properties of thin films via the change in the carrier density and reversible redox reactions by applying an electric field. An FePt thin film is one of the materials, in which the modulation of magnetic properties by the electric field has been reported,¹⁾ and shows relatively large ANE conversion efficiency²⁾. In this study, we investigated the modulation of the ANE, the anomalous Hall effect (AHE), and magnetization in an FePt thin film by the electric field effect.

An Fe seed layer (1 nm), a Au buffer layer (5 nm) and an FePt layer (2 nm) were consecutively grown on a MgO(001) single crystal substrate by a magnetron sputtering. The temperature of the substrate was 300°C during the deposition of an FePt layer and 450°C during post-annealing process. An ionic liquid (TMPA⁺-TFSI⁻) film was attached to the prepared sample as a gate dielectric in an electric double layer transistor configuration. Gated voltage was applied to the film via the ionic liquid film as the electron accumulation occurs in the FePt layer. Modulation of the Nernst voltage, Hall resistivity, and saturation magnetization was confirmed with gated voltage of +1.5 V. Detailed behavior of the modulation will be discussed.

We would like to thank Dr. Tomohiro Koyama and Dr. Daichi Chiba of Osaka University for their cooperation in the experiments of this research. Part of this research was supported by Grant-in-Aid for Scientific Research (S)(21H05016) from Japan Society for the Promotion of Science, and conducted in collaboration with Network Joint Research Center for Material and Devices.

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Tuning of the anomalous Nernst effect in Co-based maze-like structures

○(D2) Takuya Tsujimoto¹, Takeshi Fujita², Toshio Miyamachi¹, Masaki Mizuguchi¹

¹Nagoya Univ., ²Kochi Univ. Tech.

Email: mizuguchi.masaki@material.nagoya-u.ac.jp

The anomalous Nernst effect (ANE) is one of the thermoelectric conversion phenomena commonly observed in ferromagnets and expected as a next-generation energy harvesting technology [1], [2]. A characteristic of this effect is that the direction of the electric field generated by thermoelectric conversion is perpendicular to the temperature gradient. By utilizing the anomalous Nernst effect, it is now possible to fabricate highly flexible and simple-structured devices. However, the conversion efficiency of the ANE is too small to use practically, and it is a large issue to enhance the scattering of electrons for the ANE. Recently, we have reported the enhancement of the ANE in the granular thin films [3]. In nanostructures, interfaces play an important role for ANE scattering. Therefore, we focused on the interface between ferromagnetic metals and air, and investigated how ANE is affected in Co-based nanostructures.

To form interface-rich structures, we used a vapor-phase dealloying method. CoZn alloy thin films were fabricated on MgO(100) substrates by co-sputtering method. Then, rapid thermal annealing was applied to selectively remove Zn, resulting in a nanostructure with large interfaces. We studied crystallographic structures using a scanning electron microscope (SEM) and transmission electron microscope (TEM). It was confirmed that maze-like structures were obtained by a vapor-phase dealloying. Figure 1 presents the ANE efficiency (S_{yx}) as a function of a perimeter of pores in each film. In maze-like Co thin films, ANE increased as perimeter increased and reached up to $1.2 \mu\text{V/K}$, which is more than three times greater than that of the Co thin film without nanostructures. We also analyzed the scaling relation between σ_{xx} and σ_{xy} , that is, a longitudinal and transverse conductivity. In samples with large ANE, transverse conductivity decreases as longitudinal conductivity increases, which differs from a conventional tendency. These results suggest that ANE scattering mechanism is strongly tuned by increasing interfaces of Co.

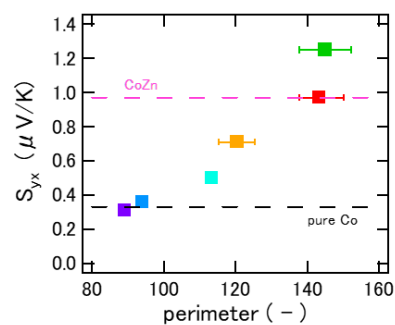


Fig1. ANE efficiency

This research was partly supported by a Grant-in-Aid for Scientific Research (S) (25220910) and the Center for Spintronics Research Network (CSRN),

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Ultrafast thermomagnetic effects in FePt thin films

Nagoya Univ., °(M1)Naoto Fukushima, Satoshi Iihama, Takahiro Moriyama, Toshio

Miyamachi, Masaki Mizuguchi

E-mail: mizuguchi.masaki@material.nagoya-u.ac.jp

Introduction

Terahertz (THz) emission from single ferromagnetic thin films excited by femtosecond pulsed lasers (fs-lasers) has attracted attention as a promising approach to expanding the high-frequency regime of spintronics[1]. A prior study indicated that fs-laser-induced voltages in L1₀-ordered FePt thin films stem from ultrafast thermomagnetic effects associated with the anomalous Nernst effect (ANE)[2]. In this study, we aim to analyze thermomagnetic effects with high spatial and temporal resolution by microfabricating FePt thin films and applying fs-laser irradiation with a reduced spot size. As an initial step, we investigated voltage responses induced by fs-laser irradiation at the microscale.

Experimental Methods

FePt thin films were deposited on MgO substrates by RF sputtering, followed by annealing. Structural and magnetic properties were characterized using X-ray diffraction (XRD) and vibrating sample magnetometer (VSM). ANE voltages were measured using a PPMS system by applying out-of-plane temperature gradients with a heater. In addition, CW laser irradiation was used to induce temperature gradients to investigate laser-induced ANE voltages. For fs-laser-induced ANE measurement as shown in Fig. 1, the wavelength and repetitions rate of the laser were 1,550 nm and 1 GHz, respectively. The laser was irradiated on microfabricated wire of the FePt thin film with a width of 5 μm . The laser-induced voltage was measured using a GHz oscilloscope.

Results and Discussion

XRD and VSM measurements confirmed that the fabricated films exhibited a disordered fct-FePt with in-plane magnetic anisotropy. ANE voltages under thermal gradients were observed with both heater and laser excitation. Under fs-laser irradiation, magnetic-field-dependent voltage signals were successfully observed via fast Fourier transformation spectrum at 1 GHz of the time-domain signal. These results demonstrate the feasibility of resolving localized ultrafast voltage responses, paving the way for spatially and temporally resolved analysis of ultrafast thermomagnetic effects. Future work will focus on detailed waveform analysis to clarify the link between magnetization dynamics and thermomagnetic effect.

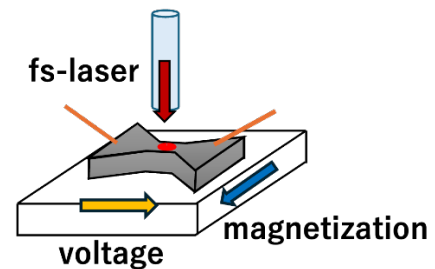


Fig. 1 Experimental setup for pulsed laser voltage measurement.

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室温における非線形熱電効果の観測**Observation of Nonlinear Thermoelectric Effect at room temperature**東大物工¹, 原子力機構先端研², 理研 CEMS³, 東大 Beyond AI⁴, 東北大 AIMR⁵平田裕也¹, 吉川貴史^{1,2}, 有沢洋希^{1,3}, 齊藤英治^{1,3,4,5}Dept. Appl. Phys., Univ. Tokyo¹, JAEA ASRC², RIKEN CEMS³, BAI Univ. Tokyo⁴, AIMR Tohoku Univ.⁵Yuya Hirata¹, Takashi Kikkawa^{1,2}, Hiroki Arisawa^{1,3}, Eiji Saitoh^{1,3,4,5}

熱電効果は物質に加えた温度勾配が電圧に変換される現象である。従来、線形熱電効果に関する研究がなされてきたが、近年、温度勾配の二次に比例する非線形熱電効果が理論提案された[1]。昨年には、第二種超伝導体 MoGe と強磁性絶縁体 Y₃Fe₅O₁₂ の接合系において非線形 Nernst 電圧が実験的に観測された[2]。この現象は温度勾配の空間/時間的変動を電力に変える新たな発電原理となりうる一方で、発現温度が MoGe の超伝導状態が許される極低温環境（5 K 以下）に限られていた。

本研究では、室温において「非線形 Seebeck 効果」の観測に成功した[3]。実験では、強磁性金属 Ni₈₁Fe₁₉ と常磁性重金属 Pt の接合系に対して複数熱源ロックイン法を用いて、非線形 Seebeck 電圧を測定した。Pt 内部を流れる電子スピンの軌道相互作用を介して Ni₈₁Fe₁₉ 界面方向に曲げられることで、熱流入力方向に関して非対称な界面磁化-スピン散乱が生じる。我々は、磁化方向や試料長に対する依存性を調べることで、観測された非線形 Seebeck 信号がこの磁化-スピン散乱過程に由来していることを明らかにした。本発表では、実験結果の詳細、及び試料内部の対称性の破れがもたらす非線形 Seebeck 効果の原理を非線形磁気抵抗効果[4]と比較して説明する。

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Observation of Unconventional Spin Current Transmission in Epitaxial NiO(001) Films Probed by Thermo-spin Effects

IMR, Tohoku Univ.¹, Tongji Univ.,² CSIS, Tohoku Univ.³, SRIS, Tohoku Univ.⁴

◦Junwei Gu^{1,2}, Takumi Yamazaki¹, Takeshi Seki^{1,3,4}

E-mail: takumi.yamazaki.d5@tohoku.ac.jp

Antiferromagnetic materials have garnered increasing attention due to their unique physical properties and potential in spintronic applications [1]. Among them, antiferromagnetic insulator NiO with high Néel temperature has been widely studied [2,3]. While long spin transmission lengths have been reported and several mechanisms have been proposed, the fundamental physics of spin transport in NiO remains controversial. Notably, most studies have focused on polycrystalline NiO, with limited investigation of epitaxial NiO films [4,5], hindering a comprehensive understanding of its spin transport properties.

In this work, we investigate spin current transmission in epitaxial NiO(001) films by measuring the thermo-spin effects [6] in Pt/NiO/CoFeB trilayers. Pt(t_{Pt})/NiO(t_{NiO}) films were epitaxially grown on MgO(001) substrates, followed by the deposition of CoFeB(20 nm) using magnetron sputtering. Polycrystalline counterparts were also prepared on Si/Si-O substrates as control samples. In Pt/NiO/CoFeB trilayers, the spin current generated via the spin Hall effect in Pt is injected into the adjacent NiO and partially transmitted to the CoFeB layer, leading to a temperature change induced by thermo-spin effects. This temperature change was detected by employing the lock-in thermorefectance technique [7], with Si-O electrical insulation and Cr/Au transducer layers deposited on the CoFeB layer.

To assess spin current transmission through NiO, we evaluated the amplitude of temperature change normalized by the injected spin current density, A_{odd}/j_s . Interestingly, this transmission efficiency in epitaxial samples shows unconventional dependence on both t_{Pt} and t_{NiO} . A_{odd}/j_s exhibits a pronounced peak at $t_{\text{NiO}} = 10$ nm with increasing t_{NiO} in epitaxial samples, which is attributable to the enhanced antiferromagnetic ordering [3,7]. In contrast, polycrystalline samples display monotonic exponential decay with increasing t_{NiO} , reflecting the conventional magnon diffusion behavior. Furthermore, in epitaxial Pt(t_{Pt})/NiO(10 nm)/CoFeB films, A_{odd}/j_s as a function of t_{Pt} exhibits an exotic oscillation-like behavior, while remaining nearly constant in their polycrystalline counterparts. Given that the spin diffusion length in Pt (~ 1.5 nm) is much shorter than the minimum t_{Pt} of 5 nm used here, this behavior likely arises not from spin transport in Pt, but from modifications in the structural or magnetic properties of NiO influenced by the underlying Pt. We speculate that the magnetic domain structure of NiO, which critically affects spin current transmission, may vary with t_{Pt} due to Pt-induced strain.

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Tungsten-Mediated Interlayer Exchange Coupling System Revisited

IMR, Tohoku Univ.¹, CSIS, Tohoku Univ.², CMSM, NIMS³, RCS, Univ. Tokyo⁴, SRIS, Tohoku Univ.⁵

°X. Hou¹, K. Ito¹, V. K. Kushwaha¹, T. Yamazaki¹, J. Gu¹, S. Sakamoto^{1,2}, Z. Wen³, K. Masuda³,

J. Okabayashi⁴ and T. Seki^{1,2,5}

E-mail: hou.xueyao.c4@tohoku.ac.jp

The exchange interaction between ferromagnetic layers separated by a nonmagnetic layer, which is called the interlayer exchange coupling (IEC), leads to the antiparallel alignment of magnetization vectors for the adjacent ferromagnetic layers. Such artificial antiferromagnetic spin structure is well known as a synthetic antiferromagnet (SyAF). The SyAFs have attracted interest for its low magnetic susceptibility, no stray magnetic field, and high frequency dynamics coming from the antiferromagnetic resonance. These features allow us to develop next-generation spintronic devices with high storage density and fast operation speed. In the SyAF structure consisting of MgO/CoFeB/Ta/CoFeB/MgO, the Ta interlayer plays the roles of IEC and the generation of spin-orbit torque (SOT) originating from the spin Hall effect [1]. Considering that W also exhibits a high spin Hall angle [2], one may expect that a SyAF with the W interlayer is another candidate for improving the device performance. Nevertheless, there are very limited works on antiferromagnetic coupling (AFC) through the W layer [3-5], and the comprehensive study focusing on the IEC with W has not been carried out yet.

This study systematically investigates the IEC in CoFeB/W/CoFeB trilayers. Thin films with the stacking structure of Ta(2.0)/MgO(1.5)/CoFeB(1.8)/W(t_w)/CoFeB(1.8)/MgO(1.5)/Ta(1.5) (in nanometer) were deposited on thermally oxidized Si substrates using ultrahigh vacuum magnetron sputtering system at room temperature. t_w was varied in the range from 0 to 4.0 nm. The post-annealing was performed for all the samples at 340°C for 1 hour under vacuum pressure of less than 5×10^{-5} Pa.

The low remanent magnetization in both magnetization curves under the out-of-plane and in-plane magnetic field was observed for $t_w = 0.6 - 2.6$ nm. In addition, the clear spin-flip behavior was observed for the films with $t_w = 1.2 - 2.0$ nm, indicating the well-defined AFC. The detailed structural characterization, done by the transmission electron microscopy and reflection high-energy electron diffraction, suggests the change in the crystal structure in the W layer depending on the W layer thickness. This finding is also supported by the theoretical calculation and extended x-ray absorption fine structure (EXAFS) measurement. Additionally, we examined the spintronic function by measuring the transport properties for the microfabricated device with the thin W layer.

This work was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (A) (JP23H00232), MEXT Initiative to Establish Next-generation Novel Integrated Circuits Centers (X-NICS) Grant Number JPJ011438, and the collaborative work with TDK corporation.

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Spin current measurement using ST-FMR in epitaxial multilayer Fe/Ru/Co

○Y. Suzuki¹, T. Hattori¹, K. Hayashi¹, S. Iihama¹, T. Moriyama¹

(¹Department of Materials Physics, Nagoya Univ.)

E-mail: suzuki.yota.e5@s.mail.nagoya-u.ac.jp

Introduction

In recent years, altermagnets have been proposed as a new magnetic phase and are attracting attention [1]. They show magnetic structures in which spins are aligned antiparallel, like antiferromagnets. But, unlike antiferromagnets, they exhibit spin polarization due to peculiar crystalline symmetry associated with the magnetic structure. Active research is ongoing in order to understand the magnetic structures, band structures, and spin transport properties of candidate altermagnets such as RuO₂ [2]. In this study, we attempt to materialize synthetic altermagnets by magnetic multilayers and experimentally investigate their magnetic and electric properties and spin transport characteristics.

Methods

The multilayer samples consisting of Fe (1.5 nm) / Ru (t_{Ru} nm) / Co (1.8 nm) / Ta (3.0 nm) were deposited on MgO(110) single-crystal substrate using magnetron sputtering at various substrate temperatures. The crystal structure of each layer was characterized by in-situ reflection high-energy electron diffraction (RHEED). The interlayer exchange coupling was evaluated by magneto-optical Kerr effect (MOKE) measurements. The spin-torque ferromagnetic resonance (ST-FMR) measurement was performed to characterize the spin transport properties.

Results

Fig. 1 shows representative RHEED patterns of each layer surface. The Fe layer is grown epitaxially on the MgO substrate, and a two-fold symmetric pattern reflecting the crystal symmetry of the MgO(110) surface was observed. For the Co layer, epitaxial growth was degraded, and no clear rotational symmetry was seen in the pattern. In the multilayer with $t_{\text{Ru}} = 0.8$ nm, the magnetization curve showed a plateau in the low magnetic field region (Fig. 2), suggesting the presence of antiferromagnetic interlayer exchange coupling between the Fe and Co layers. The results indicate that while the magnetizations in Fe and Co layers maintain the antiferromagnetic coupling, the crystalline structures in the two layers are distinct, which is analogous to the altermagnets. In the presentation, we will discuss the spin transport properties measured by ST-FMR measurement.

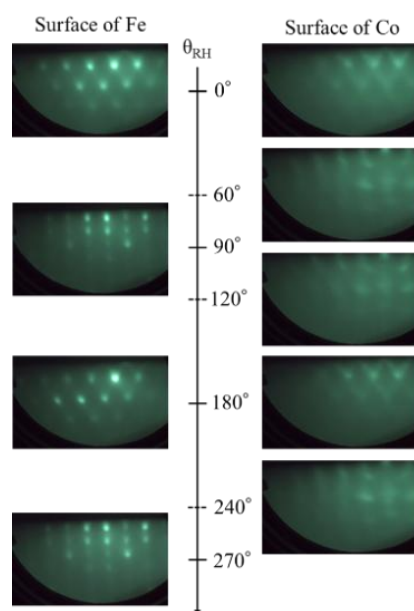


Fig.1 Surface observation results of the Fe and Co layers by RHEED.

θ_{RH} represents the in-plane angle of the sample.

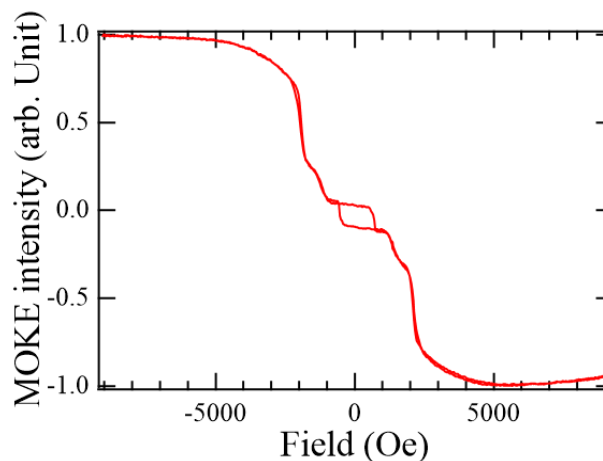


Fig.2 Magnetization measurement results of Fe (1.5 nm) / Ru (t_{Ru} nm) / Co (1.8 nm) / Ta (3.0 nm) measured by magneto-optical Kerr effect (MOKE).

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Spin-orbit torque in sputtered W-Te/Ru/CoFeB thin film

○Yukihiro Marui¹, Hideo Ohno^{1,2,3,4}, Shunsuke Fukami^{1,2,3,4,5,6}

RIEC, Tohoku Univ.¹, WPI-AIMR, Tohoku Univ.², CSIS, Tohoku Univ.³, CIES, Tohoku Univ.⁴,

Graduate School of Engineering, Tohoku Univ.⁵, Inamori Research Institute for Science⁶

E-mail: yukihiro.marui.e8@tohoku.ac.jp

Spin-orbit torque (SOT), a current-induced torque observed in nonmagnet (NM)/ferromagnet (FM) bilayers, has been extensively studied not only from a fundamental perspective but also for its potential in efficiently controlling magnetization [1-3] for nonvolatile memory and neuromorphic computing applications. Large SOT is known to arise when the NM layer consists of heavy metals such as β -W due to their strong spin-orbit coupling [4]. Recently, type-II Weyl semimetals have been shown to generate unconventional SOT in terms of the torque direction [5]. WTe₂ is a representative example, exhibiting both the unconventional characteristics and high SOT generation efficiency [6]. However, most previous studies have used samples prepared by exfoliation or molecular beam epitaxy. The properties of sputtered WTe₂/CoFeB films on silicon substrates—more relevant for practical applications—remain insufficiently explored.

In this work, we deposit W-Te/Ru/CoFeB thin films on thermally oxidized silicon substrates using DC/RF magnetron sputtering and evaluate their effective spin Hall conductivity, a parameter representing the efficiency to generate SOT per unit current density, via the harmonic Hall technique (Fig. 1) [7,8]. We investigate the effects of the W-Te composition and underlayer materials on both the thermal durability and the magnitude of the effective spin Hall conductivity. We find that the choice of underlayer significantly influences the properties of the W-Te layer and resultant effective spin Hall conductivity σ_{SH} (Fig. 2). We also fabricate W/Ru/CoFeB as a reference of conventional materials and compare the results with W-Te/Ru/CoFeB. Detailed findings will be discussed in the talk. The results offer new insights into the potential application of Weyl metals in practical spintronic devices.

We thank F. Shibata, R. Nomura, H. Sasaki, and S. Suzuki for their technical support. This work is partly supported by JSPS Kakenhi 23K19109 and MEXT X-NICS JPJ011438.

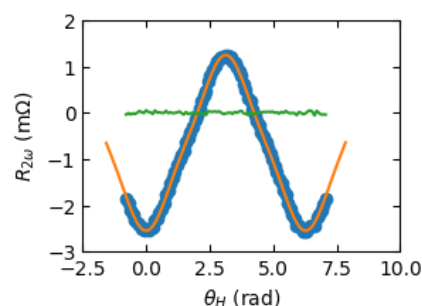


Fig.1 Angle dependent harmonic Hall resistance

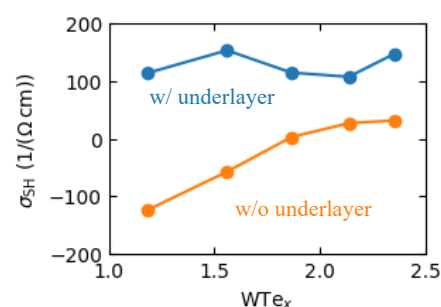


Fig. 2 Effective spin Hall conductivity as a function of W-Te composition

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Large spin Hall effect in BiSb topological insulator and perpendicularly magnetized CoFeB heterojunctions with oxide buffer and interfacial layers

¹Institute of Science Tokyo, ²Samsung Japan Corp.

^oP. V. Thuan¹, H. H. Huy¹, L. Wentao¹, S. Takahashi², Y. Kato², S. Hirayama², P. N. Hai¹

E-mail: pham.v.ac@m.titech.ac.jp

BiSb topological insulator has emerged as a promising candidate for the spin-orbit torque (SOT) layer in ultrafast [1] and ultralow power [2] SOT-MRAM devices thanks to its giant spin Hall angle (θ_{SH}) and high electrical conductivity σ [3]. Despite showing large θ_{SH} in BiSb/CoFeB heterojunctions deposited on sapphire substrates with a metallic Ti or Ru interlayer [4], BiSb can be lost during the high-temperature annealing due to its low melting point. Thus, an appropriate interfacial layer between BiSb and CoFeB that can prevent thickness loss during the high-temperature annealing process is necessary to reach the full potential of BiSb for practical SOT-MRAM applications.

In this study, we aim to realize BiSb / perpendicularly magnetized CoFeB heterojunctions with high θ_{SH} on thermally oxidized Si/SiO₂ substrate after 300°C high temperature post annealing by using oxide buffer and interfacial layers. Fig. 1(a) shows the full structure of our stacks and the annealing sequences. We first deposited TiO_x (25 nm)/TaO_x (5nm) buffer layers to suppress oxygen diffusion from the substrates and to enhance the crystallinity of BiSb. Then, a 10-nm thick BiSb was sputtered followed by a 1 nm TiO_x or TaO_x interfacial layer specially designed to prevent loss of BiSb during post-annealing at 300°C for 1 hour. Here, the oxide buffer and interfacial layers are insulating and thus helpful for reducing shunting currents. We then deposited Ta (1 nm)/CoFeB (1 nm)/MgO (2.5 nm)/Ta (2 nm) multilayers. Finally, the stacks underwent another annealing process at 250°C for 30 minutes to crystallize CoFeB and to achieve perpendicular magnetic anisotropy (PMA), as shown in Figs. 1(b) and 1(c). We found large $\theta_{SH}^{eff} > 4$ in the stacks from the second harmonic Hall measurements as shown in Figs. 1(d) and 1(e). By comparing X-ray fluorescence spectra of BiSb before and after annealing, we estimate that the BiSb thickness was reduced to approximately 9.3 nm, suggesting good protection of BiSb by the oxide interfacial layer. Thus, the combination of TiO_x/TaO_x buffer and TiO_x or TaO_x interfacial layers can prevent BiSb loss and current shunting, which are crucial for realizing high-performance SOT characteristics.

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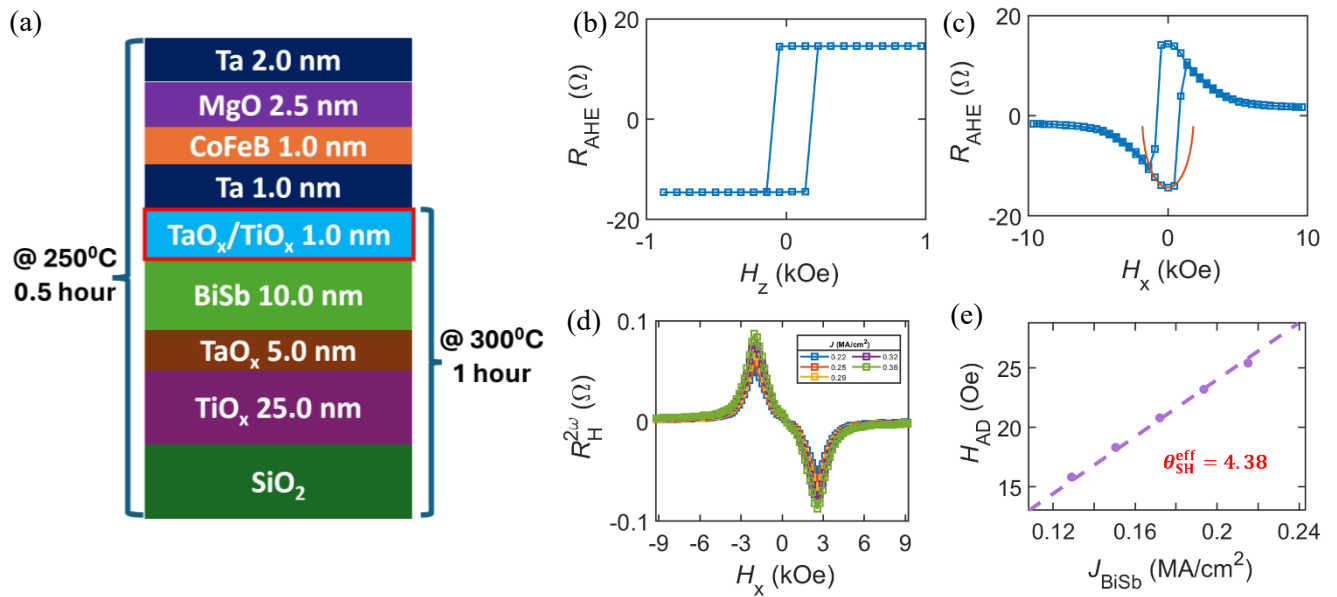


Fig. 1. (a) The schematic of our stacks. (b)(c) Anomalous Hall resistance measured in a 20×60 μm² Hall bar with a perpendicular and in-plane magnetic field, respectively. (d) Second harmonic Hall resistance and (e) antidampinglike SOT field as a function of BiSb current density.

リン添加白金を利用した低消費電力スピントルク磁化反転

Evaluation of Spin-Orbit Torque-Driven Magnetization Switching Using Phosphorus-Ion-Implanted Platinum

九州工業大¹, 豊田工業大², 山口大³, [○](M1)新宅 千輝¹, マッシュウ アルン ジャコブ¹,
(M2)岩本 輝久¹, モハマディ モジタバ², 栗野 博之², 浅田 裕法³, 福岡 康裕¹

Kyushu Inst. Tech.¹, Toyota Tech. Inst.², Yamaguchi Univ.³, [○]K. Shintaku¹, A. J. Mathew¹,

A. Iwamoto¹, M. Mohamadi², H. Awano², H. Asada³, Y. Fukuma¹

E-mail: kshintaku@fukuma-lab.info

次世代の磁気ランダムアクセスメモリ (MRAM) の実現に向けて、スピンホール効果(SHE)等から生成されたスピン流を利用したスピントルク(SOT)磁化反転が注目されている。SOT の大きさは、電流をスピン流へと変換する指標であるスピンホール角 θ_{SHE} に強く依存する。最近、リンイオンを注入した白金 Pt(P)ではスピンホール角 θ_{SHE} が従来の Pt の 0.034 から 1.17 に約 34 倍に増大することが報告されている[1]。本研究では、この Pt(P)からの SOT を利用してフェリ磁性体 $\text{Gd}_{26}\text{Fe}_{74}$ (GdFe)の磁化反転実験を行った[2]。試料は Si/SiO₂ 基板上に Pt(10 nm)をスパッタ成膜し、加速電圧 30 keV で P イオンを照射密度 $d = 5 \times 10^{16}$ ions/cm² と $d = 10 \times 10^{16}$ ions/cm² を注入後 Pt(1 nm)/GdFe(20 nm)/SiN(10 nm)をスパッタ成膜し、横 10 μm 、縦 10 μm のホールバー形状へ加工した。

第二高調波ホール測定から θ_{SHE} を見積ると、 $d = 0$ で $\theta_{\text{SHE}} = 0.06$ 、 $d = 5 \times 10^{16}$ ions/cm² で $\theta_{\text{SHE}} = 0.19$ 、 $d = 10 \times 10^{16}$ ions/cm² で $\theta_{\text{SHE}} = 0.43$ であった。次に、SOT 磁化反転実験ではまず磁化を面直方向 $\pm z$ に初期化し、面内アシスト磁場 $H_x = \pm 50$ mT を印加した状態で書き込み電流を掃引しつつ読み出し電流 1 mA で異常ホール電圧 V_{Hall} を測定した。 V_{Hall} が符号反転する点を臨界電流密度 J_{sw} と定義した。さらに、書き込み電流のパルス幅を $t_{\text{pw}} = 500$ μs から 500 ns に変化させ、 J_{sw} のパルス幅依存性を調べた。図 1 に示すように、得られた臨界電流密度 J_{sw} を熱活性モデルでフィッティングした結果、ゼロ温度電流密度 J_0 は 75%低減し、熱安定性係数 Δ は 2%の変化にとどまった。

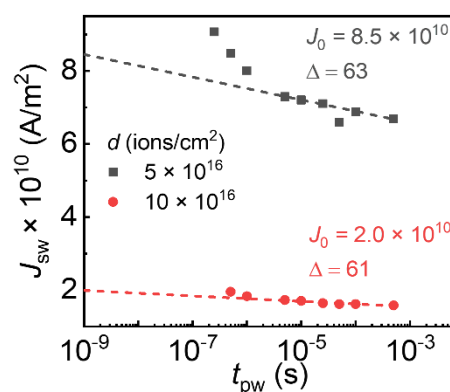


Figure 1: J_{sw} as a function of pulse width t_{pw} for different d .

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Electrical mutual switching in a noncollinear-antiferromagnetic–ferromagnetic heterostructure

Ju-Young Yoon^{1,2}, Yutaro Takeuchi^{1,3}, Ryota Takechi^{1,2}, **Jiahao Han**^{1,4*}, Tomohiro Uchimura^{1,2}, Yuta Yamane^{1,5}, Shun Kanai^{1,2,4,6,7,8,9}, Jun'ichi Ieda¹⁰, Hideo Ohno^{1,2,4,8,11}, and Shunsuke Fukami^{1,2,4,8,11,12}

¹RIEC, Tohoku Univ. ²Grad School of Eng., Tohoku Univ. ³RCMSM, NIMS. ⁴AIMR, Tohoku Univ. ⁵FRIS, Tohoku Univ. ⁶PRESTO, JST. ⁷DEFS, Tohoku Univ. ⁸CSIS, Tohoku Univ. ⁹QST. ¹⁰ASRC, JAEA. ¹¹CIES, Tohoku Univ. ¹²InaRIS.

*Presenter email: jiahao.han.c8@tohoku.ac.jp

Spin-orbit torque (SOT) provides a promising mechanism for electrically encoding information in magnetic states. Unlike existing schemes, where the SOT is passively determined by the material and device structures, an active manipulation of the intrinsic SOT polarity would allow for flexibly programmable SOT devices. Achieving this requires electrical control of the current-induced spin polarization of the spin source. In this study, we demonstrate a proof-of-concept current-programmed SOT device. Using a noncollinear-antiferromagnetic/nonmagnetic/ferromagnetic (NCAFM/NM/FM) $\text{Mn}_3\text{Sn}/\text{Mo}/\text{CoFeB}$ heterostructure at zero magnetic field, we show current-induced switching in the CoFeB layer due to the spin current polarized by the magnetic structure of the Mn_3Sn ; by properly tuning the driving current, the spin current from the CoFeB further reverses the magnetic orientation of the Mn_3Sn , which determines the polarity of the subsequent switching of the CoFeB (Fig. 1). This scheme of mutual switching can be achieved in a spin-valve-like simple protocol because each magnetic layer serves as a reversible spin source and target magnetic electrode. It yields intriguing proof-of-concept functionalities for unconventional logic and neuromorphic computing [1].

A portion of this work is supported by JSPS Kakenhi (Nos. 19H05622, 21J23061, 22KF0035, 22K14558, 24K16999, 24K22949, 24H00039, and 24H02235), MEXT Initiative to Establish Next-generation Novel Integrated Circuits Centers (X-NICS) (Grant No. JPJ011438), Iketani Science and Technology Foundation (No. 0331108-A), Casio Science and Technology Foundation (No. 39-11 and 40-4), and RIEC Cooperative Research Projects.

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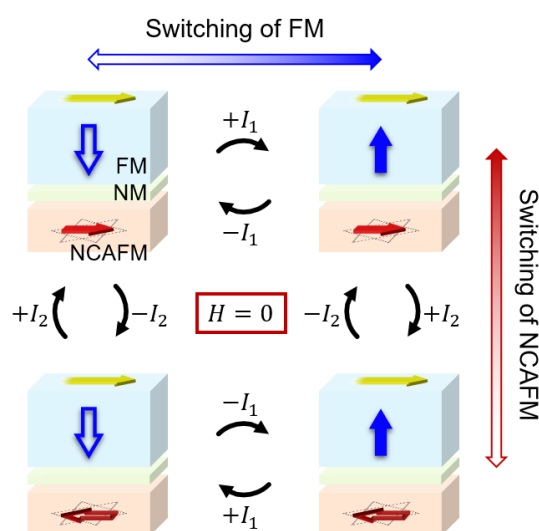


Fig. 1. Illustration of the electrical mutual switching in NCAFM/NM/FM stacks: switching of FM at current I_1 and switching of NCAFM at current I_2 ($I_2 > I_1$) in the absence of magnetic field.

Current-induced switching in epitaxial Mn_3Sn thin films: A temperature dependent study

K. Nihei^{1,2}, T. Uchimura^{1,2}, J. Han^{1,3}, S. Kanai¹⁻⁷, H. Ohno^{1-4,8}, and S. Fukami^{1-4,8,9}

RIEC, Tohoku Univ.¹, Graduate School of Engineering, Tohoku Univ.², AIMR, Tohoku Univ.³,
CSIS, Tohoku Univ.⁴, PRESTO, JST⁵, DEFS, Tohoku Univ.⁶, QST⁷, CIES, Tohoku Univ.⁸, InaRIS⁹

Presenter e-mail: nihei.kota.s3@dc.tohoku.ac.jp

Current-induced spin-orbit torques (SOTs) offer an efficient mechanism to switch the non-collinear antiferromagnetic order in Mn_3Sn [1]. While the switching experiments in epitaxial Mn_3Sn films can be consistently understood by the SOT-driven spin dynamics [2–4], some studies with polycrystalline Mn_3Sn films reveal a significant role of Joule heating [5–7], suggesting that the switching process involves a step that heats the sample close to or above the Néel temperature (T_N) of Mn_3Sn [5].

Here we evaluate the role of SOT and Joule heating from the temperature (T) dependence of current-induced switching in the $(10\bar{1}0)$ -oriented epitaxial Mn_3Sn adjacent to heavy metal W/Ta (Fig. 1a). From the switching loops (Fig. 1b), we extract the switching current I_{sw} at different T (red dots in Fig. 1c). By comparing the sample resistance as functions of T and current, we calibrate the current-induced temperature rise and, accordingly, determine $I(T \rightarrow T_N)$, the threshold current that heats the sample to the Néel temperature (black dots in Fig. 1c). We find that I_{sw} is well below $I(T \rightarrow T_N)$ at 140–300 K, indicating that the sample maintains the non-collinear antiferromagnetic order during the switching. Our results suggest the persistent role of SOT and less dominant role of Joule heating in epitaxial Mn_3Sn films than polycrystalline samples.

A portion of this study was supported by JSPS KAKENHI (Grant Nos. 23KJ0216, 24K16999, 24H00039, and 24H02235) and the MEXT X-NICS (Grant No. JPJ011438).

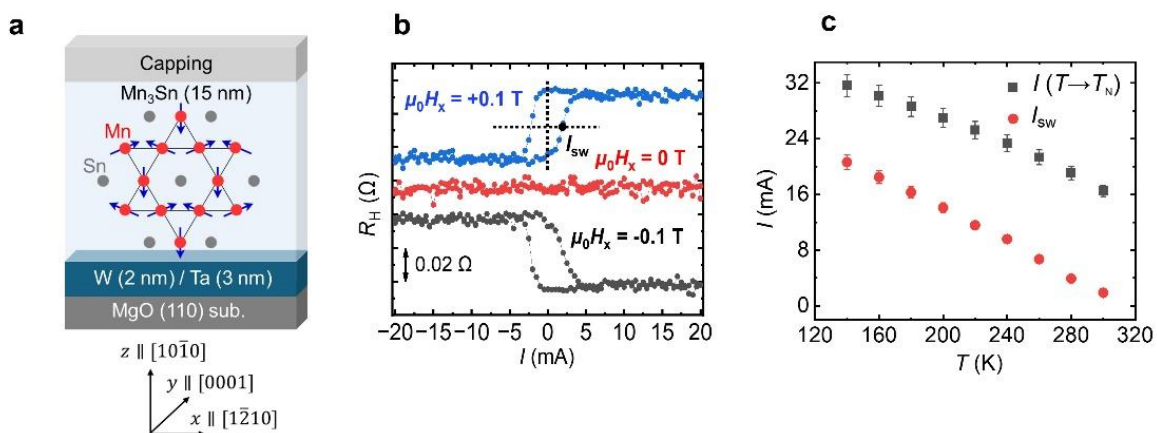


Fig. 1. (a) Sample structure. (b) Hall resistance R_H as a function of the applied pulse current under different magnetic fields at 300 K. The current and the magnetic field are along the x axis. (c) Temperature dependence of the switching current I_{sw} and the current that heats the sample to the Néel temperature, $I(T \rightarrow T_N)$.

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Pulse width dependence of spin-orbit torque switching in noncollinear antiferromagnetic Mn₃Sn nanodot

[○](D)Y. Sato,^{1,2} Y. Takeuchi,^{3,4} Y. Yamane,^{1,5} S. Kanai,^{1,2,4,6,8,9} H. Ohno,^{1,4,6,7} and S. Fukami^{1,2,4,6,7,10}

¹Laboratory for Nanoelectronics and Spintronics, RIEC, Tohoku Univ., ²Graduate School of Engineering, Tohoku Univ. ³CMSM, NIMS, ⁴WPI-AIMR, Tohoku Univ., ⁵FRIS, Tohoku Univ., ⁶CSIS, Tohoku Univ.

⁷CIES, Tohoku Univ., ⁸EFS, Tohoku Univ., ⁹QST, ¹⁰Inamori Research Institute for Science

Email: sato.yuma.q5@dc.tohoku.ac.jp

Manipulating spins in antiferromagnets (AFMs) is crucial for the AFM-based technologies [1,2]. In a noncollinear AFM Mn₃Sn, bidirectional switching by spin-orbit torque (SOT) has been reported for epitaxial [3,4] and polycrystalline [5,6] films. In epitaxial films, a competition between the chiral-spin rotation driven by the current [3] and the reorientation of the uncompensated magnetization caused by the magnetic field has been attributed as the underlying mechanism of the switching [4]. Here, we report the unconventional current pulse-width τ_p dependence of the threshold currents in an Mn₃Sn nanodot.

We fabricate an epitaxial Mn₃Sn(20nm) nanodot [7] on the Ta(3nm)/W(2nm) channel grown on the MgO(110) substrate [Fig. 1(a) and (b)]. Figure 1(c) shows the switching probability (P) versus current density into the W/Ta layer (J_{HM}), with τ_p of 5 ms, under an in-plane field $\mu_0 H_{[11\bar{2}0]}$ of 100 mT. We find that, with a given τ_p , P initially increases with current density into the W/Ta layer J_{HM} , reaches the unity, and then starts decreasing upon further increasing J_{HM} . We define two threshold current densities: J_{c1} and J_{c2} at which P hits 0.5 in the switching process and 0.75 in the switching-back process, respectively. J_{c1} decreases with τ_p , which can be understood in a straightforward manner: the Mn₃Sn nanodot is exposed to the thermal fluctuation for a longer time with a longer τ_p , hence a better chance of completing the switching at a lower J_{HM} with the thermal assistance. In contrast, J_{c2} is insensitive to τ_p , which defies a simple interpretation with no similar phenomenon known in ferromagnets. The observed behavior is reproduced well by LLG simulations. In this presentation, we discuss potential mechanism of the unconventional switching behavior. Our findings provide new insights into the dynamics of noncollinear antiferromagnets and open up prospects for novel functionalities in SOT-driven AFM devices.

This work was partly supported by JSPS Kakenhi, JST-PRESTO, MEXT X-NICS, and RIEC Cooperative Research Projects.

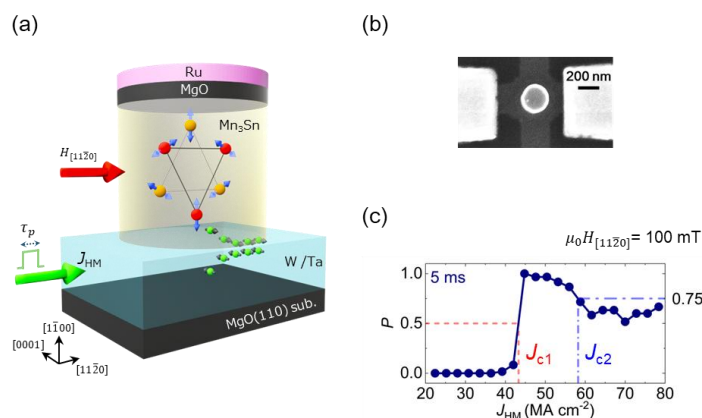


Fig.1 (a) Schematic of the switching measurement of Hall device with a Mn₃Sn nanodot. (b) The scanning electron microscope image of the fabricated device. The nominal dot diameter is 200 nm. (c) P versus J_{HM} for τ_p of 5 ms.

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Unconventional spin Hall magnetoresistance in a non-collinear antiferromagnet/heavy metal heterostructure

T. Uchimura^{1,2}, J. Han^{1,3}, P. Tang³, J.-Y. Yoon¹, Y. Takeuchi³, Y. Yamane^{1,4}, S. Kanai^{1,2,3,5,6,7,8},

G. E. W. Bauer^{3,7,9,10}, H. Ohno^{1,2,3,7,11}, and S. Fukami^{1,2,3,7,11,12}

¹RIEC, Tohoku Univ., ²Graduate School of Engineering, Tohoku Univ., ³WPI-AIMR, Tohoku Univ., ⁴FRIS, Tohoku Univ., ⁵PRESTO, JST, ⁶DEFS, Tohoku Univ., ⁷CSIS, Tohoku Univ., ⁸QST, ⁹IMR, Tohoku Univ., ¹⁰Kavli ITS, UCAS, ¹¹CIES, Tohoku Univ. ¹²InaRIS

E-mail: uchimura.tomohiro.s8@dc.tohoku.ac.jp

The spin Hall magnetoresistance (SMR) in antiferromagnet/heavy metal (AFM/HM) heterostructures helps to understand the interaction between spin current and the antiferromagnetic order [1,2]. Here we present a combined experimental and theoretical study that reveals an unconventional SMR in a non-collinear AFM/HM heterostructure.

We deposited stacks of Ru (5 nm)/Mn₃Sn (15 nm)/Pt (5 nm) on MgO(111) substrates by sputtering, followed by annealing at 500 °C. This procedure leads to the formation of (0001)-oriented epitaxial Mn₃Sn thin film in which the non-collinear spin structure aligns in the film plane [Fig. 1(a)].

Figure 1(b) shows the magnetoresistance (MR) ratio ($= [R(\theta_{xy}) - R(\theta_{xy} = 0^\circ)] / R(\theta_{xy} = 0^\circ)$) under an in-plane rotating magnetic field of 9 T, where R denotes the longitudinal resistance. The MR reaches its maximum (minimum) when the field is parallel (perpendicular) to the current direction, similar to the SMR in ferromagnets [3] but phase-shifted by 90° compared to that in collinear AFMs [1,2]. We find that the conventional SMR theory that focuses on the *damping-like* spin-transfer torque [1,2,4] fails to reproduce the measured angle dependence of Fig. 1(b). Instead, the obtained angle dependence can be explained by a Boltzmann transport theory considering the *field-like* torque, i.e., a conduction electron spin precession around the interface exchange fields of the local magnetic moments. These results can be attributed to the ineffective action of *damping-like* torque on non-collinear spin textures in the studied configuration, leading to the emergence of a previously ignored *field-like* torque as the dominant origin of SMR. The unraveled physics provides a new insight to engineer spintronic devices based on AFMs [5].

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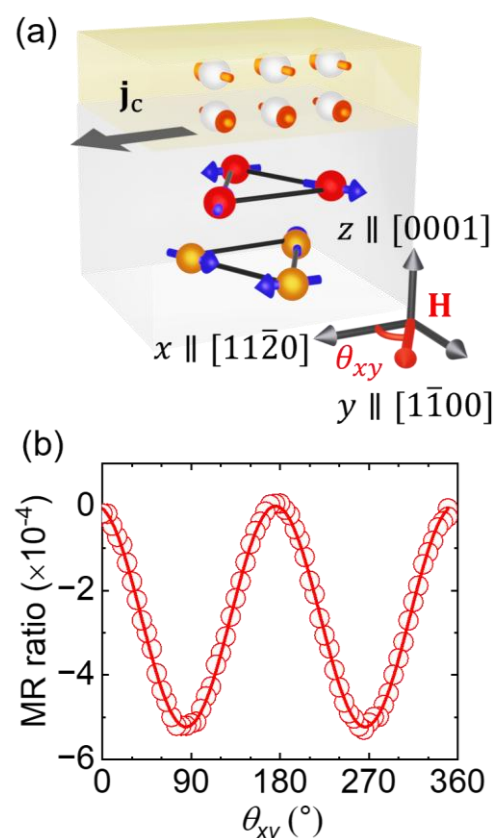


Fig. 1. (a) Schematic of angle-dependent MR measurement in (0001)-oriented Mn₃Sn/Pt. (b) Longitudinal MR as a function of the magnetic field angle θ_{xy} . Magnetic field of 9 T is applied within the film plane.

10 Spintronics and Magnetism Oral presentation : 10.3 Spin devices, magnetic memories and storages
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[9a-N303-1~9] 10.3 Spin devices, magnetic memories and storages

[9a-N303-1]

Ferromagnetic resonance in Magnetic Tunnel Junction with Pseudo Spin Valve Structure for Energy Harvesting

○(M2)Kazunari Kino^{1,2}, Takaaki Dohi¹, Harumi Chiku^{1,2}, Takanobu Shinoda^{1,2}, Shun Kanai^{1,2,3,4,5,6,7}, Hideo Ohno^{1,3,4,8}, Shunsuke Fukami^{1,2,3,4,8,9} (1.RIEC, Tohoku Univ, 2.Tohoku Univ., 3.WPI-AIMR, Tohoku Univ., 4.CSIS, Tohoku Univ., 5.PRESTO, JST, 6.DEFS, Tohoku Univ., 7.QST, 8.CIES, Tohoku Univ., 9.InaRIS)

[9a-N303-2]

Extremely Sensitive Tunnel Magneto-resistive Sensor Using Magnetic Vortex Structures

○(D)Seiya Takano¹, Takafumi Nakano^{1,3}, Takahide Kubota¹, Kosuke Fujiwara⁴, Seiji Kumagai⁴, Hitoshi Matsuzaki⁴, Satoshi Sasaki⁵, Yutaka Higo⁵, Lui Sakai⁵, Masanori Hosomi⁵, Mikihiro Oogane^{1,2} (1.Graduate School of Engineering, Tohoku Univ., 2.CSIS, Tohoku Univ., 3.Research Center for Green X-Tech, Tohoku Univ., 4.Spin Sensing Factory Corporation, 5.Sony Semiconductor Solutions)

[9a-N303-3]

Electronic and Magnetic States of Insulator/Co₂MnSi Interfaces Studied by Hard X-ray Photoelectron Spectroscopy

○Shigenori Ueda¹, Yuichi Fujita¹, Yuya Sakuraba¹ (1.NIMS)

[9a-N303-4]

Theoretical and experimental studies for understanding the TMR oscillation

○Keisuke Masuda¹, Thomas Scheike¹, Hiroaki Sukegawa¹, Yusuke Kozuka¹, Seiji Mitani¹, Yoshio Miura^{1,2} (1.NIMS, 2.KIT)

[9a-N303-5]

First-principles study of hcp-Co_{1-x}Ni_x|h-BN|hcp-Co_{1-x}Ni_x magnetic tunnel junction

○(PC)Ivan Kurniawan¹, Keisuke Masuda¹, Yoshio Miura^{1,2} (1.NIMS, 2.Kyoto Inst. Tech.)

[9a-N303-6]

Power generation in ferromagnetic FePt thin films using electromagnetic wave absorption

○Taketo Hirata¹, Qing Bowen¹, Miyamachi Toshio¹, Mizuguchi Masaki¹ (1.Nagoya Univ)

[9a-N303-7]

Fabrication and Characterization of Co-Pt Multilayer Nanowires Prepared by Dual-bath Electrodeposition

○(M2)Rio Kawana¹, Natsuko Oguchi¹, Daiki Oshima², Michiyuki Yoshida¹, Takashi Sugiura¹, Mikiko Saito³, Takayuki Homma³, Takeshi Kato², Teruo Ono⁴, Mutsuhiro Shima¹, Keisuke Yamada¹ (1.Gifu Univ., 2.Nagoya Univ., 3.Waseda Univ., 4.Kyoto Univ.)

[9a-N303-8]

In-Plane Magnetic Property Control and Nonvolatility of CoFeB via Ferroelectric Polarization

○Yan Wu^{1,2}, K. Onimura¹, H. Kobayashi², K. Kakushima^{1,2} (1.Eng. of Science Tokyo, 2.Sumitomo Chemical Next-Generation Eco-Friendly Devices Collaborative Research Cluster, of Science Tokyo)

[9a-N303-9]

Efficient spin-charge conversion at room temperature from 2DEGs in ferroelectric BaTiO₃ films

○Bibes Manuel¹ (1.Lab. Albert Fert)

Ferromagnetic resonance in Magnetic Tunnel Junction with Pseudo Spin Valve Structure for Energy Harvesting

(M2) K. Kino^{1,2}, H. Chiku^{1,2}, T. Dohi¹, T. Shinoda^{1,2}, S. Kanai¹⁻⁷, H. Ohno^{1,3,4,8}, and S. Fukami^{1-4,8,9}

¹Lab. for Nanoelectronics and Spintronics, RIEC, Tohoku Univ.,

²Graduate School of Engineering, Tohoku Univ., ³WPI-AIMR, Tohoku Univ.,

⁴CSIS, Tohoku Univ., ⁵PRESTO, Japan Science and Technology Agency (JST),

⁶DEFS, Tohoku Univ., ⁷National Institutes for QST,

⁸CIES, Tohoku Univ., ⁹Inamori Research Institute for Science

E-mail: kino.kazunari.p4@dc.tohoku.ac.jp

Ambient wireless signals can be a potential source of energy harvesting for reducing the carbon footprint. Previous studies demonstrated that magnetic tunnel junctions (MTJs) can be engineered to harvest energy from 2.4 GHz WiFi signals through the ferromagnetic resonance (FMR) [1,2]. Nevertheless, enhancing the conversion efficiency from rf input to dc output remains a key challenge for practical use. To this end, this study employs MTJs with a pseudo-spin-valve (PSV) structure (Fig. 1(a)). The PSV MTJs are known to show higher tunneling magnetoresistance (TMR) [3] than the spin-valve (SV) MTJs used in the previous work (Fig. 1(b)) [1,2], showing promise for higher conversion efficiency.

PSV and SV MTJs are deposited by sputtering and annealed at 450°C and 300°C, respectively, in a vacuum. The inset of Fig. 1(c) shows the TMR ratios of the PSV and SV MTJs as a function of magnetic field, indicating that the TMR ratio of the PSV MTJ is higher than that of the SV MTJ. We investigate the rectified voltage through the FMR [4]. Figure 1(c) shows the maximum voltage vs. input rf power. We find that the PSV MTJs exhibit significantly higher sensitivity, which can be attributed to the higher TMR ratio. This work provides a route for improving the conversion efficiency for wireless signals energy harvesting applications.

We thank H. Yang, R. Sharma, and A. Jiang of the Nat'l Univ. Singapore for fruitful discussion. This work was partly supported by JSPS Kakenhi and MEXT X-NICS.

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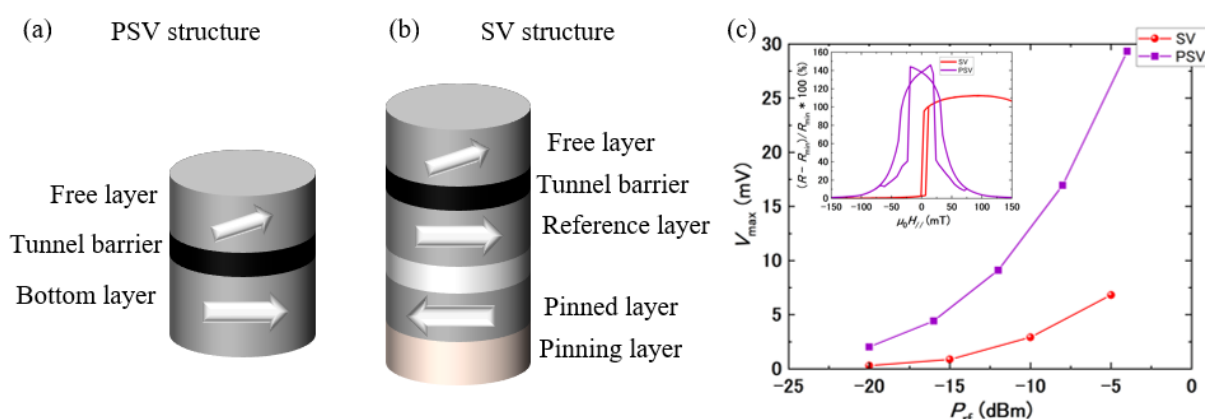


Fig. 1(a) PSV and (b) SV structures. Arrows indicate magnetization directions in each layer. (c) The maximum rectified voltage ($V_{\max}$) dependence on input rf power (P_{rf}) at 2.5 GHz. The purple and red plots represent results for PSV and SV, respectively. The inset in (c) shows the TMR ratio of PSV and SV as a function of magnetic field.

Extremely Sensitive Tunnel Magneto-resistive Sensor Using Magnetic Vortex Structures

¹Graduate School of Engineering, Tohoku Univ., ²CSIS, Tohoku Univ., ³Research Center for Green X-Tech, Green Goals Initiative, Tohoku Univ., ⁴Spin Sensing Factory Corporation, ⁵Sony Semiconductor Solutions.

[○]Seiya Takano¹, Takafumi Nakano^{1,3}, Takahide Kubota¹, Kosuke Fujiwara⁴, Seiji Kumagai⁴, Hitoshi Matsuzaki⁴, Satoshi Sasaki⁵, Yutaka Higo⁵, Lui Sakai⁵, Masanori Hosomi⁵, and Mikihiro Oogane^{1,2}

* E-mail: seiya.takano.t5@dc.tohoku.ac.jp

Tunnel magnetoresistance (TMR) sensors utilizing magnetic tunnel junctions (MTJs) are high-sensitivity magnetic sensors capable of operating at room temperature [1]. The sensitivity is defined as $\text{TMR ratio}/2H_s$ [%/Oe], where H_s is saturation field. Thus, the sensitivity can be enhanced by either increasing TMR ratio or decreasing H_s . In previous work, it was reported that miniaturizing the pinned layer increases sensitivity in vortex-based TMR sensors because a smaller pinned layer size reduces the effective H_s at which the magnetic vortex core moves to the outside of the pinned layer [2]. We fabricated the vortex-based TMR sensors with 2 $\mu\text{m}\phi$ pinned layer and a 10 $\mu\text{m}\phi$ free layer, achieving a reduction in H_s from 156 Oe down to 31 Oe and a sensitivity increase up to 4.4 %/Oe. In this work, we aim to realize nanometer-scale pinned layer for further sensitivity enhancement.

We deposited a multilayered MTJ film on a thermally oxidized Si substrate, consisting of Ta(5)/Ru(40)/Ta(5)/CoFeSiB(70)/Ta(0.2)/CoFeB(3)/MgO/CoFeB(3)/TaB(0.1)/CoFe(0.8)/Ru(0.8)/CoFe(3)/IrMn(10)/Ta(2)/Ru(7) (nominal thickness in nm) by magnetron sputtering. We microfabricated the film as free layer's diameter is $2R_b$ is 10 $\mu\text{m}\phi$ and pinned layer's diameter $2r_t$ is 40-100 nm ϕ . Subsequently, we conducted magnetic annealing process with 1T in plane magnetic field and TMR properties were measured by dc two-probe method.

We observed that H_s decreased and sensitivity increased as the pinned layer became smaller. As a result, for the smallest pinned layer of 80 nm ϕ , vanishingly small H_s of 0.28 Oe and extremely high sensitivity of 268 %/Oe were achieved within a magnetic field range of ± 0.3 Oe. Moreover, the minor-loop magnetic conductance curves exhibited low coercivity and small hysteresis in the minor loop coming from a reversible the vortex magnetization. These results demonstrate that our approach is promising for realizing highly sensitive and precise magnetic-field measurements.

This research was supported by the SIP Project, BRIDGE Project, X-nics Project, GP-Spin, CSIS, and CIES from Tohoku University.

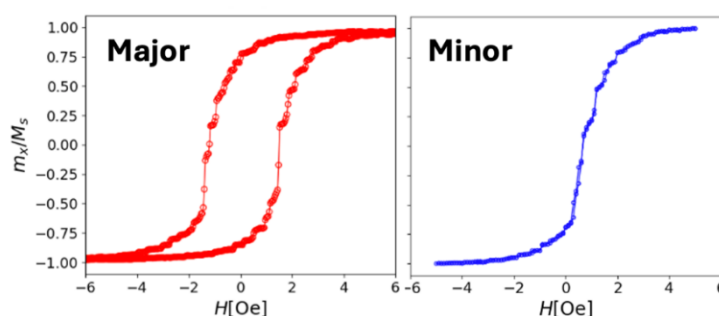


Fig. 1 Major and minor Δm_x - H_x curves for an MTJ of 80nm ϕ

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硬 X 線光電子分光による絶縁体/Co₂MnSi 界面の電子状態と磁気状態

Electronic and Magnetic States of Insulator/Co₂MnSi Interfaces Studied by

Hard X-ray Photoelectron Spectroscopy

NIMS ○上田 茂典, 藤田 裕一, 桜庭 裕弥

NIMS, °Shigenori Ueda, Yuichi Fujita, Yuya Sakuraba

E-mail: UEDA.Shigenori@nims.go.jp

フェルミ準位でのスピン偏極度が 100%であるハーフメタルは、伝導に寄与する電子が完全にスピン偏極しているため、スピントロニクスへの応用が期待されている。我々は、ハーフメタル候補物質の 1 つである Co₂MnSi に対してバルク敏感スピン分解硬 X 線光電子分光 (HAXPES)を実施し、バルク領域の Co₂MnSi は 20 K でフェルミ準位のスピン偏極度が~90%を示し、少なくとも 300 K まではスピン偏極度に温度依存性が生じていないことを明らかにしている[1]。この結果から、少なくとも Co₂MnSi を用いた巨大磁気抵抗素子やトンネル磁気抵抗素子で見られる昇温に伴う磁気抵抗比の減少[2]を、バルクのスピン偏極度からは説明できない。そのため、素子界面近傍に着目した電子状態、磁気状態の測定が必要であるものと考えられる。

本研究では、絶縁体(AlO_x, MgO)/Co₂MnSi 界面の電子状態と磁気状態をバルク領域の Co₂MnSi と比較するために、SPring-8 BL15XU にて X 線全反射を利用した HAXPES 測定($h\nu=5.95$ keV, $\Delta E=140$ meV)を室温にて行った[3]。全反射条件で界面近傍を、非全反射条件でバルク領域の磁気状態を磁気円二色性 HAXPES から測定した結果、界面近傍での Co と Mn の磁化はバルク領域の 0.77 倍になっていることが明らかとなった。この磁化の減少は、界面における磁気モーメント間の交換相互作用の減少に伴うスピン波励起で説明できる[4]。また、フェルミ準位近傍の価電子帯スペクトルにおいても、界面近傍とバルク領域の電子状態に僅かな差異が見られた。講演では、スピン波励起をスピンの揺らぎとして取り扱った理論計算[5]と比較し、界面近傍とバルク領域の Co₂MnSi の電子状態と磁気状態の議論を行う。

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TMR 振動の理解に向けた理論・実験的アプローチ

Theoretical and experimental studies for understanding the TMR oscillation

NIMS¹, 京都工繊大²○増田 啓介¹, Scheike Thomas¹, 介川 裕章¹, 小塚 裕介¹, 三谷 誠司¹, 三浦 良雄^{1,2}NIMS¹, KIT²○K. Masuda¹, T. Scheike¹, H. Sukegawa¹, Y. Kozuka¹, S. Mitani¹, and Y. Miura^{1,2}

E-mail: MASUDA.Keisuke@nims.go.jp

Tunnel magnetoresistance (TMR) oscillation is a phenomenon that the TMR ratio oscillates as a function of the thickness of the insulating barrier layer of the magnetic tunnel junction (MTJ). Since the first observation by Yuasa *et al.* in Fe/MgO/Fe(001) [1], the TMR oscillation has been observed in several crystalline MTJs. In particular, recent experiments in a series of high-quality single-crystalline MTJs [2-4] have obtained not only the highest record of the TMR ratio at room temperature but also a clear TMR oscillation with a significantly large amplitude, suggesting that understanding the origin of the TMR oscillation would provide important information for achieving even higher TMR ratios. However, many previous studies have failed to explain the origin of the TMR oscillation. For example, the Δ_1 coherent tunneling theory, which is a standard theory for the TMR effect, is known to provide a monotonic increase in the TMR ratio with increasing the thickness of the insulating barrier [5]. Although additional effects, such as interference of evanescent states [6] and nonspecular tunneling [7], have been considered based on the Δ_1 coherent tunneling theory, the experimental fact that resistance oscillations are observed in both parallel and antiparallel magnetization states has not been explained satisfactorily. In the previous JSAP autumn meeting, we proposed a theory that can explain the existing experimental results in the TMR oscillation in Fe/MgO/Fe(001). Our main idea of this theory is to take into account the superposition of wave functions between the majority-spin Δ_1 and minority-spin Δ_2 states when solving the tunneling problem for the TMR effect. However, this mechanism should be further considered and rationalized from both theoretical and experimental viewpoints.

In this work, we conduct theoretical and experimental studies for validating the mechanism of the TMR oscillation we proposed [8]. We provide a microscopic Hamiltonian for the exchange interaction between localized spins and conduction electrons at the interface of the MTJ. We show that the superposition of wave functions between the majority-spin Δ_1 and minority-spin Δ_2 states mentioned above is obtained by diagonalizing this Hamiltonian. We also conduct experiments for studying the bias-voltage dependence and material dependence of the TMR oscillation. We find that the period of the TMR oscillation hardly changes by applying the bias voltage up to 1V in Fe/Mg₄AlO_x/Fe(001). It is also found that no resistance oscillation is observed when using non-magnetic metallic materials (bcc-W and bcc-V) as electrodes of the tunnel junction. All these experimental results are consistent with the mechanism proposed in our theory. We also discuss the relation between our theory and the TMR oscillation observed in MTJs with Heusler alloys [9,10]. This work was supported by Grant-in-Aids for Scientific Research (22H04966, 23K03933, and 24H00408) and MEXT Program: Data Creation and Utilization-Type Material Research and Development Project (JPMXP1122715503).

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First-principles study of hcp-Co_{1-x}Ni_x|h-BN|hcp-Co_{1-x}Ni_x magnetic tunnel junction

¹NIMS, ²Kyoto Institute of Technology

[○]Ivan Kurniawan¹, Keisuke Masuda¹, Yoshio Miura^{1,2}

E-mail: kurniawan.ivan@nims.go.jp

Magnetic tunnel junctions (MTJs) employing single-crystalline MgO barriers suffer from significant lattice mismatch with typical ferromagnetic (FM) electrodes such as Fe, CoFe, or Heusler alloys. This mismatch induces interfacial defects that degrade spin-dependent tunneling and limit the achievable magnetoresistance (MR) ratio [1]. Two-dimensional materials like hexagonal boron nitride (h-BN) have emerged as promising alternatives, offering better lattice matching with hcp-Co and inherent perpendicular magnetic anisotropy (PMA) due to their hexagonal structure [2,3]. However, the impact of h-BN's threefold symmetry on tunneling characteristics—particularly spin-dependent transmittance—remains unclear. Moreover, the influence of Fermi level shifts on MR enhancement in such systems has not been systematically explored. In this study, we investigate the electronic transport properties of hcp-Co_{1-x}Ni_x|h-BN|hcp-Co_{1-x}Ni_x MTJs using first-principles calculations at zero bias, implemented in Quantum ESPRESSO [4]. Ni doping is modeled via the virtual crystal approximation (VCA) [5], and the electrode–barrier separation is fixed at a typical physisorption distance known to yield high MR performance [2]. As shown in Fig. 1, Ni doping enhances the MR ratio due to changes in the conductance profile in the in-plane wave number space, with the most significant contribution arising from the conductance peak of the minority-spin channel in the parallel (P) configuration near the Γ point, attributed to Δ_1 -symmetry bands at the Fermi level. Doping shifts this conductance peak closer to Γ and expands zero-conductance regions in both the parallel-majority and antiparallel (AP) configurations, thereby increasing the MR ratio. It was also found that the conductance peak position and intensity depends on the interfacial distance, which is an important information on the origin of the large MR ratio with the physisorption distance.

These findings deepen the understanding of spin-dependent tunneling in 2D-material-based MTJs and demonstrate the potential of electrode composition tuning for optimizing MR performance. This work was partially supported by Grants-in-Aid for Scientific Research (Grant No. JP22H04966 and JP23K03933) from the Japan Society for the Promotion of Science.

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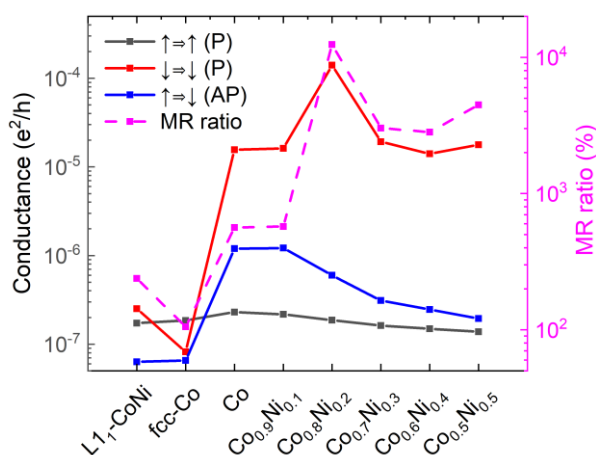


Fig. 1 Conductance and MR ratio of various FM|h-BN MTJ

Power generation in ferromagnetic FePt thin films using electromagnetic wave absorption

T. Hiratra, B. W. Qiang, T. Miyamachi, M. Mizuguchi

(Nagoya Univ.)

In recent years, there's been growing interest in energy harvesting utilizing ambient energy sources like heat and vibration, aiming for a sustainable society. Among these utilizations, the use of electromagnetic waves as a power source is gaining significant attention due to their ubiquitous presence in our surroundings. Previously, a phenomenon where current is generated by exciting spins upon irradiating thin films with electromagnetic waves under an external magnetic field has been discovered and garnered much interest [1]. In this research, we aim to achieve power generation using electromagnetic wave absorption without the need for an external magnetic field by employing ferromagnetic thin films with varying magnetic anisotropy within the film. L1₀-ordered FePt is a material with perpendicular magnetic anisotropy varying with the deposition temperature. We fabricated L1₀-ordered FePt thin films with different magnetic anisotropies within the film. By using these films, we clarified power generation by measuring the electromotive force generated when these samples were irradiated with electromagnetic waves of a specific frequency. As shown in Fig. 1, a certain change of voltage was observed by an irradiation of electromagnetic wave. In this talk, the mechanism of the power generation observed will be discussed in detail, and the related physics will be also presented.

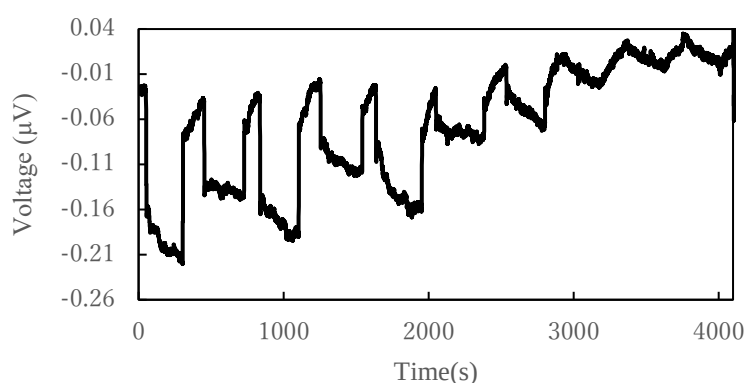


Fig. 1 Time evolution of electromotive force from FePt thin films with various magnetic anisotropies. Electromagnetic wave with several frequencies were irradiated intermittently.

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Fabrication and Characterization of Co-Pt Multilayer Nanowires Prepared by Dual-bath Electrodeposition

Gifu Univ.¹, Nagoya Univ.², Res. Org. for Nano and Life Innov. Waseda Univ.³,
Dept. of Appl. Chem. Waseda Univ.⁴, ICR Kyoto Univ.⁵, [○](M2) Rio Kawana¹, Natsuko Oguchi¹,
Daiki Oshima², Michiyuki Yoshida¹, Takashi Sugiura¹, Mikiko Saito³, Takayuki Homma^{3,4},
Takeshi Kato², Teruo Ono⁵, Mutsuhiro Shima¹, and Keisuke Yamada¹
E-mail: kawana.rio.k5@s.gifu-u.ac.jp, yamada.keisuke.p6@f.gifu-u.ac.jp

A novel three-dimensional magnetic memory device based on domain wall (DW) motion is attracting increasing attention due to its potential to achieve high-speed operation, high density, and low cost [1,2]. This type of magnetic memory is composed of magnetic nanowires consisting of DW-pinning and domain layers. Data transfer is realized by driving magnetic DWs along the nanowire using electric current. Co-Pt alloys, which exhibit magnetic properties that depend on their composition, have been proposed as promising materials for magnetic nanowires. Theoretical calculations have demonstrated that current-driven domain wall motion—essential for memory device operation—can be achieved by employing Co-Pt alloy layers with different compositions for each layer [1,2]. In this study, we aim to fabricate multilayered Co-Pt nanowires composed of Co-rich and Pt-rich layer using a dual-bath electrodeposition method, and to evaluate their structural, magnetic, and electrical transport properties.

The samples were fabricated by depositing Co-Pt alloy layers into the nanopores of a polycarbonate template using Co-rich and Pt-rich electrodeposition solutions [3]. The layer thickness of the samples was varied from $t = 3$ to 500 nm, and the number of layers was varied from several tens to thousand to achieve a total length of approximately 10 μm . The crystal structure, microstructure and magnetic properties of the nanowires were characterized using XRD, SEM-EDX, TEM, VSM and MR.

The SEM-EDX observation shown in Fig. 1(a) confirmed the alternating layers of Co-rich ($\text{Co}_{71}\text{Pt}_{29}$) and Pt-rich ($\text{Co}_{13}\text{Pt}_{87}$) compositions. The formation of FCC structure in each layer was confirmed by XRD and TEM observation (Fig. 1(b)). Fig. 1(c) shows the MR ratio was increased with decreasing layer thickness [4].

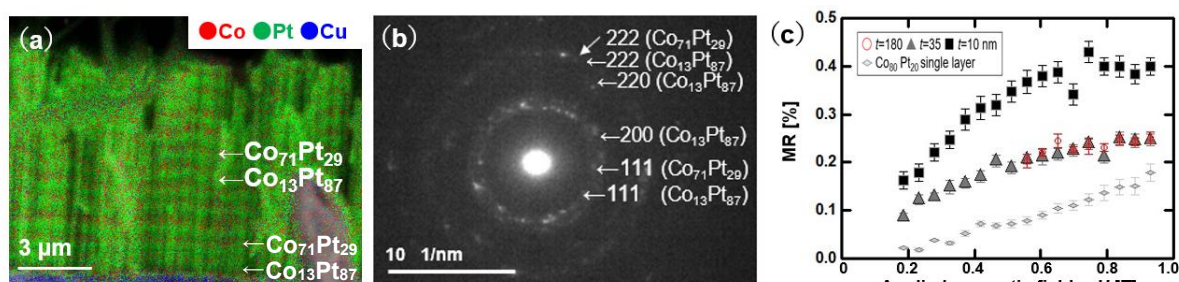


Fig. 1 Characterization of $\text{Co}_{71}\text{Pt}_{29}/\text{Co}_{13}\text{Pt}_{87}$ multilayer nanowires. (a) SEM-EDX image of nanowires with layer thickness $t = 500$ nm. (b) Electron diffraction patterns for the sample with $t = 17$ nm. (c) Magnitude of μ_0H dependence of the MR ratio.

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Acknowledgment: This research was supported by the CREST program, "Development of Three-Dimensional Magnetic Memory."

強誘電体分極を用いた CoFeB の面内磁気特性制御と不揮発性

In-Plane Magnetic Property Control and Nonvolatility of CoFeB via Ferroelectric Polarization

科学大工¹, 科学大住友化学協働研究拠点² ○呉研^{1,2}, 鬼村和志¹, 小林宏之², 角嶋邦之^{1,2}

Eng. of Science Tokyo¹, Sumitomo Chemical Next-Generation Eco-Friendly Devices Collaborative

Research Cluster of Science Tokyo², °Yan Wu^{1,2}, K. Onimura¹, H. Kobayashi², K. Kakushima^{1,2}

E-mail: yan.w.ab@m.titech.ac.jp

はじめに 面内磁化構造は、スピン軌道トルク (SOT) デバイスにおける磁化反転機構と親和性が高く、実用デバイスへの応用において重要な位置づけを占めている[1]。これまで我々は、膜厚 1.0~1.3 nm の CoFeB が垂直磁化 (PMA) 状態にある条件下で、強誘電体 $\text{Al}_{0.88}\text{Sc}_{0.12}\text{N}$ の分極方向に応じて保磁力 (H_c) が変化すること、さらにその状態が非揮発的に保持されることを示してきた。この変化は、 AlScN の分極反転により界面キャリア密度が変調され、磁気異方性や磁区壁のピンニングに影響を及ぼすためと考えられる [2]。本研究では、膜厚 2.0 nm の CoFeB に着目し、面内磁化状態においても AlScN を用いた非揮発的な磁気制御が可能であることを新たに示す。

実験 図 1 に構造を示す。 SiO_2 基板上に、Ta (1 nm)/ $\text{Co}_{0.2}\text{Fe}_{0.6}\text{B}_{0.2}$ (2 nm)/MgO (2 nm) の積層構造を製膜しメサ構造に加工し、保護膜用 SiO_2 を堆積後、強誘電体キャパシター領域のエッチングを行った後に誘電体 $\text{Al}_{0.88}\text{Sc}_{0.12}\text{N}$ 層 (50nm) と TiN (30 nm) を製膜し、TiN のパターンニングを行った。 AlScN/TaOx 間の強誘電性を小信号測定にて確認を行ったのち、印加電圧を変化させながら面内磁界印加 MOKE 測定により保磁力の変化を評価した。

結果・考察 図 2 に示すように、無電圧状態から開始し電圧を正負方向で 2 周の測定を行い、正電圧印加により H_c は減少、負電圧印加により増加する傾向が確認された。この保磁力の変調は、従来の PMA 状態で得られた挙動と同様の方向性を示しており、面内磁化においても AlScN を用いた電界制御が有効であることを実証した。

謝辞 本研究は、文部科学省次世代 X-nics 半導体創生拠点形成事業 JP J011438 と住友化学株式会社の助成を受けたものです。

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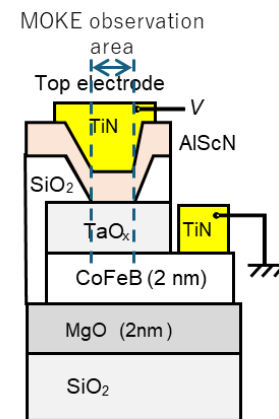


Fig. 1 Image of Ferroelectric Capacitor device

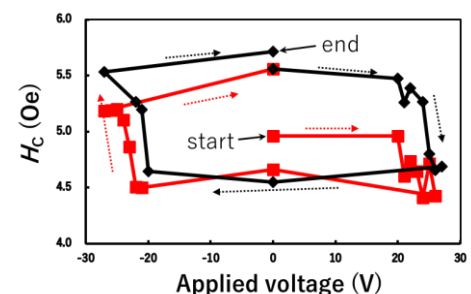


Fig.2 Transient of H_c dependent applied voltage (red: 1st sweep, black: 2nd sweep)

Efficient spin-charge conversion at room temperature from 2DEGs in ferroelectric BaTiO₃ films

R. Tomar¹, S. Chiroli¹, T. Buttiens¹, B. Fazlioglu Yalcin², A. S. Goossens¹, A. Raji³, S. Mallik^{1,4}, E. Gradauskaite¹, L. M. Vicente-Arche¹, A. Barthélémy¹, L. Vila^{5,6}, J.P. Attané^{5,6}, A. Gloter³, L. Iglesias¹, I. Boventer¹, R. Engel-Herbert^{2,7}, M. Bibes^{1,6}

¹ Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91797 Palaiseau, France

² Pennsylvania State University, University Park, PA 16802, USA

³ Laboratoire de Physique des Solides, CNRS, Université Paris-Saclay, 91405 Orsay, France

⁴ Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Kolkata 700 064, India

⁵ Spintec, CEA, CNRS, Université Grenoble Alpes, 17 Av. des Martyrs, 38054 Grenoble

⁶ NELLLOW, 32 Avenue Alsace-Lorraine, 38000 Grenoble

⁷ Paul Drude Institute for Solid State Electronics, Leibniz Institute within Forschungsverbund Berlin eV, Hausvogteiplatz 5-7, 10117, Berlin, Germany

Two-dimensional electron gases (2DEGs) at oxide interfaces have emerged as highly promising platforms for spin-orbitronics, where the interplay between spin and charge degrees of freedom can be harnessed for low-power, non-volatile electronic applications¹. These systems naturally exhibit strong Rashba spin-orbit coupling due to the inversion symmetry breaking at the interface, allowing for gate-tunable spin textures and efficient interconversion between spin and charge currents. Among them, 2DEGs formed at SrTiO₃-based interfaces have demonstrated record spin-charge conversion efficiencies, primarily via the inverse Edelstein effect, which converts a non-equilibrium spin accumulation into a transverse charge current².

A particularly appealing direction involves integrating this functionality with ferroelectricity, enabling non-volatile electrical control of spintronic properties without the need for sustained power input³. This opens new opportunities for logic-in-memory architectures and neuromorphic computing schemes. In this context, ferroelectric spin-orbit (FESO) systems could revolutionize spintronic device paradigms by combining non-volatility, ultralow switching energy, and reconfigurability.

Here, we report a major advance toward the implementation of such FESO devices by demonstrating spin-charge conversion at room temperature in 2DEGs formed within epitaxial BaTiO₃ thin films. These films exhibit robust ferroelectricity, with Curie temperatures exceeding 300°C, ultra-low switching voltages in the range of 100 millivolts, and fatigue-free operation beyond 10¹¹ polarization cycles, making them highly suitable for integration into energy-efficient electronics. When these BaTiO₃-based 2DEGs are coupled to a ferromagnetic layer, we observe a clear spin-to-charge conversion signal at ambient conditions, with efficiencies comparable to those reported for SrTiO₃-based systems.

Our findings establish ferroelectric BaTiO₃ as a viable platform for spin-orbitronics at room temperature and demonstrate the compatibility of epitaxial growth, ferroelectric switching, and spin-charge conversion within a single functional oxide system. These results represent a significant step toward the development of scalable, attojoule-class spintronic devices based on non-volatile oxide interfaces, and lay the foundation for FESO architectures.

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10 Spintronics and Magnetism | Oral presentation : 10.4 Spintronics in semiconductor, topological material, superconductor, and multiferroics

[10a-N303-1~11] 10.4 Spintronics in semiconductor, topological material, superconductor, and multiferroics

[10a-N303-1]

[The 58th Young Scientist Presentation Award Speech] Advancing optical evaluation of persistent spin helix states in a GaAs/AlGaAs two-dimensional electron gas via programmable spin helix patterning

○Keito Kikuchi¹, Jun Ishihara¹, Miari Hiyama¹, Sota Yamamoto¹, Yuzo Ohno², Makoto Kohda^{1,3,4,5} (1.Grad. Sch. of Eng., Tohoku Univ., 2.Univ. of Tsukuba, 3.CSIS, Tohoku Univ., 4.DEFS, Tohoku Univ., 5.QUARC, QST)

[10a-N303-2]

ab initio Quasi-Particle calculations and Spin Other Orbital Coupling for Bi₂Se₃

○Jun Inagaki¹ (1.HISOR)

[10a-N303-3]

Quantitative consideration of spin-relaxation mechanisms in (110) GaAs/AlGaAs quantum wells II

○Yuzo Ohno^{1,2}, Satoshi Iba² (1.Univ. of Tsukuba, 2.AIST)

[10a-N303-4]

Linear Photogalvanic Effect in Centrosymmetric Dirac Semimetals

○Yuta Kobayashi¹, Akihiro Ozawa¹, Masashi Kawaguchi¹, Shunzhen Wang¹, Ryota Miyazaki¹, Kohei Fujiwara², Ryo Shimano¹, Atsushi Tsukazaki¹, Takashi Oka¹, Masamitsu Hayashi¹ (1.Univ. Tokyo, 2.Rikkyo Univ.)

[10a-N303-5]

Spatial modulation of electron spin wave in a (001) GaAs/AlGaAs quantum well toward NOT gate operation

○Koga Akagi¹, Futa Sugawara¹, Jun Ishihara¹, Keito Kikuchi¹, Daiki Sekine², Sota Yamamoto¹, Kohda Makoto^{1,2,3,4} (1.Grad. Sch. of Eng., Tohoku Univ., 2.QUARC, QST, 3.CSIS, Tohoku Univ., 4.DEFS, Tohoku Univ.)

[10a-N303-6]

Circularly polarized electroluminescence properties of spin-polarized light-emitting diodes using multilayer InGaAs quantum dots

○Itsu Tanaka¹, Daiki Mineyama¹, Ayano Morita¹, Hiroto Kise¹, Junichi Takayama¹, Akihiro Murayama¹, Satoshi Hiura¹ (1.IST, Hokkaido Univ.)

[10a-N303-7]

Effect of light-absorbing layer thickness on light polarization detection properties of GaNAs photodiode based on defect-enabled spin filtering

○Daiki Mineyama¹, Itsu Tanaka¹, Kaito Nakama², Hidetoshi Hashimoto², Keisuke Minehisa², Junichi Takayama¹, Fumitaro Ishikawa², Akihiro Murayama¹, Satoshi Hiura¹ (1.IST, Hokkaido Univ., 2.RCIQE, Hokkaido Univ.)

[10a-N303-8]

Device Design Guideline for High-Performance Si-based Spin MOSFETs

○Yuki Takahashi¹, Shoichi Sato^{1,2}, Masaaki Tanaka^{1,2}, Ryosho Nakane^{1,3} (1.EEIS, Tokyo Univ., 2.CSRN, Tokyo Univ., 3.d.lab, Tokyo Univ.)

[10a-N303-9]

Non local detection of current induced magnetization switching using lateral spin-valve device

○(DC)Mineto Ogawa¹, Yu Osada¹, Michihiko Yamanouchi¹, Tetsuya Uemura¹ (1.IST. Hokkaido Univ.)

[10a-N303-10]

Weak anti-localization effect in In-doped SnTe thin films

○Ryota Uesugi¹, Ryo Ando², Masaomi Mizuno¹, Tomosuke Aono¹, Takahiro Chiba³, Takashi Komine¹ (1.Ibaraki Univ., 2.Ibaraki College, 3.Yamagata Univ.)

[10a-N303-11]

Large field-free superconducting diode effect in α -Sn / β -Sn planar heterostructures

○Yuta Okuyama¹, Le Duc Anh^{1,2}, Masaaki Tanaka^{1,2} (1.Univ. of Tokyo, 2.CSRN, Univ. of Tokyo)

Advancing optical evaluation of persistent spin helix states in a GaAs/AlGaAs two-dimensional electron gas via programmable spin helix patterning

Grad. Sch. of Eng., Tohoku Univ.¹, Univ. of Tsukuba², CSIS, Tohoku Univ.³,
DEFS, Tohoku Univ.⁴, and QUARC, QST⁵

○K. Kikuchi¹, J. Ishihara¹, M. Hiyama¹, S. Yamamoto¹, Y. Ohno², and M. Kohda^{1,3-5}

Email: keito.kikuchi.t5@dc.tohoku.ac.jp

Persistent spin helix (PSH) states, which emerge when the Rashba and Dresselhaus spin-orbit interactions (SOIs) are balanced, offer a promising route to achieving long-lived spin coherence in nonmagnetic semiconductors [1]. These helical spin textures are of great interest for spintronic applications, as their spatial periodicity can be exploited for information encoding, storage, and transport [2]. Conventional approaches to evaluating PSH dynamics, however, often rely on sample processing, external magnetic fields, or spatial scanning, which limit experimental flexibility and accessibility.

To overcome these limitations, we previously developed a fully optical method that combines time-resolved Kerr rotation with programmable spin helix patterning using a spatial light modulator (SLM) [3]. This approach, illustrated schematically in Fig. 1, enables the generation of spin helices with arbitrary wavenumbers and provides a high-throughput means to extract SOI parameters such as Rashba and Dresselhaus coefficients, as well as the spin diffusion constant, by analyzing the wavenumber dependence of spin relaxation.

In this commemorative presentation, we aim to extend this technique to explore the anisotropy of the PSH state and to perform a more detailed analysis of the anisotropic properties of SOI. By taking advantage of the SLM's ability to flexibly rotate the spin helix pattern in-plane, we can optically access the angular dependence of spin relaxation without the need for mechanical rotation or sample modification. As shown in Fig. 2, this capability enables us to generate spin helices oriented along different in-plane directions and map the relaxation dynamics in reciprocal space, thereby providing a two-dimensional view of the SOI landscape. The combination of PSH anisotropy and programmable spin helix patterning opens the door to high-resolution, orientation-sensitive characterization of SOI in low-dimensional semiconductor systems.

This research was supported by JSPS KAKENHI Grant No. 21H04647 and JST FOREST, CREST, PRESTO, and SPRING programs (Grant Nos. JPMJFR203C, JPMJCR22C2, JPMJPR24L4, and JPMJSP2114).

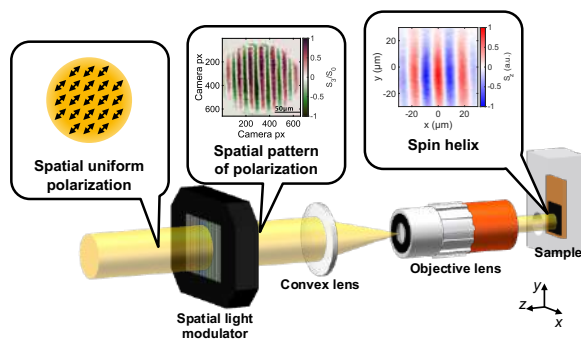


Fig 2: Optical setup for generating spin helices with arbitrary wavevectors via programmable polarization patterning.

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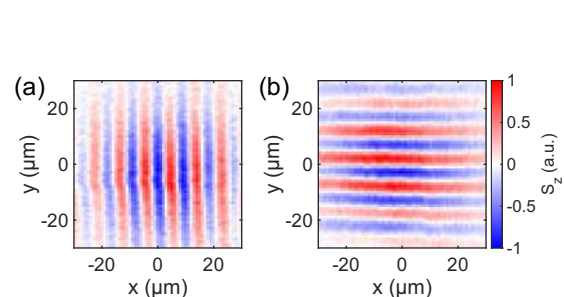


Fig 2: Spin helix patterns observed with wavevector aligned along (a) the x-direction and (b) the y-direction.

Bi₂Se₃ の第一原理準粒子状態計算および 2 粒子のスピン軌道相互作用 ab initio Quasi-Particle calculations and Spin Other Orbital Coupling for Bi₂Se₃

広大放射光¹, ○稲垣 淳¹

HiSOR¹, Jun INAGAKI¹

E-mail: inajun@hiroshima-u.ac.jp

典型的トポロジカル絶縁体 Bi₂Se₃ の第一原理準粒子状態計算に基づき, 2 粒子のスピン軌道相互作用すなわち Spin Other Orbital Coupling (SOOC) について考察を行った.

角度分解光電子分光 (ARPES) は表面から励起した準粒子状態への直接のアクセスを与えるため, 近年の創発的量子状態を示す材料系に広く用いられている. ARPES スペクトルの理論では電子相関係の一粒子 Green 関数によって自己エネルギーとスペクトル関数を記述する[1]. 一方 GW 近似+SOC のフレームワークは従来, 摂動論的固有値補正にとどまっていたが, DFT 計算で得たスピノル波動関数を GW 近似計算に使用する Spinor Full Relativistic GW が実装され, 強いスピン軌道相互作用を持つトポロジカル絶縁体への適用が可能となった. Bi₂Se₃ バルクの DFT 計算では Γ 点の価電子バンド端 (VBM) においてくぼみ (dimple, camel back) が現れるが, 自己エネルギー Σ の非対角成分を含めることによりはじめて ARPES 実験結果と整合するパラボラ型バンド形状が再現される (FIG.) [2].

当日はこの準粒子状態計算手法と, その結果を踏まえた 2 粒子スピン軌道相互作用 SOOC の理論的考察について報告する.

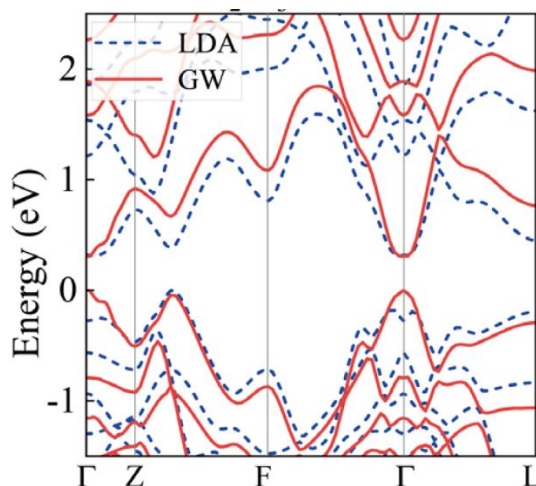


FIG. Electronic band structure at the G_0W_0 (solid red curve) and LDA (dashed blue curve) of bulk Bi₂Se₃ (Figure is from *Phys. Rev. Lett.*, **130**, 216402 (2023). Courtesy of Prof. D. Qiu, Yale University).

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(110)GaAs/AlGaAs 量子井戸におけるスピン緩和機構の定量的考察 II

Quantitative consideration of spin-relaxation mechanisms

in (110) GaAs/AlGaAs quantum wells II

筑波大院数理¹, 産総研², 大野裕三^{1,2}, 揖場聡²Univ of Tsukuba¹ and AIST², Yuzo Ohno^{1,2}, and Satoshi Iba²

E-mail: ono.yuzo.gb@u.tsukuba.ac.jp

前回の応用物理学会において、D'yakonov-Perel'機構が抑制された(110)面 GaAs/AlGaAs 量子井戸における2次元電子のスピン緩和機構について詳細な理論解析を行い、Elliott-Yafet (EY) 機構、励起子スピン緩和機構、およびサブバンド間散乱によるスピン緩和の3つを考慮することでその温度依存性や励起強度依存性を定量的に説明できることを報告した[1]。このうち、サブバンド間スピン緩和時間の算出には、光学フォノンによるサブバンド間散乱を考慮し、終状態をランダムに決定してモンテカルロシミュレーションにより平均化を行っていた。その結果、Dresselhaus のスピン軌道相互作用定数 γ をフィッティングパラメータとしたとき、 $20 \text{ eV}\text{\AA}^3$ で実験結果とよく一致することを示した[2]。しかし、近年の永久スピン旋回の顕微カー回転測定法による実験[3]や第一原理計算[4]などでは、 γ は約 $10 \text{ eV}\text{\AA}^3$ の値をとることが報告されている。今回、我々は γ の決定にかかわる(110)量子井戸構造におけるサブバンド間スピン緩和を中心にさらに解析を進めた。具体的には、①モンテカルロシミュレーションでは数値計算結果のスピン緩和時間の値にばらつきがあったため、スピンハミルトニアンを散乱マトリクス要素を数値積分により計算し平均化して精度を上げた。また、②2次元系における音響フォノンによるサブバンド内・サブバンド間の散乱時間をそれぞれ数値計算で求め、光学フォノン散乱に加えて音響フォノン散乱を考慮してサブバンド間スピン緩和時間を計算した。さらに③EY 機構についても基底状態と第一励起状態それぞれのスピン緩和時間を計算し、電子の熱分布に応じて平均化してスピン緩和時間を求めた。

室温におけるスピン緩和時間の励起電子密度依存性の計算結果を Fig. 1 に示す。今回の解析では、 $\gamma=10 \text{ eV}\text{\AA}^3$ として数値計算を行った。実験結果と比較すると、計算結果は実験値とよく一致していることがわかる。当日は温度依存性についても議論する。

本研究は科研費 (JP24H00426, JP24K01391)、X-NICS スピントロニクス融合半導体創出拠点の援助で行われた。

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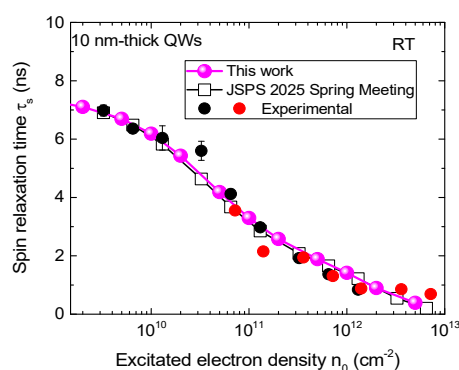


Fig. 1 (110)GaAs/AlGaAs 量子井戸における室温での電子のスピン緩和時間の励起電子密度依存性

ディラック半金属における直線フォトガルバニック効果

Linear Photogalvanic Effect in Centrosymmetric Dirac Semimetals

Univ. Tokyo ¹, Rikkyo Univ.², °Yuta Kobayashi¹, Akihiro Ozawa¹,

Masashi Kawaguchi¹, Shunzhen Wang¹, Ryota Miyazaki¹, Kohei Fujiwara², Ryo Shimano¹, Atsushi

Tsukazaki¹, Takashi Oka¹, Masamitsu Hayashi¹

E-mail: yuta.kobayashi@phys.s.u-tokyo.ac.jp

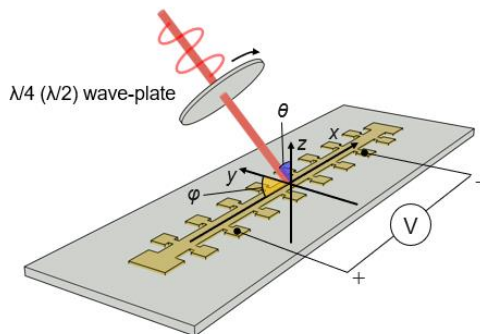
Photogalvanic effects provide a direct probe of symmetry breaking, offering insights into charge transport and light-matter interactions [1]. Recently, the helicity dependent photogalvanic effect, also known as the circular photogalvanic effect (CPGE), has been extensively studied in topological materials largely due to its direct connection to the spin-momentum locked topological states[2,3,4].

For the experimental evaluation of CPGE, the following phenomenological equation is commonly used

$$\frac{I}{P} = C \sin 2\alpha + L_1 \sin 4\alpha + L_2 \cos 4\alpha + D,$$

where $\frac{I}{P}$ is a photocurrent normalized by laser power and α is the rotation angle of the quarter waveplate used to control the helicity of the incident light. The first term represents the CPGE, which intuitively reflects the response of the system on circularly polarized light. The second term in the equation is the change in the photocurrent under illumination of circularly and linearly polarized light and referred to as linear photogalvanic effect (LPGE). The L_1 term, like the C term, is known to exhibit a relatively large value in topological materials. Despite this characteristic behavior of L_1 , the underlying mechanism remains poorly understood. The third and last terms often reflect polarization dependent absorption and photo-thermal induced response, respectively.

In this study, we investigated the underlying mechanism of the L_1 term. Thin films of centrosymmetric Dirac semimetals (Bi and $\text{Co}_3\text{Sn}_2\text{S}_2$) were photolithographically fabricated into the wires. Photocurrent responses were evaluated under different illumination configurations. In the presentation, we discuss the material dependence and symmetry considerations associated with the origin of the L_1 term.



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Fig. Schematic illustration of the photocurrent measurement.

Spatial modulation of electron spin wave in a (001) GaAs/AlGaAs quantum well toward NOT gate operation

Grad. Sch. of Eng., Tohoku Univ.¹, CSIS, Tohoku Univ.², DEFS, Tohoku Univ.³, QUARC, QST⁴,

[○]K. Akagi¹, F. Sugawara¹, J. Ishihara¹, K. Kikuchi¹, D. Sekine⁴, S. Yamamoto¹, and M. Kohda¹⁻⁴

E-mail: akagi.koga.t3@dc.tohoku.ac.jp

Electron spin waves emerged in a persistent spin helix state [1] exhibit wave-like characteristics and have the potential to serve as information carriers for multiplexed and parallel information processing. These systems require fewer components than current CMOS-based devices [2]. A previous study has simulated majority logic gate based on the interference of electron spin waves, which can implement AND and OR gate operations [3]. However, the NOT gate operation with electron spin wave has not been demonstrated. To this end, we demonstrated the spatial modulation of electron spin wavelength in a semiconductor wire structure with different widths.

We used a one-side modulation doped (001) GaAs/AlGaAs quantum well and designed a NOT gate structure consisting of different width of channels of 20 μm and 5 μm , as shown in the inset of Fig 1. The different widths of channel provide the different drift velocity v_{dr} , enabling in the modulation of electron spin wavelength according to the relation $\lambda_{\text{SO}} \propto [|\alpha| + \beta_1 - \beta_3(1 + 6(v_{\text{dr}}/v_{\text{F}})^2)]^{-1}$, where α and $\beta_{1,3}$ are Rashba and Dresselhaus parameters, and v_{F} is Fermi velocity [4]. The electron spins were excited at $x = 0 \mu\text{m}$ by circularly polarized pump beam and transported by an in-plane electric field. The spatial distribution of electron spin was measured at 5 K by magneto-optical Kerr rotation (KR) microscopy.

Figure 1 shows the spatial distribution of the KR signal as a function of the distance from excitation position. The electron spin shows oscillatory behavior, indicating the electron spin wave formed by spin orbit effective magnetic field. The induced electron spin waves propagate accompanied by the drift motion of electrons. While the electron spin wave is drifted through the entire wire through different channel width, the oscillation period changes in 20 μm - and 5 μm -width regions. We fit the experimental data with the product of exponential and cosine functions, as shown with red solid lines in Fig. 1. The evaluated electron spin wavelengths are 15.9 μm and 18.5 μm in 5 μm and 20 μm regions, respectively. This indicates wavelength of the electron spin waves is modulated by the channel width due to the modulation of spin-orbit-induced effective field.

This research was supported by JSPS KAKENHI Grant No. 21H04647, JST FOREST, CREST, and PRESTO programs (Grant Nos. JPMJFR203C, JPMJCR22C2, and JPMJPR24L4), and RIEC, Tohoku University.

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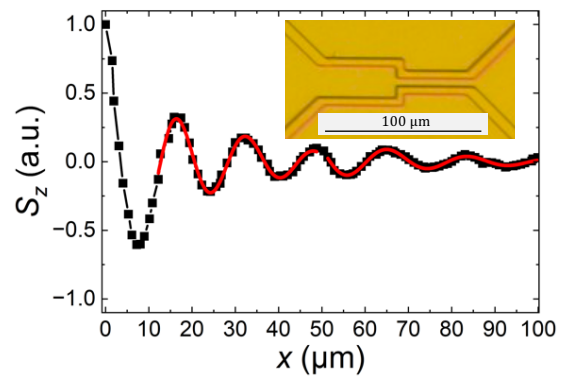


Fig. 1 Spatial distribution of electron spin wave in the channel. Inset shows the device structure.

多層 InGaAs 量子ドットスピン偏極発光ダイオードの円偏光発光特性

Circularly polarized electroluminescence properties of spin-polarized light-emitting diodes using multilayer InGaAs quantum dots

北大院情報科学 ○田中 聡, 峯山 大輝, 森田 彩乃, 木瀬 寛人, 高山 純一, 村山 明宏, 樋浦 諭志

Faculty of Information Science and Technology, Hokkaido Univ.

○I. Tanaka, D. Mineyama, A. Morita, H. Kise, J. Takayama, A. Murayama and S. Hiura

E-mail: tanaka.itsu.w7@elms.hokudai.ac.jp

近年、待機電力消費のない不揮発性スピンメモリと信号伝送の熱損失がない光配線から構成されるスピンベースの光電情報システムの構築が期待されている[1]。スピン偏極発光ダイオード(スピンLED)は、金属強磁性体電極から半導体活性層への電子スピン注入を介して、電子のスピン偏極情報を円偏光に転写できる[2,3]。実用的なデバイス応用には、高い発光円偏光度と高輝度な電流注入発光(EL)が必要不可欠である。そこで、我々は強い量子効果が働くことで高い発光効率[4]と長いスピン緩和時間[5]を示す III-V 族半導体量子ドット(QD)をスピンLEDの活性層に用いることに着目してきた。QD層を多層化することでQD全体のキャリア捕獲効率が向上することが期待されるが、QD層数が円偏光EL特性に与える影響については十分に明らかにされていない。本研究では、QD層数を変えたスピンLEDを作製し、その円偏光EL特性を調べた。

試料構造を図1(a)に示す。 p -GaAs(100)基板上に $\text{In}_{0.6}\text{Ga}_{0.4}\text{As}$ QDを含む活性層の層数を3層、5層と変化したLED構造を分子線エピタキシー法により、MgOトンネルバリアを電子ビーム蒸着法により成長した。その後、大気を介してスパッタリング装置に試料を移動し、MgO表面を熱処理した後に $\text{Co}_{0.4}\text{Fe}_{0.4}\text{B}_{0.2}/\text{Mo}$ スピン注入層を成膜した。測定温度は室温であり、EL測定では試料面直方向に500 mTの磁場を印加した。図1(b,c)にEL強度が同程度の3層・5層試料における、異なる電流での円偏光ELスペクトルとCPDを示す。ここで、CPDはEL強度で規格化された左右円偏光ELの強度差と定義し、QDの電子スピン偏極率を反映する。5層試料では、より低い電流で3層試料と同等のEL強度が得られた。これは、多層化による電子注入効率の向上に起因する。また、3層試料ではQD基底準位のEL CPDは7%であったのに対して、5層試料では10%に増加した。この結果は、多層化が高効率なスピン偏極発光の実現に有効であることを示している。

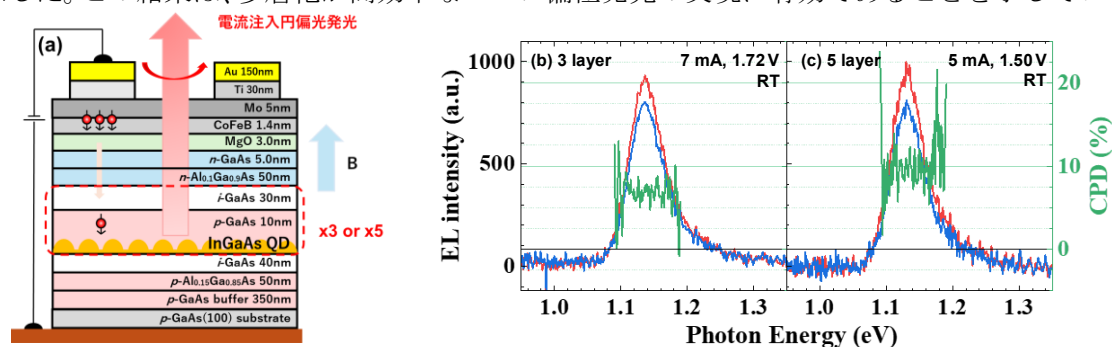


Fig. 1 (a) Schematic of spin LED using 3 or 5 layers of InGaAs QDs with $\text{Co}_{0.4}\text{Fe}_{0.4}\text{B}_{0.2}/\text{MgO}$ spin injector. Circularly polarized QD EL spectra and corresponding CPD of (b) 3-layer sample with an injection current of 7 mA and (c) 5-layer sample with 5 mA, measured at room temperature under $B = 0.5$ T.

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Effect of light-absorbing layer thickness on light polarization detection properties of GaNAs photodiode based on defect-enabled spin filtering

IST, Hokkaido Univ.¹, RCIQE, Hokkaido Univ.²,

[○]Daiki Mineyama¹, Itsu Tanaka¹, Kaito Nakama², Hidetoshi Hashimoto², Keisuke Minehisa²,
Junichi Takayama¹, Fumitaro Ishikawa², Akihiro Murayama¹ and Satoshi Hiura¹

E-mail: mineyama.daiki.i0@elms.hokudai.ac.jp

Recent advances in polarization-sensitive photodetectors are expected to contribute to next-generation high-speed optical communications, medical diagnostics and advanced sensing technologies [1–3]. Recently, we developed a polarization-sensitive photodiode based on dilute nitride GaNAs, which is expected to operate at ten GHz [4]. In GaNAs, the incorporation of nitrogen into GaAs generates Ga²⁺ interstitial defects which behave as spin-filtering defects. These defects have unpaired electron spins which become dynamically polarized in the same spin direction as those of conduction electrons generated by circularly polarized light excitation. The resulting capture efficiency of conduction electrons is different between circularly and linearly polarized light due to the Pauli exclusion principle. A previous study showed that GaNAs-based photodiode required an incident light power of at least 3 mW for efficient light polarization detection [4]. For practical use, a device operation with a lower light power is desirable. In this work, we fabricated GaNAs-based photodiodes with different intrinsic layer thicknesses and investigated the light polarization detection properties.

The sample structures are shown in Fig. 1. Using nitrogen plasma-assisted molecular beam epitaxy, we fabricated PIN photodiodes with different *i*-GaNAs layer thicknesses of 38.5 and 250 nm. The nitrogen contents were estimated as 2.5 and 2.9% by x-ray diffraction. The light intensity and polarization state of a pulsed laser ($\lambda = 1025$ nm) were modulated using an optical chopper and a photoelastic modulator. The figure of merit of polarization detection was defined as $F = \Delta i / 2i_{photo}$, where Δi represents the difference in photocurrent between circularly and linearly polarized light, and i_{photo} is the polarization-independent photocurrent. Here, note that the MgO/CoFeB/Mo structure has no perpendicular magnetic anisotropy because of no rapid temperature annealing performed. Figure 2 shows the F values as a function of light power at -0.5 V with no magnetic field. For the 38.5-nm sample, F increased up to 4.8% at 0.5 mW and then decreased to 2% at 4.5 mW. In contrast, the 250-nm sample exhibited no saturation of F within the measured range. These findings indicate that by adjusting the thickness of the light-absorbing GaNAs layer, the optimum operating light power for polarization-sensitive GaNAs photodiodes can be widely controlled.

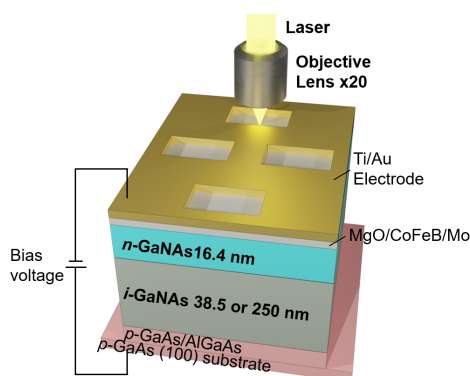


Fig. 1 schematic illustration of GaNAs-based PIN photodiode developed in this study.

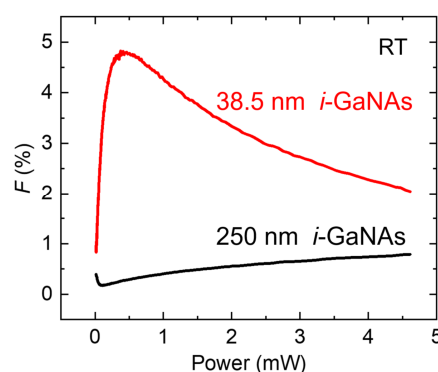


Fig. 2 F as a function of light power at -0.5 V with a laser wavelength of 1025 nm.

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Device Design Guideline for High-Performance Si-based Spin MOSFETs

Yuki Takahashi¹, Shoichi Sato^{1,2}, Masaaki Tanaka^{1,2}, and Ryosho Nakane^{1,3}

¹Dept. of Electrical Eng. and Information Systems, ²Center for Spintronics Research Network (CSRN),

³Systems Design Lab (d.lab), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

E-mail: takahashi-yuki950@g.ecc.u-tokyo.ac.jp

Si-based Spin MOSFETs [1] have been proposed as semiconductor devices that can be applied to non-volatile random-access memory and reconfigurable logic circuits for low power electronics. A spin MOSFET has the same device structure as an ordinary MOSFET while its source and drain (S/D) electrodes are ferromagnetic materials, which allows the change in the output current according to the relative magnetization between parallel and antiparallel states. Several demonstration examples of Si-based Spin MOSFETs have been reported, but further improvement in performance is necessary for practical applications. Here, we study various characteristics of spin MOSFETs with a ferromagnetic Fe/Mg/MgO/SiO₂/n⁺-Si tunnel junction, to find a device design guideline for spin MOSFETs with higher magnetoresistance ratio. Based on our spin transport model [2, 3], the bias dependence of MR ratio (γ^{MR}) and the spin polarization P_S are mainly analyzed through spin-valve and Hanle signals.

Fig. 1 shows the back-gate-type Spin MOSFET used in this study. The device was fabricated using a p-type B-doped SOI ($1 \times 10^{15} \text{ cm}^{-3}$) substrate. For the source/drain, ferromagnetic tunnel junctions consisting of Fe (4 nm)/Mg (1 nm)/MgO ($t_{MgO} = 1.0 \sim 1.5 \text{ nm}$)/SiO₂ ($\sim 0.2 \text{ nm}$)/n⁺-Si (5 nm) are employed. To reduce the high resistance due to the Schottky barrier, the Si region directly beneath the electrodes is n⁺ with heavily P-doped to a degenerate level ($1 \times 10^{20} \text{ cm}^{-3}$). The SiO₂ layer was formed using RF plasma oxidation at room temperature, which is reported to reduce the interface state density D_{it} , leading to an increase in P_S [4]. Spin-valve signals are obtained by applying a back-gate voltage, driving a constant current between the S/D electrodes, and measuring the voltage difference between them while sweeping the external magnetic field. Fig. 2 shows the spin-valve signals measured for a device with $t_{MgO} = 1.2 \text{ nm}$ under conditions of $V_{GS} = 30 \text{ V}$ and $I_{DS} = 4 \text{ mA}$. As shown in the figure, clear major and minor loops are observed. Fig. 3(b) shows the P_S obtained from the spin-valve signals and analysis as a function of the junction bias voltage V_J . The results indicate that P_S exhibits V_J dependence and has a peak, which may be explained by a theoretical model based on the junction band profile [5]. According to the spin diffusion transport model [3], γ^{MR} can be approximately expressed as $\gamma^{MR} \sim P_S^2 / 2R_J$, where R_J is the junction resistance. Therefore, achieving a high MR ratio requires both a high P_S and a high junction conductance $1/2R_J$. However, as shown in Fig. 3, increasing $1/2R_J$ by reducing the tunnel barrier thickness is found to decrease P_S . To overcome this conflicting problem and realize Si-based Spin MOSFETs with a high γ^{MR} , it is necessary to reduce the interface state density to prevent a decrease in P_S , while simultaneously employing a thin tunnel barrier to avoid excessive increases in R_J , which would otherwise lower γ^{MR} .

Acknowledgment: This work was partly supported by Grants-in-Aid for Scientific Research (20H05650, 23K17324, 23H00177) and Spintronics Research Network of Japan (Spin-RNJ). This work is partly supported by the CREST Program of JST (No. JPMJCR1777) and Spin-RNJ.

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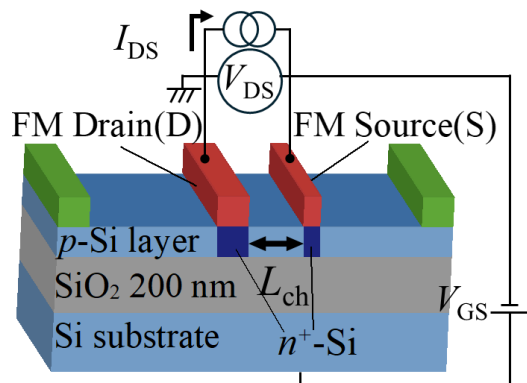


Fig. 1 Schematic Si-based spin MOSFET device structure and setup to measure spin signals.

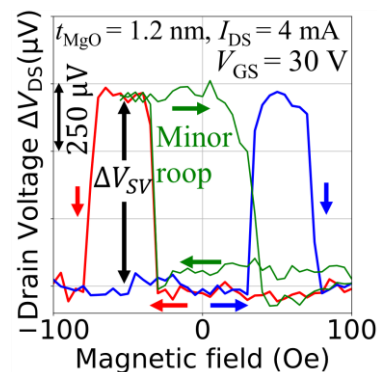


Fig. 2 Spin-valve signals for $t_{MgO} = 1.2 \text{ nm}$

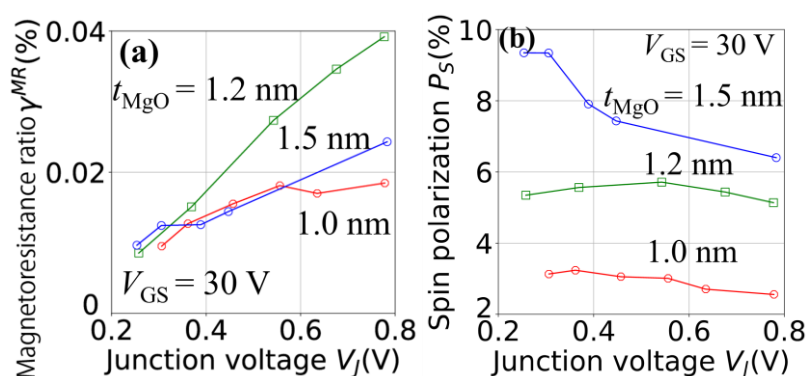


Fig. 3 (a) $\gamma^{MR} - V_J$ (b) $P_S - V_J$ plots for various t_{MgO} values, where $V_{GS} = 30 \text{ V}$.

Non local detection of current induced magnetization switching using lateral spin-valve device

Grad. School of Information Science and Technology, Hokkaido University.

°Mineto Ogawa, Yu Osada, Michihiko Yamanouchi, Tetsuya Uemura

E-mail: iavtre@eis.hokudai.ac.jp

Spin injection from ferromagnetic electrode into semiconductor and an electrical manipulation of magnetization direction are indispensable technologies for realizing spin transistors. In this work, we detected the spin-orbit torque (SOT) induced magnetization switching of in-plane magnetized CoFe electrode through the non-local spin-valve measurement.

A lateral spin valve device with Pt/CoFe electrodes and n-GaAs spin transport channel was fabricated. After initializing the magnetization directions for the injector and detector contacts by applying the in-plane magnetic field $B_y = -0.3$ T in the y-direction, a pulse current I_p with its duration of 1 s was applied to the injector electrodes parallel to the y-direction under the out-of-plane magnetic field $B_z = 0.45$ T to induce the magnetization switching, where y-axis direction is orthogonal to the GaAs channel direction. Then the non-local voltage V_{NL} was measured by sweeping the B_y from 0 to 0.08 T to detect the magnetization configuration. All the measurements were performed at 77 K.

Figure 1 shows V_{NL} as a function of B_y after $I_p = \pm 13.5$ mA was applied. In case for $I_p = +13.5$ mA, the magnetization configuration between injector and detector contact switched from parallel (P) to antiparallel (AP) at $B_y \approx 0.025$ T, and switched back again from AP to P at $B_y \approx 0.04$ T. In case for $I_p = -13.5$ mA, on the other hand, the magnetization configuration was already AP state at $B_y = 0$, and it switched only one time from AP to P at $B_y \approx 0.04$ T. These results indicate that the SOT-induced magnetization switching occurred at $I_p = -13.5$ mA. Thus, we successfully demonstrated SOT-induced magnetization switching through non-local spin-valve signals.

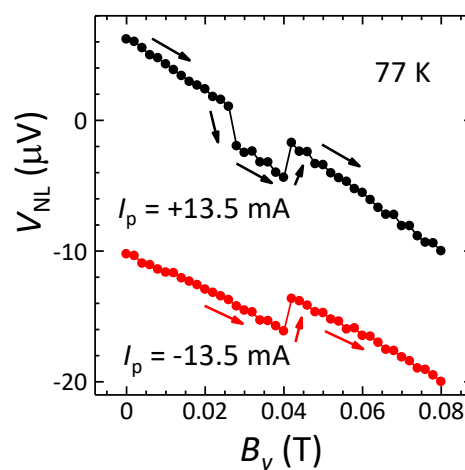


Fig.1 non-local voltage as a function of in-plane magnetic field starting at zero field after $I_p = \pm 13.5$ mA was applied to the injector electrode under $B_z = 0.45$ T measured at 77 K.

This work was supported in part by JSPS KAKENHI (25K0127905), MEXT X-NICS (JPJ011438), MEXT ARIM (JPMXP1225HK0012), JST CREST (JPMJCR22C2), and JST SPRING (JPMJSP2119).

Weak anti-localization effect in In-doped SnTe thin films

○R. Uesugi¹, R. Ando², M. Mizuno¹, T. Aono¹, T. Chiba³, and T. Komine¹

1. Ibaraki Univ., 2. Ibaraki College, 3. Yamagata Univ.

E-mail: Ryota.uesugi.nb29@vc.ibaraki.ac.jp

SnTe is known as a topological crystalline insulator protected by mirror symmetry, and it is of interest in surface states and applications.¹⁾ SnTe is easily defective in the Sn site and tends to be a p-type semiconductor with a carrier density of $\sim 10^{20} \text{ cm}^{-3}$. In this work, the effect of In-doping on the Weak Anti-Localization (WAL) which appeared in topological surface states was investigated to clarify the surface state of SnTe films.

The SnTe films were deposited on MgO(001) single-crystal substrates using magnetron sputtering. We employed co-sputtering with Sn–Te and (Sn, In)–Te alloy targets to control the In composition of the films. It is expected that the surface state of SnTe(001) will appear in the SnTe deposited on MgO(001) due to the substrate orientation. After depositing the SnTe films, they were annealed at 240 °C in vacuum to improve the crystallinity and to suppress Sn defects. X-ray diffraction was used for crystal structure analysis, X-ray fluorescence for compositional analysis, and PPMS was used to measure a magneto-conductance $\Delta G = G(B) - G(0 \text{ T})$ and the Hall resistance from 2–300 K in order to evaluate the carrier density and mobility. From the measured ΔG as shown in Fig. 1, the WAL due to the two-dimensionality of the surface state was evaluated using the Hikami–Larkin–Nagaoka equation.²⁾

$$\Delta G = -\alpha \frac{e^2}{\pi h} \left[\psi \left(\frac{B_\phi}{B} + \frac{1}{2} \right) - \ln \frac{B_\phi}{B} \right], \quad B_\phi = \frac{4el_\phi^2}{\hbar},$$

where ψ , α , and l_ϕ are the digamma function, the channel number, and the phase coherence length, respectively.

The temperature T dependence of α and l_ϕ at low temperatures are shown in Fig. 2. Because the conduction channel of the surface state was observed in both the SnTe and In-doped SnTe films, it is confirmed the existence of the two-dimensional surface state was independent of the In-doping. On the other hand, the T dependence of l_ϕ was observed for the T^{-1} in the SnTe films, while $T^{-1/2}$ in the In-doped SnTe films. In general, the exponent in the temperature of the phase coherence length represents the dominant scattering factor in quantum interference effects, and it is considered that the electron-electron scattering is dominant due to the In-doping.

This work was partially supported by JST-ALCA-Next (Grants No. JPMJAN24B3) and Grants-in-Aid for Scientific Research (Grants No. 24K00916, 24H00018, 25H02105, 25K08296, 24K06912). Low-temperature measurements were performed with the support of CROSS-Tokai.

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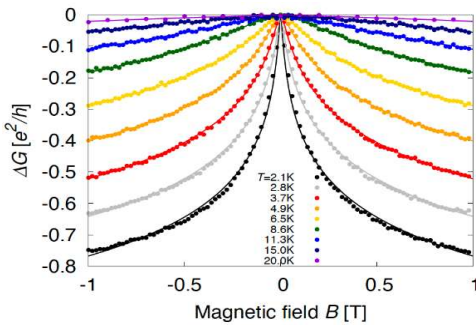


Fig. 1 Field dependence of magneto-conductance in SnTe films

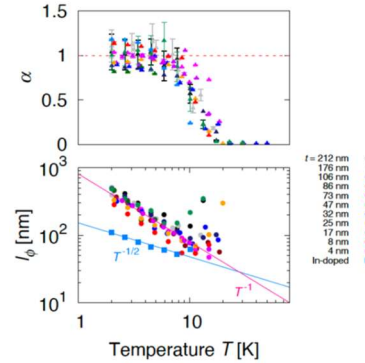


Fig. 2 Characteristic parameters of WAL.

Large field-free superconducting diode effect in α -Sn / β -Sn planar heterostructures

[○]Yuta Okuyama¹, Le Duc Anh^{1,2} and Masaaki Tanaka^{1,2}

¹Department of Electrical Engineering and Information Systems, The University of Tokyo,

²Center for Spintronics Research Network (CSRN), The University of Tokyo,

E-mail: okuyama-yuta395@g.ecc.u-tokyo.ac.jp

Fault-tolerant quantum computing (FTQC) is essential for the development of practical quantum computers. Utilizing topological superconductivity (TSC) with Majorana zero modes (MZMs) is a promising way to achieve FTQC, and MZMs are theoretically predicted to appear in heterostructures of topological materials (TM) and superconductors (SC) [1]. Here, we focus on Sn-based planar heterostructures. Sn has α and β phases distinguished by its crystal structure. α -Sn has a diamond-type crystal structure, which is known as a topological Dirac semimetal (TDS) [2], while β -Sn has a tetragonal crystal structure, which is a BCS superconductor at low temperature. Recently, we have successfully fabricated any shape of α -Sn/ β -Sn planar heterostructures by irradiating a focused ion beam (FIB) on α -Sn films, where FIB-irradiated regions are selectively heated by ion collisions and undergo a phase transition from α -Sn to β -Sn [3,4]. The FIB-induced β -Sn nanowires embedded in α -Sn exhibit a superconducting diode effect (SDE) in the presence of an external magnetic field parallel to the current. This SDE was thought to occur at the β -Sn/ α -Sn interfaces, because the center part of the β -Sn nanowires was heavily destroyed by the strong ion collision [3].

In this study, we study the formation and superconducting transport properties of β -Sn nanowires embedded in α -Sn thin films under various FIB irradiation conditions. The α -Sn films were grown on InSb (001) substrate by molecular beam epitaxy in an Sb-free chamber at very low temperature ($< -20^\circ\text{C}$) after the growth of an InSb buffer layer; this process improves the quality of the α -Sn films compared with the previous work [3,4]: The reflection high energy electron diffraction patterns of the α -Sn films are streaky in this study, which was not observed in the previous samples of refs [3,4]. X-ray reflection diffraction shows a peak from α -Sn with clear fringes. β -Sn nanowires with widths around 450 nm are fabricated by repeating the focused ion beam (FIB), as shown in Fig. 1a. During the cooling process to measure superconducting properties, β -Sn nanowires fabricated under the same conditions as refs [3,4] partially reverted to α -Sn, exhibiting the well-known "tin pest" phenomenon, and those nanowires did not show superconducting transition. This suggests that β -Sn regions in those nanowires in this work possess less impurities than those in our previous reports [3,4], because impurities such as Sb atoms in β -Sn incorporated from the chamber atmosphere or diffused from the InSb substrate are considered to prevent Sn pest [5]. β -Sn nanowires in this work with larger FIB writing iterations for suppressing "tin pest" phenomenon showed superconducting transitions at 3.7 K, which corresponds to superconducting transition temperature of β -Sn. Upon switching the current direction, a large critical current difference $\Delta I_c = 81\mu\text{A}$ was observed with a diode efficiency $\eta = 11\%$, indicating a large SDE. Furthermore, a sizable SDE is observed even in the absence of an external magnetic field (Fig. 1b). This prominent, field-free SDE may be caused by origins different from those of the samples in our previous work [3,4]. The realization of such a zero-field SDE is particularly promising for practical applications, including its potential use in rectifying elements for superconducting circuits. This work was partly supported by Grants-in-Aid for Scientific Research, CREST of JST, and Spintronics Research Network of Japan (Spin-RNJ).

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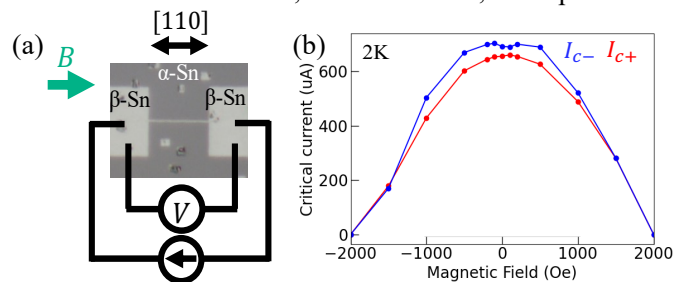


Fig. 1 (a) Top view of a nanowire (width of 450 nm), taken by optical microscopy, and measurement setup. (b) Forward (backward) critical current I_{c+} (I_{c-}) measured at 2 K under various magnetic fields B applied parallel to the current.

10 Spintronics and Magnetism | Oral presentation : 10.4 Spintronics in semiconductor, topological material, superconductor, and multiferroics

[10p-N303-1~9] 10.4 Spintronics in semiconductor, topological material, superconductor, and multiferroics

[10p-N303-1]

Detection of spin polarization in superconducting $\text{FeTe}_{0.6}\text{Se}_{0.4}$ via potentiometric method

○Ryo Ohshima¹, Kosuke Ohnishi¹, Taiki Nishijima¹, Shinya Kawabata¹, Sigeru Kasahara^{2,3}, Yuichi Kasahara³, Yuichiro Ando^{1,4}, Youichi Yanase³, Yuji Matsuda³, Masashi Shiraishi¹ (1.Dept. of Eng., Kyoto Univ., 2.RIIS, Okayama Univ., 3.Dept. of Phys., Kyoto Univ., 4.PRESTO-JST)

[10p-N303-2]

Experiment and Theory of Interfacial Multiferroics Driven by Super-Orbital Splitting at Room Temperature

○Hiroshi Naganuma¹, Kenji Nawa², Tomohiro Ichinose², Kenta Amemiya³, Takahisa Shiraishi⁴, Yukio Sato⁴, Tetsuya Fukushima² (1.Nagoya Univ.NUIAS, 2.AIST, 3.KEK, 4.Kumamoto Univ.)

[10p-N303-3]

Enhancement of orbital magnetic moment via epitaxial lift-off of $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$

○Takahito Takeda¹, Takuma Arai², Daigo Matsubara², Kohei Yamagami³, Le Duc Anh^{2,4}, Masaaki Tanaka^{2,4}, Masaki Kobayashi^{2,4}, Shinobu Ohya^{2,4} (1.Dept. Chemsys, The Univ. of Tokyo, 2.Dept. EEIS, The Univ. of Tokyo, 3.JASRI, 4.CSRN, The Univ. of Tokyo)

[10p-N303-4]

Epitaxial growth and characterization of a superconducting Sn/InSb heterostructure on a GaAs substrate

○Shingen Miura¹, Hirotaka Hara¹, Hideki Maki¹, Le Duc Anh^{1,2}, Masaaki Tanaka^{1,2} (1.Univ. of Tokyo, 2.CSRN, Univ. of Tokyo)

[10p-N303-5]

Magnetic Properties of Fe_3O_4 membranes Transferred from a SrTiO_3 substrate via dissolution of a BaO Sacrificial Layer

○Daigo Matsubara¹, Takahito Takeda¹, Masaaki Tanaka^{1,2}, Ohya Shinobu^{1,2} (1.Tokyo Univ., 2.CSRN, Tokyo Univ.)

[10p-N303-6]

Growth and characterization of superconducting Vanadium / semiconductor InAs heterostructures

○Kouta Iwakura¹, Tomoki Hotta¹, Hideki Maki¹, Le Duc Anh^{1,2}, Masaaki Tanaka^{1,2} (1.UTokyo, 2.CSRN)

[10p-N303-7]

Enhanced Organic Dye Degradation via Photocatalysis and Piezocatalysis Using Sintered NiFe_2O_4 Nanoparticles

○(M1)Xinyu Jin¹, Tomoyuki Kurioka^{1,2}, Chun-Yi Chen^{1,2}, Masato Sone¹, Yung-Jung Hsu^{1,2,3}, Satoshi Okamoto^{1,2}, Tso-Fu Mark Chang^{1,3} (1.Science Tokyo, 2.Sumitomo Chemical, 3.NYCU)

[10p-N303-8]

Hydrothermal Synthesis of Bismuth Ferrite-based Nanoparticles and the Application in Piezocatalytic Dye Degradation

○(D)Chen YuHao¹, Jin XinYu¹, Kurioka Tomoyuki^{1,2}, Chen Chun-Yi^{1,2}, Sone Masato^{1,2}, Hsu YungJung^{1,2,3}, Okamoto Satoshi^{1,2}, Chang Tso-Fu Mark^{1,2} (1.Institute of Science Tokyo, 2.Sumitomo Chemical, 3.NYCU)

[10p-N303-9]

Superconducting proximity effect in an in-situ grown heterostructure consisting of superconductor Al / InAs / ferromagnetic semiconductor (Ga,Fe)Sb

○Hiroataka Hara¹, Lukas Baker², Shingen Miura¹, Keita Ishihara¹, Melissa Mikalsen², Patrick Strohbeen², Jacob Issokson², Masaaki Tanaka^{1,3,4}, Javad Shabani², Le Duc Anh^{1,3} (1.EEIS, Univ. of Tokyo, 2.CQIP, New York Univ., 3.CSRN, Univ. of Tokyo, 4.Nano Quine, Univ. of Tokyo)

Detection of spin polarization in superconducting $\text{FeTe}_{0.6}\text{Se}_{0.4}$ via potentiometric method

Dept. of Eng., Kyoto Univ.¹, RIIS, Okayama Univ.², Dept. of Phys., Kyoto Univ.³, PRESTO-JST⁴,

[○]Ryo Ohshima¹, Kosuke Ohnishi¹, Taiki Nishijima¹, Shinya Kawabata¹, Sigeru Kasahara^{2,3},

Yuichi Kasahara³, Yuichiro Ando^{1,4}, Youichi Yanase³, Yuji Matsuda³, and Masashi Shiraishi¹

E-mail: ohshima.ryo.2x@kyoto-u.ac.jp

FeTeSe has been collecting much attention as one of the possible candidates of topological p -wave superconductors, hosting Majorana quasiparticles. In fact, recent studies using scanning tunnelling microscopy have revealed that the zero-energy state can appear in vortex cores in FeTeSe by applying a perpendicular external magnetic field [1,2]. Spontaneous time-reversal symmetry breaking in FeTeSe has been also reported and indicated a possible spin polarized state at the surface of FeTeSe as a nature of effective topological p -wave superconducting state [3-5]. On the other hand, the experimental technique to access the topological p -wave state is still limited. Here, we demonstrate electrical detection of spin polarization in superconducting $\text{FeTe}_{0.6}\text{Se}_{0.4}$ via potentiometric method.

An $\text{FeTe}_{0.6}\text{Se}_{0.4}$ flake was exfoliated from a bulk crystal synthesized by chemical vapor transport method and transferred onto a thermally oxidized silicon substrate by using scotch tape. The thickness of the $\text{FeTe}_{0.6}\text{Se}_{0.4}$ flake was approximately 70 nm and $\text{Au}(70\text{ nm})/\text{Co}(30\text{ nm})$ electrodes were equipped onto the flake as a spin detector by electron-beam evaporation. We also prepared a spin device made of FeSe , instead of $\text{FeTe}_{0.6}\text{Se}_{0.4}$. FeSe is the mother superconducting material of FeTeSe but is a conventional s -wave superconductor. Figure 1(a) shows a schematic image of the device and measurement setup. Magnetic field was applied along the longitudinal direction of the Au/Co electrode and potentiometric method was applied with a local electrical three-terminal setup. Figure 1(b) shows the result obtained from the potentiometric method below the transition temperatures. A clear spin voltage hysteresis was observed from the $\text{FeTe}_{0.6}\text{Se}_{0.4}$ device in the superconducting state whereas no spin voltage was observed from the FeSe device. The results indicate that the spin polarization appearing in superconducting $\text{FeTe}_{0.6}\text{Se}_{0.4}$ was detected by the potentiometric method [6].

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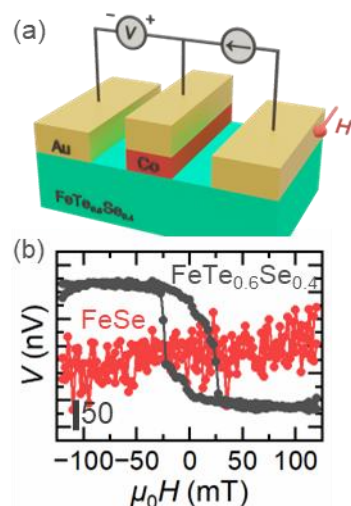


Fig. 1 (a) A schematic image of device structure and measurement setup. (b) Signals obtained by the potentiometric method from the superconducting $\text{FeTe}_{0.6}\text{Se}_{0.4}$ and FeSe .

室温動作する超軌道分裂型の界面マルチフェロイックの実験と理論

Experiment and Theory of Interfacial Multiferroics Driven

by Super-Orbital Splitting at Room Temperature

名古屋大 NUIAS¹, 産総研², 高エネ研³, 熊本大⁴, [○]永沼博¹, 名和 憲嗣², 一ノ瀬 智浩²,
雨宮 健太³, 白石 貴久⁴, 佐藤 幸生⁴, 福島 徹夜²

Nagoya Univ.¹, AIST², KEK PF³, Kumamoto Univ.⁴, [○]Hiroshi Naganuma¹, Kenji Nawa², Tomohiro
Ichinose², Kenta Amemiya³, Takahisa Shiraishi⁴, Yukio Sato⁴, Tetsuya Fukushima²

E-mail: hiroshi.naganuma.c3@tohoku.ac.jp

Magnetoelectric (ME) coupling in multiferroics is a key focus for developing ultra-low-power memory and highly sensitive sensors. However, conventional multiferroics suffer from low transition temperatures and weak ME responses at room temperature, which limits their applications. We previously reported that when Ru is deposited on BiFeO₃, the magnetization of Fe increases at room temperature.¹⁾ In this study, we demonstrate a new type of interfacial multiferroic that exhibits a large ME effect at room temperature, and we also performed first-principles calculations to clarify the physical origin of magnetism. This effect emerges at the interface between multiferroic BiFeO₃ and a metallic Co overlayer. Structural and spectroscopic analyses reveal the formation of a ~1 nm interfacial layer, where X-ray magnetic circular dichroism (XMCD) measurements at KEK-PF BL-16 detect a strong, electrically switchable interfacial magnetic moment driven by the small electric field. First-principles calculations using FUGAKU reveal that this interfacial state originates from electronic reconstruction resulting from oxygen vacancies and partial Co substitution at Fe sites in BiFeO₃. The calculations reproduce the experimental XMCD spectra and reveal that the interface remains insulating despite these modifications. This is attributed to an unconventional orbital configuration we called “super-orbital-splitting. These results highlight the potential of interface engineering to induce multiferroic properties not found in bulk materials. Our findings offer a promising strategy for realizing room-temperature, tunable magnetoelectric devices through atomic-scale control at oxide-metal interfaces.

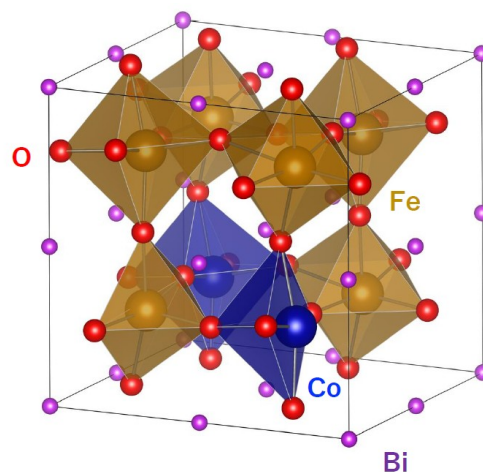


Fig. 1 Bi(Fe,Co)O_x supercell obtained by first-principles calculations using FUGAKU

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Acknowledgements: This work was partly supported by KAKENHI Grant-in-Aid for Transformative Research Areas (B) (No.23H03803), Grant-in-Aid for Scientific Research (B) (No. 24K01346), JSPS core to core (No. JPJSCCA20230005)

Enhancement of orbital magnetic moment via epitaxial lift-off of $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$

[○]Takahito Takeda¹, Takuma Arai,² Daigo Matsubara,² Kohei Yamagami,³

Le Duc Anh,^{2,4} Masaaki Tanaka,^{2,4} Masaki Kobayashi,^{2,4} and Shinobu Ohya^{2,4}

¹*Department of Chemical System Engineering, The University of Tokyo*

²*Department of Electrical Engineering and Information Systems, The University of Tokyo*

³*Japan Synchrotron Radiation Research Institute*

⁴*Center for Spintronics Research Network, The University of Tokyo*

Email: ttakeda@g.ecc.u-tokyo.ac.jp

Perovskite oxides have attracted significant attention due to their diverse properties and device applications. In particular, $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ (LSMO) is a promising ferromagnet due to the Curie temperature (T_C) above 300 K and half metallicity. The ferromagnetism of LSMO is due to the double-exchange interaction through Mn^{3+} -O- Mn^{4+} . While LSMO-based spintronic devices show intriguing performances [1], their performance is suppressed by a "dead layer" near interfaces with other perovskite oxides, which degrades the ferromagnetism and conductivity of LSMO. It is considered that this dead layer originates from interfacial effects such as epitaxial strain and oxygen octahedral rotation induced by the substrate material. Epitaxial lift-off of LSMO thin films using a water-soluble sacrificial buffer layer is one of the promising solutions for the dead layer problem. Recent studies demonstrate that epitaxial lift-off improves the magnetization and/or T_C and reduces the dead layer in LSMO [2,3]. For device applications, understanding the mechanism of ferromagnetism enhancement through epitaxial lift-off is crucial.

We epitaxially grew an LSMO (30 unit cells ~ 12 nm) / $\text{Sr}_4\text{Al}_2\text{O}_7$ (17 nm) heterostructure on an STO (001) substrate by molecular beam epitaxy, and transferred the LSMO layer onto a p-Si substrate after dissolving the $\text{Sr}_4\text{Al}_2\text{O}_7$ layer in water. The LSMO membrane showed saturation magnetization of $3.2 \mu_B/\text{Mn}$ at 5 K and T_C of 323 K, which are higher than those of the as-grown film ($2.0 \mu_B/\text{Mn}$ and 312 K, respectively) [3]. To investigate the ferromagnetism enhancement in the LSMO membrane, we performed X-ray absorption spectroscopy (XAS) and X-ray magnetic circular dichroism (XMCD) at the Mn $L_{2,3}$ absorption edge. The XAS spectra of both as-grown film and membrane reflect mixed $\text{Mn}^{3+}/\text{Mn}^{4+}$ valence states [Figs. 1(a) and 1(b)]. The XMCD spectra of the LSMO membrane show that the spectral shapes strongly depend on the direction of the applied magnetic field compared to these of the as-grown film, possibly due to magnetostriction [Figs. 1(a) and 1(b)]. Using the XMCD sum rules, we estimate the spin and orbital magnetic moments of Mn $3d$ electrons, indicating that epitaxial strain release from the STO substrate reduces the anisotropy of orbital magnetic moments while enhancing their magnitude. This enhancement of orbital magnetic moments directly explains the observed improvement the ferromagnetism in LSMO.

This work was partly supported by Grants-in-Aid for Scientific Research, CREST of JST, and the Spintronics Research Network of Japan (Spin-RNJ).

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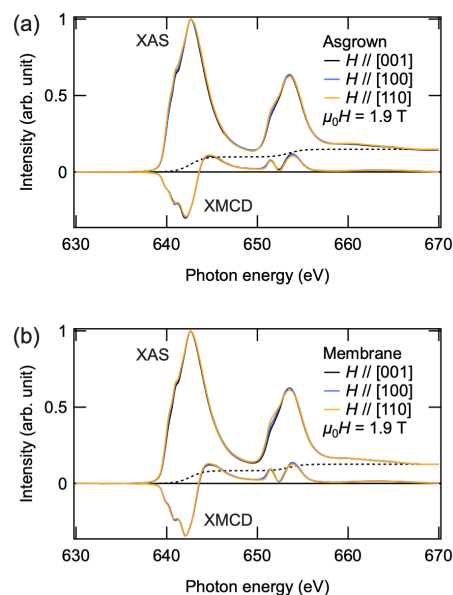


Fig. 1: Applied magnetic field direction dependence of the XAS and XMCD spectra at the Mn L_3 absorption edge of (a) the as-grown film and (b) the membrane taken at 45 K. The dotted curves are the backgrounds of the XAS spectra.

Epitaxial growth and characterization of a superconducting Sn/InSb heterostructure on a GaAs substrate

[○]Shingen Miura¹, Hirotaka Hara¹, Hideki Maki¹, Masaaki Tanaka^{1,2} and Le Duc Anh^{1,2}

Department of Electrical Engineering and Information Systems, The University of Tokyo¹,

Center for Spintronics Research Network (CSRN), The University of Tokyo²,

E-mail: shingen-miura0516@g.ecc.u-tokyo.ac.jp

Topological superconductivity has attracted significant attention as an essential research subject for realizing fault-tolerant topological quantum computers, owing to the potential existence of Majorana fermions that are protected from external disturbances. Theoretically, it has been predicted that a topological superconducting state can be induced through the superconducting proximity effect in heterojunction systems comprising superconductors and semiconductors with strong spin-orbit interaction [1, 2].

In this study, we grew Sn/InSb heterostructures on GaAs substrates using molecular beam epitaxy (MBE) and studied their crystal structure and transport properties. The Sn layer exhibits superconductivity below 5 K, whose critical magnetic field and critical current exhibit twofold symmetry upon applying a rotating magnetic field: The superconducting critical current and magnetic field weaken when the in-plane magnetic field was applied parallel to the current direction, whereas it remained relatively large when the in-plane magnetic field was perpendicular to the current direction (Fig. 1). This anisotropy cannot be explained solely by conventional β -Sn superconductivity, which follows the BCS theory. Additionally, in XRD measurements we observed peaks corresponding to both α -Sn and β -Sn. It is known that when α -Sn, a topological Dirac semimetal, exhibits superconductivity, it can become a topological superconductor [3]. These results suggest that our Sn film contains both α -Sn and β -Sn, and the α -Sn regions might become superconducting through the superconducting proximity effect from the neighboring β -Sn regions, which could potentially exhibit topological superconductivity.

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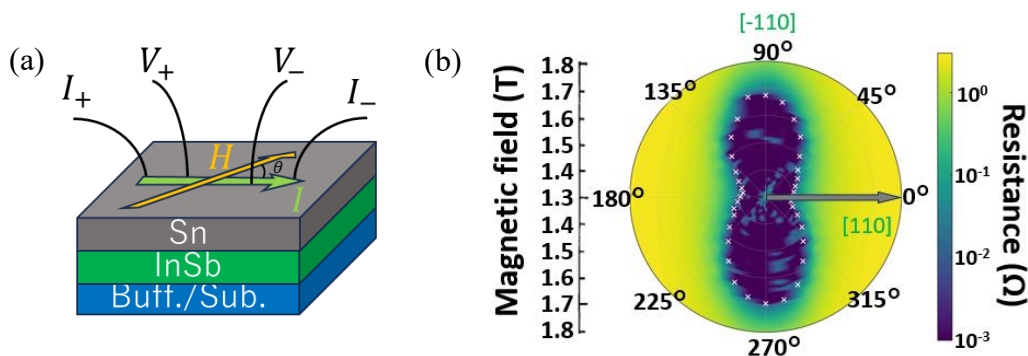


Fig.1 (a) Schematic illustration of the Sn/InSb heterostructure epitaxially grown on a GaAs (001) substrate, with electrodes patterned for transport measurements. The current I flows along the $[110]$ direction, while the magnetic field H is applied in-plane and rotated at an angle θ from the current I direction. (b) Polar plot of the electrical resistance as a function of in-plane magnetic field angle θ (logarithmic scale). The resistance shows maxima at $\theta = 90^\circ$ and $\theta = 270^\circ$, indicating in-plane anisotropic superconductivity with two-fold symmetry in the Sn film.

Magnetic Properties of Fe₃O₄ membranes Transferred from a SrTiO₃ substrate via dissolution of a BaO Sacrificial Layer

Daigo Matsubara¹, Takahito Takeda², Masaaki Tanaka^{1,3} and Shinobu Ohya^{1,3}

¹Department of Electrical Engineering and Information Systems, The University of Tokyo

²Department of Chemical System Engineering, The University of Tokyo

³Center for Spintronics Research Network, The University of Tokyo

E-mail: matsubara-daigo419@g.ecc.u-tokyo.ac.jp

Techniques of transferring epitaxial thin films onto different substrates using water-soluble sacrificial layers have attracted considerable attention in recent years. Those methods are particularly promising for developing novel approaches to controlling physical properties through strain engineering, leading to flexible device applications [1]. Also, the ferrimagnetic oxide Fe₃O₄ [Fig. 1(a)] is known for its rich properties: high Curie temperature $T_C \approx 850$ K, theoretically 100% spin polarization near the Fermi level [2], and its metal-insulator transition, called the Verwey transition, near 120 K [3]. In a previous report, a Fe₃O₄ thin film was transferred onto a polydimethylsiloxane (PDMS) film using Sr₃Al₂O₆ as a water-soluble sacrificial layer, and notably, its magnetization remained stable even under bending deformation [2]. However, the composition control of Sr₃Al₂O₆ is difficult, and the process requires long-time immersion in water (≤ 1 day), which can lead to degradation of the target functional film.

In this study, we employed BaO, which is an easily grown binary compound, as a sacrificial layer. It readily dissolves in water only within ~ 1 hour. Using molecular beam epitaxy (MBE), we grew a heterostructure composed of Fe₃O₄ (thickness $d = 50$ nm) /BaO ($d = 4$ nm) on a SrTiO₃ (STO) (001) substrate. The thin film was subsequently transferred onto a SiO₂/Si substrate [Fig. 1(b), (c)]. The temperature dependence of the magnetization exhibited a peak at the Verwey transition temperature (118 K) [Fig. 1(d), (e)], which is lower than that reported for Fe₃O₄ thin films on STO substrates (120 K) [4]. The decrease in the transition temperature may result from the enhanced superexchange interactions along the direction perpendicular to the substrate due to strain release. This facilitates the suppression of three-Fe-site polarons called trimersons [5] - regarded as the origin of the Verwey transition - at lower temperatures. The use of BaO enabled the reproducible realization of thin Fe₃O₄ film properties, and this technique provides a platform for exploring intrinsic physical properties of thin films free from epitaxial strain.

This work was supported by JSPS KAKENHI, JST ERATO, and the Spintronics Research Network of Japan (Spin-RNJ).

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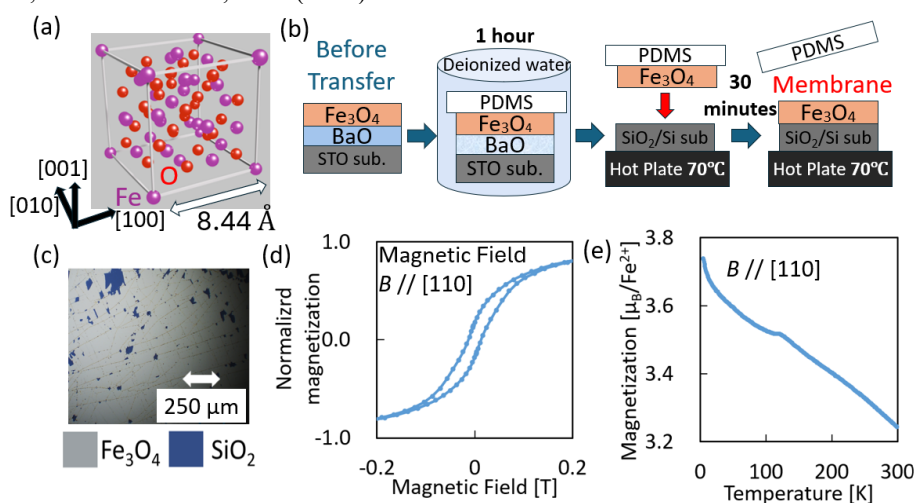


Fig. 1: (a) Unit cell of Fe₃O₄, which has an inverted cubic spinel structure. (b) Schematic illustrations of the film transferring method. (c) Optical microscope image of the Fe₃O₄ membranes transferred onto a SiO₂/Si substrate. (d) Normalized magnetization curve obtained at 300 K measured for the Fe₃O₄ membranes transferred onto a SiO₂/Si substrate. (e) Temperature dependence of the magnetization measured for the Fe₃O₄ membranes under field-cooling conditions with a magnetic field of 0.04 T applied.

Growth and characterization of superconducting Vanadium / semiconductor InAs heterostructures

Kouta Iwakura¹, Tomoki Hotta¹, Hideki Maki¹, Le Duc Anh^{1,2}, Masaaki Tanaka^{1,2}

¹Department of Electrical Engineering and Information Systems, The University of Tokyo

²Center for Spintronics Research Network (CSRN), The University of Tokyo

E-mail: iwakura-kota0227@g.ecc.u-tokyo.ac.jp

For the realization of error-tolerant topological quantum computers, developing devices composed of superconductor/semiconductor heterostructures attracts much attention [1]. In such superconducting junction devices, it is essential to achieve both strong magnetic-field tolerance and a robust superconducting proximity effect, as well as to ensure high-quality superconductor/semiconductor interfaces. A representative material system in this context is Al/InAs heterostructures [2]. However, bulk aluminum exhibits superconducting transition temperature of only 1.2 K, and its critical magnetic field is approximately 0.01 T. Conversely, bulk Vanadium (V) undergoes superconducting transition at 5.2 K, and its critical field reaches 0.1 T. Moreover, the lattice constant of the V with bcc structure is twice that of InAs, which is frequently employed with its high mobility and strong spin-orbit coupling. Although V/InAs heterostructures can be a highly promising material system, there has been no report on its successful epitaxial growth and characterization.

In this research, we have successfully grown V/InAs thin film heterostructures on GaAs(001) substrates for the first time. AlAs/AlSb buffer layers and InAs layer were grown on a GaAs(001) substrate by molecular beam epitaxy, and a Vanadium thin film (thickness $t = 15, 20, 30$ nm) was grown *in situ* by electron beam deposition (EB) and sputtering (SP) (Fig. 1(a)). As shown in Fig. 1(c), X-ray diffraction (XRD) peaks of V {110} are observed for the samples grown by sputtering. The XRD reciprocal space mapping and lattice images taken by transmission electron microscope (TEM) (fig. 1(b)) reveal an epitaxial relationship of (110)[111]V // (001)[110]InAs. As shown in fig.1(d), all the samples show superconducting transition, which depends on the V thickness. Furthermore, the perpendicular critical magnetic field reaches 1.3 T ($t = 20$ nm), while the in-plane one reaches 3.7 T ($t = 30$ nm), largely surpassing the value (~ 250 mT) of Al/InAs [3]. The successful growth of high-quality V/InAs heterostructure and understanding their properties are important steps for their applications to quantum devices.

This work was partly supported by Grants-in-Aid for Scientific Research, CREST Program of JST, and Spintronics Research Network of Japan (Spin-RNJ).

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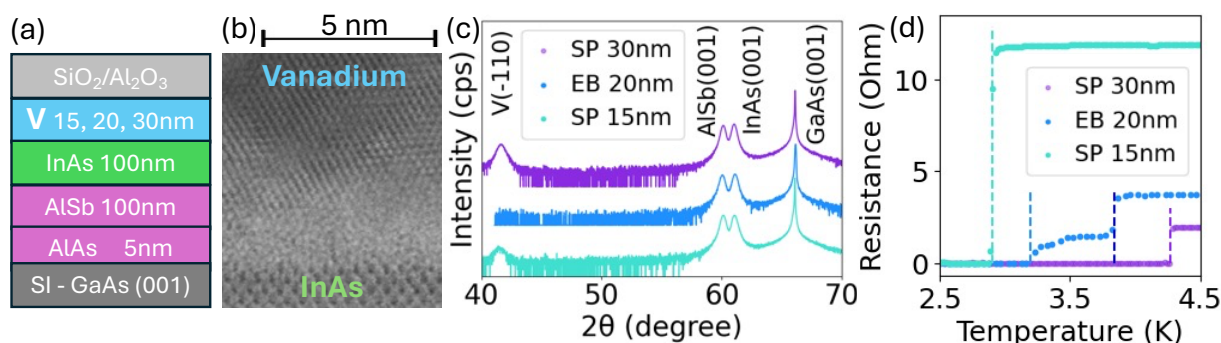


Fig 1: (a) Schematic sample structure. (b) Lattice image from the [110] direction of the substrate taken by TEM. (c) XRD results in all three samples. (d) Temperature dependence of the resistance of V thin films.

Enhanced Organic Dye Degradation via Photocatalysis and Piezocatalysis Using Sintered NiFe_2O_4 Nanoparticles

Science Tokyo¹, Sumitomo Chemical², NYCU³, Xinyu Jin¹, Tomoyuki Kurioka^{1,2}, Chun-Yi Chen^{1,2}, Masato Sone¹, Yung-Jung Hsu^{1,2,3}, Satoshi Okamoto^{1,2}, Tso-Fu Mark Chang^{1,2}

E-mail: jin@ames.pi.titech.ac.jp

Persistent organic pollutants (POPs) like Malachite Green (MG) are hazardous due to their toxicity and resistance to conventional treatment. As major pollutants from textile and aquaculture industries, they require efficient removal strategies. Photocatalysis and piezocatalysis, as advanced oxidation processes (AOPs), offer effective degradation via reactive oxygen species (ROS) generation.

In this work, NiFe_2O_4 (NFO) nanoparticles were synthesized and systematically sintered at various temperatures to enhance catalytic performance¹. As shown in Figure (a), under visible light and ultrasonic agitation, NFO generates separated charge carriers through photoexcitation and piezoelectric effects, leading to ROS formation ($\cdot\text{OH}$, $\cdot\text{O}_2^-$) for dye degradation².

Figure (b) shows that NFO sintered at 700 °C exhibited the highest photocatalytic activity due to improved crystallinity from thermal treatment. Figure (c) highlights the synergistic effect under combined light and ultrasound, surpassing individual effects. These findings confirm that sintering significantly enhances the degradation efficiency, making NFO a promising electromechanical catalyst for sustainable wastewater treatment.

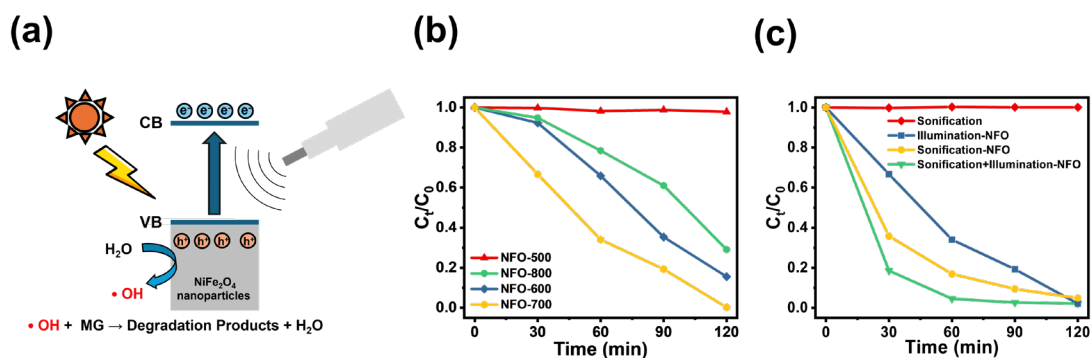


Figure 1. (a) Schematic illustration of degradation mechanism. (b) The influence of photocatalytic degradation efficiency by sintering temperature. (c) Degradation efficiency in different conditions.

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Hydrothermal Synthesis of Bismuth Ferrite-based Nanoparticles and the Application in Piezocatalytic Dye Degradation

Science Tokyo¹, Sumitomo Chemical², NYCU³, °Yu-Hao Chen,¹ Xin-Yu Jin,¹ Tomoyuki Kurioka,^{1,2} Chun-Yi Chen,^{1,2} Masato Sone,^{1,2} Yung-Jung Hsu,^{1,2,3} Satoshi Okamoto,^{1,2} Tso-Fu Mark Chang^{1,2}

E-mail: chen@ames.pi.titech.ac.jp

Humanity is currently facing the dual challenges of environmental degradation and energy crises. In pursuit of sustainable development, the search for alternative and renewable energy sources has become a global priority. Among various candidate materials, the perovskite oxide BiFeO_3 (BFO) has attracted significant attention due to its exceptional multiferroic properties—exhibiting both ferroelectricity and antiferromagnetism at room temperature—which make BFO-based nanoparticles highly promising for applications in environmental remediation and energy conversion. Additionally, BFO exhibits excellent piezoelectric properties, with a spontaneous polarization exceeding $100 \mu\text{C}\cdot\text{cm}^{-2}$ and a piezoelectric coefficient (d_{33}) as high as $70 \text{ pm}\cdot\text{V}^{-1}$, further enhancing its potential for piezocatalytic dye degradation. In this study, BFO-based nanoparticles were synthesized via a hydrothermal method, as illustrated in Figure 1(a). In the methylene blue (MB) degradation experiments, 40 mg of pure BFO nanoparticles were added to a solution containing $40 \mu\text{M}$ MB and 20 mL of deionized water. The suspension was stirred under dark conditions for 2 hours, during which a piezocatalytic degradation efficiency of approximately 2.3% was observed, confirming the intrinsic piezocatalytic activity of BFO. To further enhance the piezocatalytic performance, Al_2O_3 particles were introduced to increase the frequency of collisions between the particles. As shown in Figure 1(b), the addition of Al_2O_3 significantly enhanced the piezocatalytic activity, resulting in a 204% increase in dye degradation efficiency compared to the system without Al_2O_3 . This indicates that interparticle interactions can effectively promote piezocatalytic reactions, thereby validating the feasibility and application potential of the approach proposed in this study.

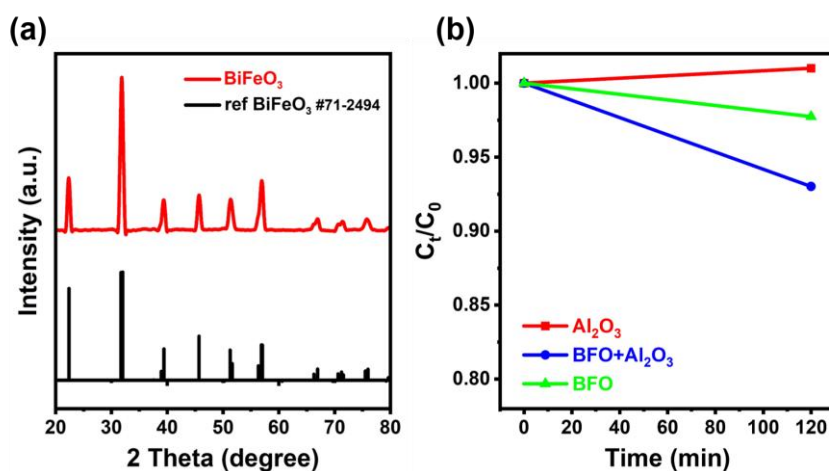


Figure 1. (a) XRD patterns of pure BiFeO_3 nanoparticles synthesized via the hydrothermal method. (b) Piezocatalytic degradation efficiency of MB dye using Al_2O_3 , BiFeO_3 and BiFeO_3 mixed with Al_2O_3 .

Superconducting proximity effect in an in-situ grown heterostructure consisting of superconductor Al / InAs / ferromagnetic semiconductor (Ga,Fe)Sb

Hiroataka Hara^{1*}, Lukas Baker², Shingen Miura¹, Keita Ishihara¹, Melissa Mikalsen², Patrick Strohhoben², Jacob Issokson², Masaaki Tanaka^{1,3,4}, Javad Shabani², and Le Duc Anh^{1,3}

¹Dept. of Electrical Engineering and Information Systems, The University of Tokyo,

²Center for Quantum Information Physics, Physics Dept., New York University,

³Center for Spintronics Research Network, The University of Tokyo,

⁴Nano Quine, The University of Tokyo

*E-mail: hara-hiroataka390507@g.ecc.u-tokyo.ac.jp

Superconductor / ferromagnetic semiconductor heterostructures provide a compelling platform for both fundamental research and emerging device applications, owing to their electrically tunable superconducting and magnetic properties. In this study, we investigate heterostructures comprising a superconducting Al layer, a nonmagnetic semiconductor InAs quantum well, and a ferromagnetic semiconductor (Ga,Fe)Sb layer. These heterostructures are particularly attractive due to their capability for *in situ* epitaxial growth [1], and the tunable spin-splitting in the InAs channel induced by the magnetic proximity from the adjacent (Ga,Fe)Sb layer [2][3].

The heterostructure consists of Al (10 nm)/(In,Ga)As (5 nm)/InAs (15 nm)/(Ga,Fe)Sb (20 nm, 14.6% Fe), grown by molecular beam epitaxy. Epitaxial growth of Al directly on the III-V semiconductor layers yields superconductivity below 1.3 K. Using this platform, we fabricated planar Josephson junctions with superconducting Al electrodes and a 100 nm-long InAs/(Ga,Fe)Sb channel (Fig. 1(a)). These junctions exhibit a zero-resistance state and clear Fraunhofer interference patterns (Fig. 1(b)), which display magnetic-field sweep-direction hysteresis and multiple flux jumps—signatures indicative of proximity-induced superconductivity in the magnetized InAs layer. A detailed analysis of the Fraunhofer patterns reveals node lifting [4] and even/odd modulation [5], suggesting the presence of superconducting edge-channel transport within the InAs quantum well. This interpretation is consistent with previous studies on InAs/(Ga,Fe)Sb hybrid systems [6]. These findings point to the emergence of unconventional superconducting transport modes and highlight the rich physics enabled by magnetic proximity effects in superconductor/ferromagnet hybrid structures. Our results motivate further systematic exploration of these hybrid systems to fully understand the interplay between magnetism and superconductivity at the nanoscale.

This work was supported in part by the Grants-in-Aid for Scientific Research, the CREST program of JST, and the Spintronics Research Network of Japan (Spin-RNJ).

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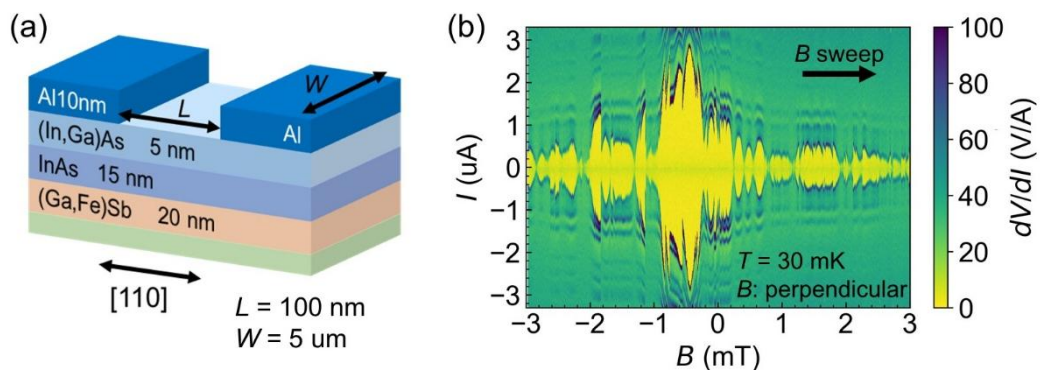


Fig. 1 (a) Schematic device structure of the planar Josephson junction containing superconducting Al electrodes, a III-V heterostructure of nonmagnetic semiconductor (InGa)As/InAs and a Fe-doped ferromagnetic semiconductor (Ga,Fe)Sb. (b) Fraunhofer interference pattern observed at 30 mK under a perpendicular magnetic field in the Josephson junction shown in (a).

10 Spintronics and Magnetism | Oral presentation : 10.5 Application of magnetic field

[8a-N303-1~8] 10.5 Application of magnetic field

[8a-N303-1]

Spectral analysis of solid-state oxygen-17 NMR spectra of hexagonal ice

○Kazuhiko Yamada¹ (1.Nihon Univ.)

[8a-N303-2]

Preparation and characterization of Gd-doped Mn-Zn ferrite nanoparticles for theranostics applications

Oyu kusumoto¹, naoki hoshikawa², kuon miura², shotaro watanabe¹, yuko ichiyanagi^{1,3} (1.Grad. Sch. of Eng. Sci., Yokohama Nat Univ, 2.Fac. of Sci. and Eng., Yokohama Nat. Univ., 3.Grad. Sch. of Sci., Osaka Univ.)

[8a-N303-3]

3D magnetic alignment of target-adsorbed MOF and application to NMR

○Ryosuke Kusumi¹, Maho Ikeda², Masaaki Sadakiyo², Noriyuki Hirota³ (1.FFPRI, 2.Tokyo Univ. of Sci., 3.NIMS)

[8a-N303-4]

Magnetic Alignment of (Y_{1-x}Dy_x)Ba₂Cu₃O₇ under Rotating Magnetic Fields

○Fumiko Kimura¹, Futo Fukuyama¹, K. G. P. Kahagalla¹, Muhammad Afiq Ahmed¹, Shigeru Horii¹ (1.Kyoto University of Advanced Science)

[8a-N303-5]

Orientation of hybrid films composed of CaCO₃@Fe₂O₃ composite particles and PLLA

○Keiya Kawamura¹, Atsushi Furukawa¹, Shuta Hara², Kohki Takahashi³, Akihiro Fukawa¹, Koichi Takase⁴, Mitsuaki Kogo⁴, Yoshiyuki Kojima⁴, Shigeru Shimizu⁴, Hiroki Ikake⁴ (1.Grad. Nihon Univ., 2.Kanagawa Univ., 3.IMR, Tohoku Univ., 4.Nihon Univ.)

[8a-N303-6]

Magnetic Properties and Martensitic Transformation in Ni-substituted MnCoGe Prepared by Reactive Sintering

○Taisei Tsunematsu¹, Masahira Onoue¹, Yoshifuru Mitsui¹, Rie Y. Umetsu², Keiichi Koyama¹ (1.Kagoshima Univ., 2.IMR Tohoku Univ.)

[8a-N303-7]

Evaluation of magnetic energy of the pure iron using high temperature magnetization measurements and magnetic field dependence of α-γ transformation temperature

○Reisho Onodera¹, Kohki Takahashi² (1.NIT, Ibaraki Col., 2.IMR Tohoku Univ.)

[8a-N303-8]

Attempt of increase in *B* on permanent magnet arrays for linear-drive type MRF

○Shigeru Horii¹, Walid Bin Ali¹ (1.Kyoto Univ. Adv. Sci.)

氷 I_h 相の固体酸素 17 核磁気共鳴 (NMR) スペクトルの解析

Spectral analysis of solid-state oxygen-17 NMR spectra of hexagonal ice

日大理工 $\circ$ 山田 和彦Nihon Univ., $\circ$ Kazuhiko YamadaE-mail: yamada,kazuhiko@nihon-u.ac.jp

Experimental and theoretical investigations of line shapes in solid-state ^{17}O NMR spectra of hexagonal ice, I_h , have been presented. Stationary ^{17}O NMR spectra of ice I_h at temperatures from 143 to 280 K are obtained at 11.7 and 16.4 T. Line shapes drastically change as temperatures increase from 143 and 243 K; at 253 K and above, pseudo-isotropic line shapes appear, indicating the presence of re-orientational motions. The Ratcliffe's model, which involves twelve orientations and four-step jumps for water re-orientational motions, is applied for analyzing the NMR spectra at temperatures below 243 K. At 253 K and above, it is found that the isotropic line shapes arise from proton disorder with respect to the solid-state ^{17}O NMR time scale, producing pseudo-icosahedral motional averaging that can completely average out second-order quadrupole interactions.

Figure 1 shows stationary ^{17}O NMR spectra of ice I_h at various temperatures, acquired at 11.7 T. There have been no reports of structural changes or phase transitions in I_h over this range of temperatures at atmospheric pressure. At 273 K, the spectrum shows a very sharp peak (data not shown), which is assigned to liquid water. At 143 K, the lowest temperature in this study, molecular motions seem to be frozen. At temperatures above 193 K, the line shapes are similar to that at 143 K, but, the whole line shapes have become more rounded and both shoulders fade away. In the temperature range between 253 and 268 K, pseudo-symmetric line shapes appear, which are inconsistent with the previous observations by Ratcliffe and co-workers. The pseudo-isotropic chemical shifts are found to be approximately -43 ppm. In this presentation, results of the spectral analysis of solid-state ^{17}O NMR spectra of I_h will be discussed, with particular emphasis on the reason for the presence of the pseudo-isotropic peak above 253 K.

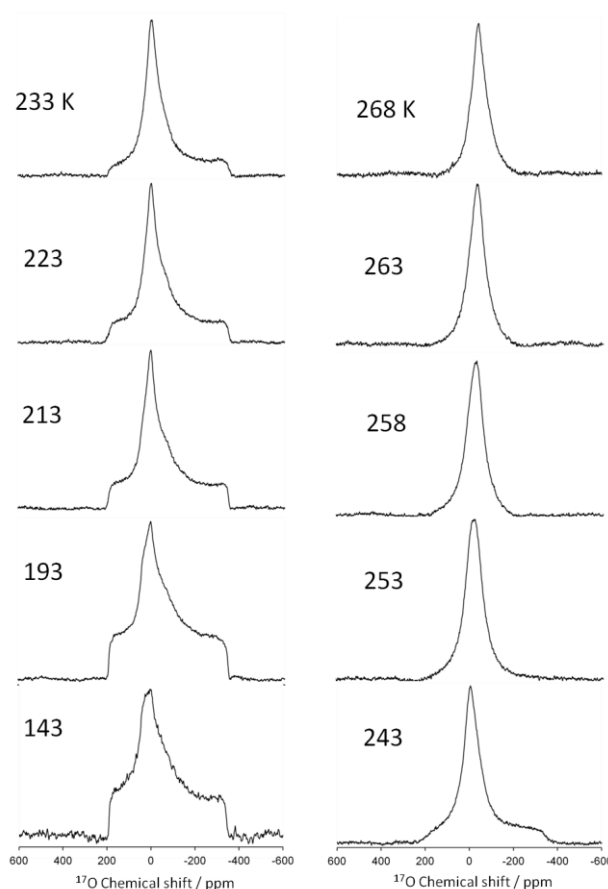


Fig. 1 Stationary ^{17}O NMR spectra of hexagonal ice, observed at 11.7 T.

セラノスティクス応用に向けた Gd ドープ Mn-Zn ferrite ナノ微粒子の 作製と物性評価

Preparation and characterization of Gd-doped Mn-Zn ferrite nanoparticles for theranostics applications

横国大院理工¹, 横国大理工², 阪大基礎工³ ◯楠本 悠羽¹, 星川 直輝², 三浦 玖遠²,
渡邊 将太郎¹, 一柳 優子^{1,3}

Grad. Sch. of Eng. Sci., Yokohama Nat Univ¹, Fac. of Eng. Sci., Yokohama Nat Univ², Grad. Sch. of
Eng. Sci., Osaka Univ³, ◯Yuu Kusumoto¹, Naoki Hoshikawa², Kuon Miura², Shotaro Watanabe¹,
Yuko Ichiyanagi^{1,3}

E-mail: kusumoto-yu-nt@ynu.jp

新規医療イメージング手法として挙げられる Magnetic Particle Imaging (MPI)は、超常磁性ナノ微粒子の非線形的な磁化応答を利用したもので、外部から交流磁場を印加した際の第三高調波応答をシグナルとして用いる。理論的にナノサイズの解像度を実現することができ、がん細胞のイメージングに大きな期待を寄せている。しかし、空間分解能の向上は研究課題のひとつとして存在する。本研究ではその空間分解能向上に向け、新たな Gd ドープ Mn-Zn ferrite ナノ微粒子を提案するとともに、診断と治療を同時に行うセラノスティクス応用に向けた可能性を検討した。

試料は湿式混合法により、 $\text{Mn}_{0.8-x}\text{Zn}_{0.2}\text{Gd}_x\text{Fe}_2\text{O}_4$ となるように焼成前駆体を作製した。ここで、焼成前駆体は小数第二位まで組成が合うように、Gd のドープ量は $x = 0.01 \sim 0.09$ の間で 0.01 刻みで調整した。SQUID による磁化測定と放射光を利用した局所構造の解析も行った。その後、酸化による不純物の生成を防ぐため Ar 雰囲気下で焼成し、粒径は10 ~ 20 nmに制御した。Gd ドープ量の異なる試料の第三高調波測定を行った(Fig. 1)。その結果、Mn-Zn ferrite に Gd を1 ~ 7 % ドープすることで応答強度が 1.5 倍以上に増大することが確認できた。しかし、Gd ドープ量 8%以上だと Gd の不純物が生成されることで応答が減少してしまうことも確認できた。また、交流磁場中で昇温測定を行った(Fig. 2)。その結果、作製した粒子で5 °Cの昇温が確認でき、同一の粒子が磁気ハイパーサーミアとしても応用が有効であることが分かった。将来のセラノスティクスへの応用に期待できる。

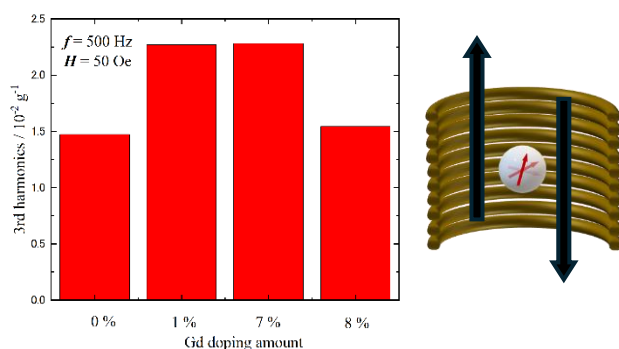


Fig. 1 Gd ドープ量別の第三高調波応答

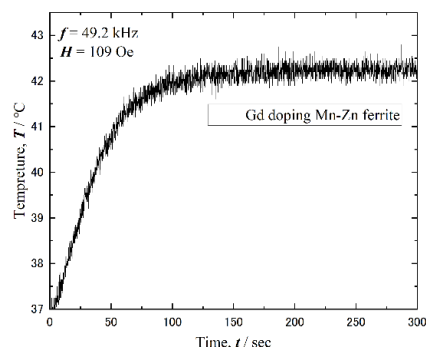


Fig. 2 Gd ドープ Mn-Zn ferrite の昇温結果

標的吸着 MOF の三次元磁場配向化と NMR への応用

3D magnetic alignment of target-adsorbed MOF and application to NMR

森林総研¹, 東京理大², 物材機構³ ○久住 亮介¹, 池田 真穂², 貞清 正彰², 廣田 憲之³

FFPRI¹, Tokyo Univ. of Sci.², NIMS³

○Ryosuke Kusumi¹, Maho Ikeda², Masaaki Sadakiyo², Noriyuki Hirota³

E-mail: rkusumi@ffpri.affrc.go.jp

核磁気共鳴 (NMR) 分光法は現代化学において不可欠な解析ツールである。NMR は気体・溶液・固体などあらゆる状態での測定が可能であるが、スペクトルから原理的に抽出可能な情報量は単結晶が最も豊富である。単結晶 NMR 法は化学シフトをはじめとする核スピン相互作用の異方性へのアクセスを可能とし、原子核周りの電子環境についての精緻な情報 (化学シフトテンソルなど) を提供する。同様の情報は、汎用の溶液・固体高分解能 NMR では取得困難である。ただし、一般にその解析に必要な振動パターンの取得には数 mm サイズの単結晶が要求され、汎用性に乏しい。三次元磁場配向下の NMR 法¹⁾では対象を数 μm サイズにまで拡張できるものの、個々の微結晶は単結晶である必要がある。そこで本研究では、金属有機構造体 (MOF) の優れたデザイン性・選択吸着性に着目し、標的化合物を吸着させた MOF を三次元磁場配向の NMR に供することで、標的の結晶化を経ずに化学シフトテンソルを解析することを試みた。

Fig. 1(b)は、フェニルホスホン酸 (PPA) を吸着させた Zr 系 MOF (MIL-140A²⁾: 単斜晶 $C2/c$ 、Fig. 1(a)) の粉末を UV 硬化樹脂に分散させ、13 T にて間欠型の変調回転磁場³⁾ (40 rpm で 180° 回転させ 1 s 停止を繰り返す) を印加後に UV 照射して得られた複合体 (MOMA) の X 線回折像である。スポット状の回折が認められるとともに、その発現パターンが X 線の入射方向に応じて変化する様子が観測された。この結果は PPA 吸着 MOF が三次元的に配向していることを示している。同 MOF 内にて、PPA 分子は特異的な相互作用を通じ規則正しく配列した形で充填されている。したがって、得られた MOMA について単結晶 NMR 測定を行えば、PPA の化学シフトテンソルを決定できるはずである。当日はその結果についても報告する。

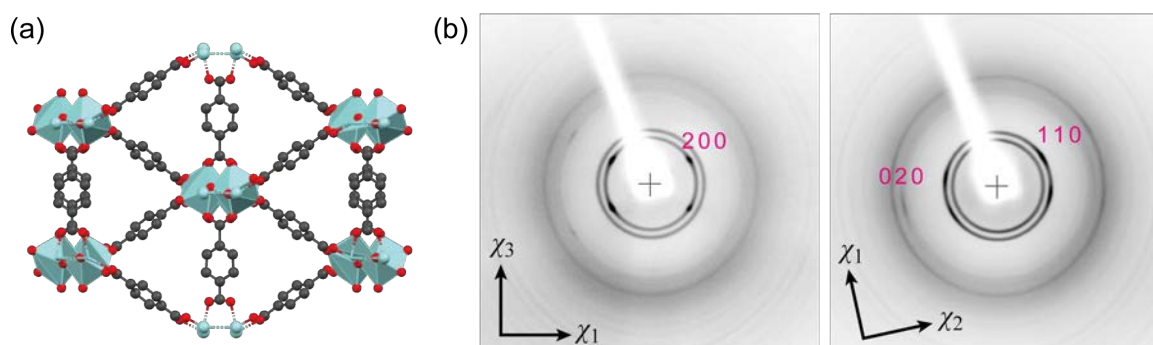


Fig. 1 (a) Crystal structure of MIL-140A and (b) X-ray diffraction patterns of the MOMA of PPA-adsorbed MIL-140A obtained with the X-ray impinging along the χ_2 (left) and χ_3 (right) axes.

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回転磁場下における $(Y_{1-x}Dy_x)Ba_2Cu_3O_7$ の配向挙動

Magnetic Alignment of $(Y_{1-x}Dy_x)Ba_2Cu_3O_7$ under Rotating Magnetic Fields

京都先端科学大学 [○]木村史子, 福山風人, カハガッラパモータピュマリー,
アーメドムハンマドアフイク, 堀井滋

Kyoto Univ. Adv. Sci., [○]F. Kimura, F. Fukuyama, K. G. P. P. Kahagalla, M. A. Ahmed, S. Horii

E-mail: kimura.fumiko@kuas.ac.jp

【緒言】1987年に90 K級の高い臨界温度を持つ $YBa_2Cu_3O_7$ (Y123)が発見されて以来、超伝導材料の実用化に向けた研究が活発に行われている。Y123は液体窒素温度(77 K)で超伝導性を示すため、冷却コストの面でも有利であり、応用面で非常に有望である。Y123を含む $REBa_2Cu_3O_y$ (RE123, RE: 希土類元素)は、単位格子内に2つの2次元的 CuO_2 超伝導層と1つの CuO ブロック層を含み、これらが c 軸方向に積層されている。この層状構造により、粒界間での高い超伝導性を維持するには、 c 軸の整列が不可欠である。さらに、RE123におけるクーパー対の短いコヒーレンス長と d 波対称性のため、粒界での a 軸および b 軸のわずかなずれが臨界電流密度を大きく低下させることから、二軸配向制御が極めて重要となる。

我々は、結晶軸に沿った磁化率異方性を利用した磁場配向法に着目し、より高い配向性を得るためにDyをドーピングする手法を採用している。Dyは大きな磁気モーメントを持ち、磁化率の制御に有効である。しかし、RE123は(110)面を共有する双晶構造を有し、結晶粒レベルの a 軸と b 軸の磁化率異方性がドメイン比次第で小さくなり、理想的な二軸配向が得られない場合がある。本研究では、回転磁場を用いた磁化困難軸の配向を試み、Y123に対するDyドーピング量の違いが磁化率異方性に与える影響を検討した。

【実験】Y123、 $(Y_{0.98}Dy_{0.02})_{123}$ 、 $(Y_{0.95}Dy_{0.05})_{123}$ 、及び $(Y_{0.90}Dy_{0.10})_{123}$ のポリ結晶を950°Cで40時間焼結し、次に40時間かけて300°Cまで冷却し、300°C酸素雰囲気下で40時間アニールした。得られた結晶を粉砕して試料とした。

試料を3種類の高粘度媒体に分散させ、約10 mass%の懸濁液を得た。ガラスキャピラリーに詰めて試料とした。1 Tの静磁場下で0.05から300 rpmまで回転速度を上げてキャピラリーを回転させ、in-situ X線回折測定(Mo線源)を行った。

【結果と考察】3種類の高粘度媒体を用いて回転速度依存性のデータを取得したが、これらのデータには媒体の粘度の違いによる影響が含まれている。そこで、粘度補正を行い、媒体の粘度が12 Pa·sであった場合に相当する条件に正規化した結果をFigureに示す。回折データにおいて、{200}の回折は磁化中間軸、{006}の回折は磁化容易軸に対応している。図に示すように、Dyのドーピング量が増加するにつれて、回折強度のピーク位置が高回転速度側へとシフトしており、これは磁化率異方性の増大を示している。特に、Dyを10%ドーピングした試料では、Y123と比較して約10倍の磁化率異方性が得られた。この結果は、Dyドーピングが磁気異方性の制御に有効であることを示しており、配向制御材料としての応用可能性を示唆するものである。なお、発表ではこれらの実験結果に加えて、シミュレーションによる配向挙動の解析結果も併せて報告する予定である。

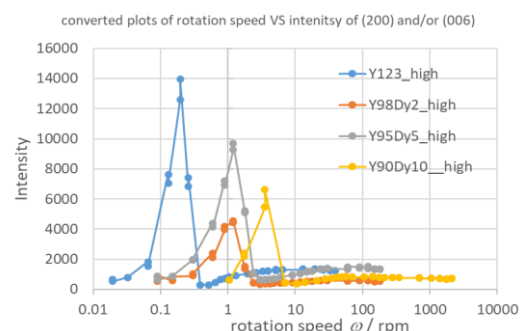


Figure X-ray diffraction intensity of the {006} reflection or the combined intensity of {006} and {200} reflections from a $(Y_{1-x}Dy_x)Ba_2Cu_3O_7$ suspension as a function of rotation speed, ω .

CaCO₃@Fe₂O₃ 複合粒子と PLLA からなるハイブリッドフィルムの配向化 Orientation of hybrid films composed of CaCO₃@Fe₂O₃ composite particles and PLLA

日大院理工¹, 神奈川大化学生命², 東北大金研³, 日大理工⁴ ○河村 慶弥¹, 古川 敦士¹,
原 秀太², 高橋 弘紀³, 府川 明宏¹, 高瀬 浩一⁴, 向後 光亨⁴, 小嶋 芳行⁴, 清水 繁⁴, 伊掛 浩輝⁴
Grad. Nihon Univ.¹, Kanagawa Univ.², IMR, Tohoku Univ.³, Nihon Univ.⁴ ○Keiya Kawamura¹,
Atsushi Furukawa¹, Shuta Hara², Kohki Takahashi³, Akihiro Fukawa¹, Koichi Takase⁴,
Mitsuaki Kogo⁴, Yoshiyuki Kojima⁴, Shigeru Shimizu⁴, Hiroki Ikake⁴
E-mail: cske24013@g.nihon-u.ac.jp

近年、環境問題を考慮した低環境負荷材料の開発が進んでいる。その中でも生分解性を有するポリ-L-乳酸(PLLA)は盛んに研究が行われているプラスチックの1つである。そして、PLLA材料の造核剤としてよく用いられているのがカルシウムカーボネート(CaCO₃)粒子であるが、土壌中にも含まれる成分であることから、PLLAと組み合わせることで環境負荷の少ないハイブリッド材料が創製できる。さらに、PLLAマトリックス中の粒子の配向状態を制御することで、ハイブリッド材料の力学的な性質を制御することが可能となる。そこで本研究では、磁場を用いることでPLLAとCaCO₃からなる環境に優しい異方性ハイブリッド材料の作製を試みた。

柱状CaCO₃粒子にFe₂O₃ナノ粒子を被覆したCaCO₃@Fe₂O₃複合粒子は既報に基づいて調製したり、その複合粒子とPLLAを1.5Tの磁場環境下で複合化することで異方性ハイブリッドフィルムを調製した。さらに複合している粒子の配向方向を磁場の印加方向を変えることで制御し、磁場の印加方向、すなわち、粒子の配向方向の違いがもたらすフィルムの力学的性質を評価した。

複合粒子の分散状態や配向評価は当日会場にて報告する。材料の配向方向が与える力学的性質の変化は動的粘弾性(DMA)の周波数依存性測定から得られた弾性率(E')と損失正接($\tan \delta$)から評価し、その結果をFigure 1に示す。90°のサンプルでは E' 値は測定方向に依存性は見られず同等の数値を示した。しかし、45°のサンプルでは E' 値が約5倍に変化しており、これは複合した粒子がフィルム内部でDMA

測定時にかかる応力に対して拮抗する力に差があることを意味する。配向方向を制御することで、ユニークな材料物性を生み出し、新たな異方性材料としての有用性を示すものである。

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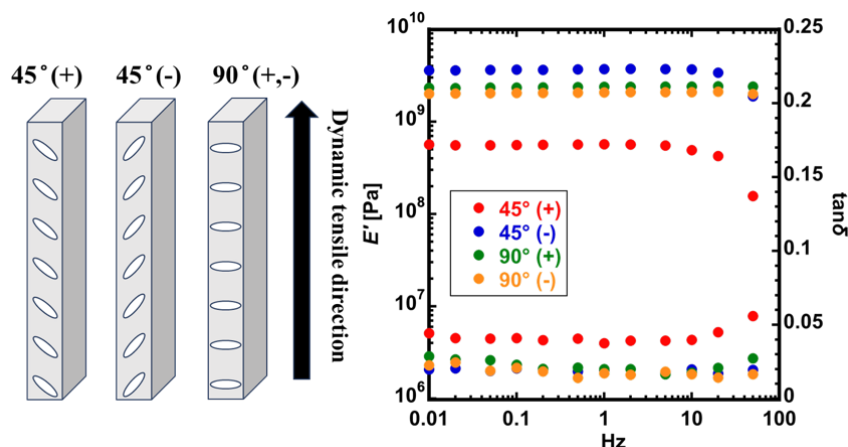


Figure 1. Frequency dependence of storage modulus and loss tangent of hybrid materials.

Magnetic Properties and Martensitic Transformation in Ni-Substituted MnCoGe Prepared by Reactive Sintering

Kagoshima Univ.¹, IMR, Tohoku Univ.²

°Taisei Tsunematsu¹, Masahira Onoue¹, Yoshifuru Mitsui¹, Rie Y. Umetsu²,

Keiichi Koyama¹

E-mail: k3520291@kadai.jp

Ferromagnetic MnCoGe alloys exhibit a martensitic transformation from a hexagonal Ni₂In-type structure (P-phase) to an orthorhombic TiNiSi-type structure (M-phase) above room temperature. For obtaining the magnetostructural transition, the martensitic transformation temperature of MnCoGe is controlled by element substitution [1] and heat treatment [2]. Recently, we found that the preparation method also affects the martensitic temperature of MnCoGe. When MnCoGe was prepared by reactive sintering, the martensitic transformation disappeared [3]. It is pointed out that the disappearance of the transformation is due to the distribution of voids and precipitates.

To suppress the precipitations/voids and recover the martensitic transformation, it is important to improve the phase stability of the MnCoGe phase. In this study, we focused on the Ni-substituted MnCoGe because antiferromagnetic MnNiGe shows similar crystallographic properties to MnCoGe. The magnetic and structural properties of Ni-substituted MnCoGe prepared by reactive sintering were evaluated.

MnCoGe, MnNiGe, and MnCo_{1-x}Ni_xGe were prepared by reactive sintering method. The solid-phase reaction was performed at 1123 K for 48 h, following slow cooling for 24 h. X-ray diffraction (XRD) was performed to evaluate the structural properties. Magnetic properties were evaluated by SQUID magnetometer.

The XRD patterns indicated that MnCoGe was the P-phase with few impurities, and the martensitic transformation was suppressed or disappeared. Meanwhile, the diffraction patterns of MnNiGe showed the M-phase with lattice parameters $a = 0.603$ nm, $b = 0.375$ nm and $c = 0.708$ nm, which was consistent with a previous report in which samples were prepared by a melting method [4]. Therefore, it is suggested that Ni-substitution stabilizes the M-phase of MnCoGe. In the presentation, we will show the magnetic properties and microstructures of Ni-substituted MnCoGe.

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高温磁化測定を用いた純鉄の磁気エネルギー評価と α - γ 変態温度の磁場依存性

Evaluation of magnetic energy of the pure iron using high temperature magnetization measurements and magnetic field dependence of α - γ transformation temperature

茨城高専¹, 東北大金研² [○]小野寺 礼尚¹, 高橋 弘紀²

NIT, Ibaraki college¹, IMR Tohoku Univ.², [°]Reisho Onodera¹, Kohki Takahashi²

E-mail: onodera@ibaraki-ct.ac.jp

【はじめに】鉄(Fe)、鋼(Fe-C)の相変態における磁場効果を評価する上で、理論計算やシミュレーションは重要であり、状態図計算はCALPHAD法、組織形成シミュレーションはPhase-field法でそれぞれ実施される[1,2]。多くの報告は、Feの高温磁化、その磁場依存性について平均場近似を用いて見積もっている。しかしながら、遍歴磁性体である鉄に対して平均場近似をもって磁化を見積もることは適切ではなく、平均場近似によって計算された磁化を用いて磁場効果を議論することの信頼性は担保できない。一方で、上記のような計算をした結果、実験値に一致しシミュレーション手法の妥当性を評価する多くの報告で述べられている。このギャップを埋め、シミュレーション結果に信頼性を与えるためには、高温磁化を実験的に求め、変態温度、磁気エネルギーなど磁場効果の評価を行うことが望ましい。本研究では、高温・強磁場中で純鉄の磁化測定を実施し、得られた高温磁化を用い、自由エネルギーの計算、変態温度の見積を行ったため報告する。

【実験・計算方法】磁化測定は東北大金研強磁場センターで共同利用に供されている高温・強磁場磁化測定装置を用いた[3]。測定は磁場：0.5 – 19 T、温度：300 – 1250 Kの範囲で実施した。試料には厚さ 50 μm の純鉄箔を用い、その面内に磁場が印加される方向にセットした。この純鉄箔の磁化の熱磁化曲線を測定し純鉄の α - γ 変態の観察を行なった。

得られた熱磁化曲線から各温度における磁化の磁場依存性を見積り、各温度・磁場における磁気エネルギーを見積もった。得られた磁気エネルギーを用いて、 α 構造(bcc)、 γ 構造(fcc)それぞれの自由エネルギーを計算し、変態温度を得た。自由エネルギーの計算に用いた各パラメータは、SGTE(Scientific Group thermodata Europe)によってまとめられた値を用いた[4]。

【結果と考察】Figure 1 には得られた熱磁化曲線($B \leq 10$ T)と、同じ磁場で平均場近似により求めた熱磁化曲線を示す。Fig. 1 からわかる通り、実線で示した測定結果と破線で示した計算磁化は異なる温度依存性を示していることがわかる。特に、600 – 1000 K ではその差が大きく、減衰する熱磁化曲線の曲率が異なっていることが明瞭にわかる。 α - γ 変態温度の磁場依存性については、熱磁化曲線からの見積りと、実験から求めた磁気エネルギーを用いて計算した値を比較した。この結果については当日報告する。

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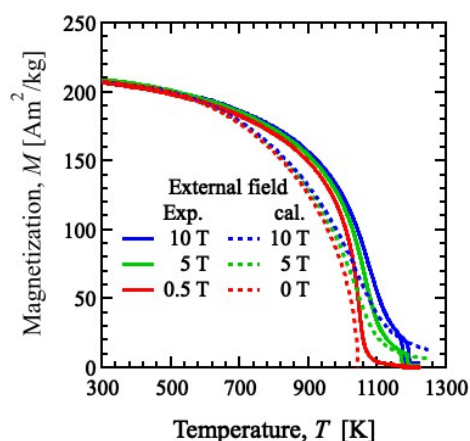


Fig. 1 Temperature dependence of the magnetization of pure iron at high magnetic fields. The solid lines show the experimental values, and the dashed lines show the calculated values.

リニア駆動型回転変調磁場用配列磁石の磁場増強の試み

Attempt of increase in B on permanent magnet arrays for linear-drive type MRF

京都先端科学大・工：堀井滋，アリ ワリド

Kyoto Univ. Adv. Sci.: S. Horii, Walid Bin Ali

Email: horii.shigeru@kuas.ac.jp

1. Introduction

Magnetic alignment by modulated rotating magnetic field (MRF) enables formation of triaxially aligned microstructure of a substance with triaxial magnetic anisotropy. Recently, our group has developed the linear-drive type MRF (LDT-MRF) equipment with a permanent magnet array [1,2], and MRF is generated only by reciprocation motion of the magnet array. That is, motion of samples and rotation of magnets are not required. Figure 1 shows a schematic of cross-section of a conceptual magnet array with magnetic flux distribution calculated by the finite element method (FEM). The most essential point of the magnet array is the presence of two different regions. One is a region in which magnetic flux points upward or downward uniformly, and the other is a region in which direction of magnetic flux is changed from upward to downward or from downward to upward. During the reciprocating motion of the magnet array, the two regions lead to the generation of static field and rotating field at “A”, respectively.

However, within several magnet arrays our group produced, their magnetic flux densities (B) at 2mm in height reached 0.9 T at maximum. The improvement of B is one of the issues for practical use of LDT-MRF system. This is because magnetic orientation energy is proportional to the square of B and the increase in B leads to the reduction of required magnetic anisotropy of a material for magnetic alignment. In the present study, to obtain directions on the magnet array with higher B , change in B was investigated as functions of several magnet-related parameters by using a fundamental magnetic circuit.

2. Experimental procedure

Figure 2 shows the fundamental magnetic circuit used in the present study. Four different parameters are prepared, magnetic material “Z”, its width W , air-gap length G and height H . Nd-Fe-B permanent magnet, iron (Fe) and joint of Fe and Nd-Fe-B are used as “Z”. Magnetic flux densities at $H = 1$ and 2 mm were calculated by FEM (software: FEMM) by changing values of G ($G = 5$ and 8 mm) and W ($W = 4, 6, 8, 10$ and 15 mm).

3. Results and discussion

In Fig. 2, the magnetic material “Z” accepts magnetic flux lines from the two transversely magnetized Nd-Fe-B magnets, then needs to release them to Fe of the top array. When $Z = \text{Nd-Fe-B}$, $W = 10$ mm and $G = 8$ mm,

the B values are 1.17 T and 1.31 T at $H = 2$ and 1 mm, respectively. This means that higher B is obtained when the sample position approaches to the top plane of the bottom array (decrease in H). When we focus on the effects of Fe as “Z”, the increase in B was observed for $W = 8$ mm or less in the condition of $H = 1$ mm and $G = 5$ mm. It is qualitatively explained in terms of the area of the top plane of “Z”. Number of magnetic flux lines provided by the two permanent magnets is constant. If “Z” = Fe, which is a “soft” ferromagnetic material and is not permanent magnet, B is directly affected by the area.

In the present study, details of dependences of B on W , G and “Z” at different H will be shown. We discuss the direction on the design of magnet array for triaxial magnetic alignment based on results obtained by the electromagnetic simulation.

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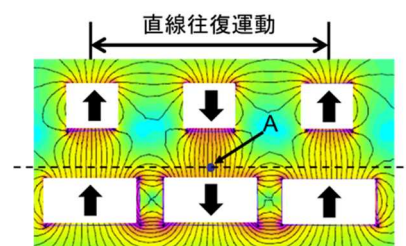


Fig. 1. Cross section of the conceptual magnet array. Magnetic flux lines are also shown.

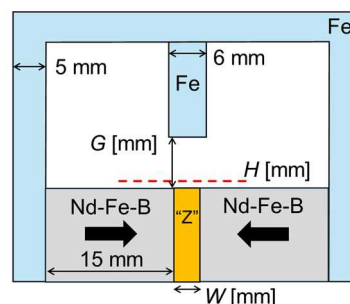


Fig. 2. A schematic of cross-section of the fundamental magnetic circuit. “Z” means magnetic material, Fe, Nd-Fe-B or joint of Fe and Nd-Fe-B.