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研究課題名（和文）Deciphering spin-orbit torque in magnetic single layers: Towards spin-torque devices with extended scalability

研究課題名（英文）Deciphering spin-orbit torque in magnetic single layers: Towards spin-torque devices with extended scalability

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研究成果の概要（和文）：本研究課題では、(1)組成、温度および歪みによって特性制御可能な２種類のMg-Ru系合金を作製し、磁場に対する応答は小さいが電場や温度勾配によって大きな電気信号が得られることを示した。そして、それらの合金を利用して（２）磁区制御が単層のスピン軌道トルクの発現に強く関係していることを明らかにした。さらに、（３）スピンホール効果を用いてスピン変換効率を高めるための材料設計指針を示し、その知見をもとに(4)いくつかの系で大きなスピンホール効果が発現することを実証した。

研究成果の学術的意義や社会的意義
我々は現在"Big Data"時代へと突入し、高い書換耐性と低消費電力を備える低コストな超高密度データストレージへの要望が高まっている。本研究課題は、そのような要請を満足しうる磁気ランダムアクセスメモリ技術の研究や開発に資するものである。また学術的観点からは、本研究で得られた成果は、スピンに関連した特性を発揮できる材料を設計するための指針を与え、将来の新材料開発を加速するためのガイドラインとなる。社会的な観点からは、本研究の成果は、上記の理想的なスピントロニクスメモリの実現に向けた一歩と位置付けられる。

研究成果の概要（英文）：The main achievements of this project include: (1) Realizing two types of manganese and ruthenium-based alloys showing high tunability of properties by varying composition, temperature, and strain. Unlike the usual magnetic materials, these alloys with very limited magnetic response can however generate a large electrical signal from an electric field or a temperature gradient. (2) Providing evidence that domain twinning control will closely influence the spin-orbit torque in magnetic single layers. However, producing twinning-free samples remains to be a challenge. (3) Revealing material design principles for realizing efficient charge-to-spin conversion using the spin Hall effect. (4) Applying the knowledge from (3) to demonstrate large spin Hall effect in various material systems.

研究分野：スピントロニクス

キーワード：Compensated ferrimagnet　Spin-orbit torque　Spin-orbitronics　Spin caloritronics　Anomalous Nernst effect

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１．研究開始当初の背景

Current-induced spin torque is a key mechanism for realizing electrical control of a nanomagnet, with potential applications in magnetic random-access memory (MRAM), logic and sensor. However, due to the limited perpendicular magnetic anisotropy at the ubiquitous CoFeB/MgO interface, it is challenging to continue the downscaling of the MRAM cell beyond ~20 nm node, while maintaining sufficient thermal stability. To keep the competitiveness of MRAM technology and to further extend the Moore's Law, a paradigm shift is urgently required to overcome this limitation. One alternative is to go beyond the existing spin torque contribution, which is essentially an interfacial effect and look instead for the "bulk" spin torque term that stems from the lowering of the crystal symmetry in the magnetic layer, so called the Néel-order spin-orbit torque. Meanwhile, it is essential to improve the charge-spin conversion efficiency in the adjacent heavy metal layer to further reduce the power consumption.

２．研究の目的

This project aims to explore various means that help to extend the scalability of the existing spin-torque devices. Notably, the Néel-order spin-orbit torque (SOT) in magnetic single layer can be exploited to allow efficient switching of devices with lateral diameter below 10 nm, where the magnetic state of the free layer with high aspect ratio is stabilized by the magnetic shape anisotropy. An important scientific question of this project is: How can we control and engineer the spin-orbit torque in magnetic single layers?

３．研究の方法

Samples were grown by magnetron sputtering in ultrahigh vacuum. We focus on highly-tunable compensated ferrimagnetic Mn-Ru-Ga and Mn-Ru-Al based inverse Heusler compounds to study the single layer SOT and other electrical responses to the external stimuli. The two inequivalent magnetic sublattices and the non-centrosymmetric crystal structure are keys to induce Néel-order SOT in such compound. For certain atomic composition and temperature, magnetic compensation can be achieved where the material exhibits zero net magnetic moment. Yet, the compensated compound shows large anomalous Hall effect and high spin polarization. The well-established SOT quantification method called the harmonic Hall technique may be adapted for the characterization of SOT in such compounds. A harmonic Hall measurement platform was built and attached to a PPMS system with a horizontal sample rotator to perform the measurement at large magnetic field, at varying temperatures and field angles. This setup is also used to quantify the SOT in other magnetic heterostructures.

４．研究成果

1. <u>Anomalous Nernst effect in compensated ferrimagnetic Mn_2Ru_xGa</u>

Mn_2Ru_xGa (MRG) films of varying Ru concentrations were grown on single crystal MgO(001) substrates by co-sputtering Mn_2Ga and Ru targets. For the film with x ~ 0.6, we achieved magnetic compensation at room temperature. Harmonic Hall technique shows a response that can be partly attributed to the thermoelectric effect. We then systematically study the anomalous Nernst effect (ANE), the Seebeck effect and the transverse thermoelectric conductivity of MRG and found that all the thermoelectric signals switch sign across the magnetic compensation. The anomalous Hall effect of MRG also shows very similar behavior. These results suggest the orientation of one magnetic sublattice moment governs the magnetoelectric and thermoelectric properties of MRG. In contrast, the total net moment is less important. Finite anomalous Hall effect and ANE signals were found in MRG even when the net moment is vanishingly small. This work gives rise to two oral presentations (JSAP spring meeting 2021 and INTERMAG 2021).

2. Realizing new ternary inverse Heusler compound Mn-Ru-Al

Epitaxial Mn-Ru-Al (MRA) films crystallizing in the inverse Heusler structure were grown on MgO(001) substrates by co-sputtering $Mn_{55}Al_{45}$ and Ru targets. The MRA exhibits compensated ferrimagnetism similar to that observed in MRG. Replacing the Ga atoms of MRG by Al reduces the lattice parameter of MRA to a level comparable with that of MgO substrate. The negligible substrate-induced strain and the lack of uniaxial anisotropy of the cubic inverse Heusler structure give rise to the weak perpendicular magnetic anisotropy of MRA. Magnetic compensation is achieved in MRA by varying the Ru concentration as demonstrated by the sign reversal of the measured Kerr rotation.

Next, we attempt to grow by sputtering the MRG and MRA films on zinc-blende-structured substrates, e.g., the semi-insulating GaAs and Fe-doped InP. These noncentrosymmetric substrates are expected to induce preferential domains in MRG and MRA, if epitaxy can be established. However, we found severe interdiffusion at the substrate/film interface that prevents the epitaxial growth. A seed layer suitable for sputtering deposition should be developed.

3. Measuring SOT in a Ni-Fe single layer

In collaboration with Prof. Seki in IMR, the SOT of Ni-Fe single layers of varying thicknesses and interfacial conditions were investigated using spin-torque ferromagnetic resonance (ST-FMR) technique. We found appreciable damping-like SOT acting on the Ni-Fe single layer when the layer thickness is thinner than a threshold of ~ 3nm and when the top and bottom interfaces of the magnetic layer are asymmetric, i.e., when the Ni-Fe layer is sandwiched by two different insulating materials (SiO_2 and AlO_x). A toy model is further proposed to model the measured self-induced SOT. This work was published in Phys. Rev. B 104, 094430 (2021).

4. Material design principles and SOT quantification in various heterostructures

The harmonic Hall measurement setup attached to the PPMS allows quantification of SOT in magnetic heterostructures using large magnetic field and at varying temperatures. In Pt-Al alloy system, we found highly fcc-textured epitaxial Pt_3Al film grown on MgO(001) possesses significantly higher spin Hall efficiency than the polycrystalline Pt_3Al of the same composition, grown on SiO_2. We highlight that maintaining the fcc structure is a prerequisite for obtaining large spin Hall effect in Pt-based alloys (APL Materials 9 081113 (2021)).

We have also systematically measured the anomalous Hall effect and the spin Hall effect in a series of cobalt shandite films. We found that the giant anomalous Hall effect of the undoped ferromagnetic $Co_3Sn_2S_2$ and the giant spin Hall effect of the paramagnetic Ni-doped $Co_2Ni_1Sn_2S_2$ share the common intrinsic origin. The two Hall effects are intercorrelated. A preprint on this work is under reviewed and has been posted on arXiv (arXiv:2203.02356).

In addition, we have investigated the spin Hall effect in another Weyl semimetal Co_2MnGa and demonstrated spin-orbit torque switching (Applied Physics Letters 118, 062402 (2021)). On the other hand, the exotic spin-1 chiral semimetallic CoSi shows very small spin Hall effect (Physical Review Research 3, 033101 (2021)).

Overall, this project leads to 4 scientific publications and 8 oral presentations. In addition, several works related to this project are under peer-review or in preparation.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　0件）

１．著者名 Tang Ke, Wen Zhenchao, Lau Yong-Chang, Sukegawa Hiroaki, Seki Takeshi, Mitani Seiji	４．巻 118
２．論文標題 Magnetization switching induced by spin-orbit torque from Co2MnGa magnetic Weyl semimetal thin films	５．発行年 2021年
３．雑誌名 Applied Physics Letters	６．最初と最後の頁 062402～062402
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0037178	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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１．発表者名 Y.-C. Lau, J. Wang, T. Kubota, K. Takanashi
２．発表標題 Anomalous Nernst effect in compensated ferrimagnetic Mn2RuxGa
３．学会等名 第68回応用物理学会春季学術講演会
４．発表年 2021年

１．発表者名 Y.-C. Lau, J. Ikeda, K. Fujiwara, A. Ozawa, T. Seki, K. Nomura, A. Tsukazaki, and K. Takanashi
２．発表標題 Anomalous Hall and spin Hall effect in kagome-lattice cobalt shandite films
３．学会等名 令和3年東北大学電気通信研究所共同プロジェクト研究会「固体中のスピン・軌道ダイナミクスとその制御」
４．発表年 2021年

１．発表者名 Y.-C. Lau, J. Ikeda, K. Fujiwara, T. Seki, A. Tsukazaki, K. Takanashi
２．発表標題 Spin Hall effect in paramagnetic kagome-lattice semimetal Co3Sn2S2(CSS)
３．学会等名 65th Annual Conference on Magnetism and Magnetic Materials (MMM) 2020（国際学会）
４．発表年 2020年

1．発表者名 Y.-C. Lau, J. Ikeda, K. Fujiwara, T. Seki, A. Tsukazaki, K. Takanashi
2．発表標題 Spin Hall effect in paramagnetic kagome-lattice topological semimetal Co3Sn2S2
3．学会等名 第81回応用物理学会秋季学術講演会
4．発表年 2020年

1．発表者名 Y.-C. Lau, Z. Wen, K. Ito, J. Ieda, T. Sasaki, T. Seki and K. Takanashi
2．発表標題 Perpendicular magnetic anisotropy and spin Hall effect in X/Co/Y (X, Y = Pt, Pd) metallic trilayers
3．学会等名 Spin-RNJ若手オンライン研究発表会
4．発表年 2020年

1．発表者名 Y.-C. Lau, Z. Wen, K. Ito, J. Ieda, T. Taniguchi, T. Sasaki, T. Seki and K. Takanashi
2．発表標題 Origin of field-like torque enhancement with decreasing Co thickness in X/Co/Y (X, Y = Pt, Pd) metallic trilayers
3．学会等名 IEEE International Magnetics Conference (INTERMAG) 2020 - Canceled（国際学会）
4．発表年 2020年

1．発表者名 Y.-C. Lau, J. Wang, T. Kubota, K. Takanashi
2．発表標題 Anomalous Nernst effect in compensated ferrimagnetic Mn2RuxGa
3．学会等名 IEEE International Magnetics Conference (INTERMAG) 2021（国際学会）
4．発表年 2021年

１．発表者名 Y.-C. Lau, T. Seki, K. Takanashi
２．発表標題 Highly fcc-textured Pt-Al alloy films grown on MgO(001) showing enhanced spin Hall efficiency
３．学会等名 JSAP Autumn Meeting 2021
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

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