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研究課題名（和文）Investigation of the efficiency of spin-orbit torque induced magnetization switching in Functional oxide/ ferromagnetic stack films for a new In-memory computing

研究課題名（英文）Investigation of the efficiency of spin-orbit torque induced magnetization switching in Functional oxide/ ferromagnetic stack films for a new In-memory computing

研究代表者

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研究成果の概要（和文）：本研究では、RuO2/強磁性積層膜におけるスピン軌道トルク（SOT）誘起磁化スイッチングを研究し、新しいスピントロニクスデバイス応用に向けた新しい機能の実現を目指しました。
RuO2 薄膜は、結晶性、表面、抵抗率がよく制御されて製造されました。 極性がよく理解されている RuO2 薄膜内で生成されるスピン流を使用して、FM 層の磁化反転を誘導しました。 有効な SOT 磁場が調査され、RuO2 結晶構造の対称解析の下でスピン ホール伝導率テンソルを考慮することにより、これらの SOT 磁場の起源は主にスピン分割効果に起因すると考えられました。

研究成果の学術的意義や社会的意義
This research fulfilled the lack of investigation of the SOT-induced magnetization switching under the spin-split origin in RuO2/FM bilayer by a well-controlled crystallinity of RuO2 and a thoughtful combination of experiment and calculation. This also open a new switching mechanism for SOT devices.

研究成果の概要（英文）：In this study, spin-orbit torque (SOT) induced magnetization switching in Functional oxide/ ferromagnetic (FO/FM) stack films has been investigated with the realization of new functionality towards the novel spintronic devices application.
The RuO2 thin film was fabricated with well-controlled crystallinity, surface, and resistivity. The spin current was generated in the RuO2 thin film with well-understood polarity, which was then used to induce the magnetization switching of the FM layer placing adjacent to the RuO2 layer. The effective SOT fields in RuO2/FM stack film have been investigated using harmonic Hall measurement and the origin for these SOT fields was attributed mainly to the spin-split effect by considering the spin Hall conductivity tensor under the symmetry analysis for the RuO2 crystal structure. This research is important for the further research on the current-induced magnetization switching using functional oxides.

研究分野：応用物理工学

キーワード：Spin orbit torque　Spin split effect　Spin Hall effect　Antiferromagnetic　SOT-MRAM　RuO2　Functional oxides　RuO2/FM bilayer

１．研究開始当初の背景

Having been regarded as a typical metal with conventional electrical transport properties for a long time, however, RuO_2 recently revealed its specific band structure with the Dirac nodal lines which induce a strong spin Hall effect for spintronic applications [1]. In addition, RuO_2 is an antiferromagnetic material up to at least room temperature when the lattice is distorted from the rutile symmetry ($P4_2/mnm$), and the Neél vector aligns along [001] axis [2]. A recent theoretical paper has shown that in the collinear antiferromagnetic RuO_2, the corner and the center Ru atoms with opposite spins are surrounded by the different crystal fields of the oxygen octahedrons (90^o rotation). Thanks to this difference, the anisotropic spin-split band in momentum space was supposed to exist when an electric field was applied in a certain direction in the RuO_2 crystal, and thus, a spin current would be generated with a high efficiency as a result of the spin-split effect [3]. With these new functionalities, RuO_2 has drawn considerable attention and is potential for application as a spintronic material.
Utilizing RuO_2, some reports have shown the current-induced magnetization switching in RuO_2/FM bilayers thanks to the spin-split effect in RuO_2, which is potential for application in SOT-MRAM with new functionality [4-6]. However, a detailed investigation of the effective spin-orbit torque (SOT) fields is lacking and the clear explanation of the spin-split effect in RuO_2 is insufficient. Therefore, **it is needed to carefully investigate the effective SOT fields in RuO_2/FM bilayer and explain the origin of these fields under the support of a symmetry calculation in the RuO_2 with a well-controlled crystallinity**.

２．研究の目的

In this research, we aim at the investigation of the effective SOT fields in RuO_2/FM bilayer and explain the origin of these fields. The following investigations have been conducted for this research:
(1) Fabrication of the RuO_2 thin film with well-controlled crystallinity, surface, resistivity.
(2) Investigation of the SOT fields in RuO_2/FM bilayers.
(3) Explain the origin of the generation of the SOT fields in RuO_2/FM bilayers.

３．研究の方法

To achieve the mentioned-above purposes, the following methods have been conducted:
(1) Fabrication of the RuO_2 thin film with well-controlled crystallinity, surface, resistivity.
RuO_2 thin film and RuO_2/FM bilayers were fabricated using sputtering method. Formation of RuO_2 film on α-Al_2O_3(0001) substrate was confirmed by XAS, Raman. Crystallinity of RuO_2 film was investigated using XRD. Surface quality was confirmed by RHEED.
(2) Investigation of the SOT fields in RuO_2/FM bilayers.
SOT devices based on RuO_2/FM bilayers were prepared by photolithography followed by an etching process. SOT fields was evaluated by harmonic Hall measurement with other physical parameters evaluated by anomalous Hall measurement, four-probe measurement, VSM measurement.
(3) Explanation of the origin of the SOT field generation in RuO_2/FM bilayers: Symmetry calculation was done to understand the angular dependence of the spin Hall conductivity in RuO_2 film. The calculation and the experimental data will be compared to show the origin.

４．研究成果

The clear RHEED patterns were observed as a result of the good surface with low roughness in the samples. The VSM data showed the in-plane magnetic anisotropy in all samples. XRD θ - 2θ pattern for RuO_2 film grown on α-Al_2O_3 is shown in Fig. 1 (a). Only h00 diffraction peaks of rutile-type RuO_2 were observed for the film, indicating no impurity. A six-fold symmetry of the RuO_2 thin films in the in-plane direction was shown by the 220

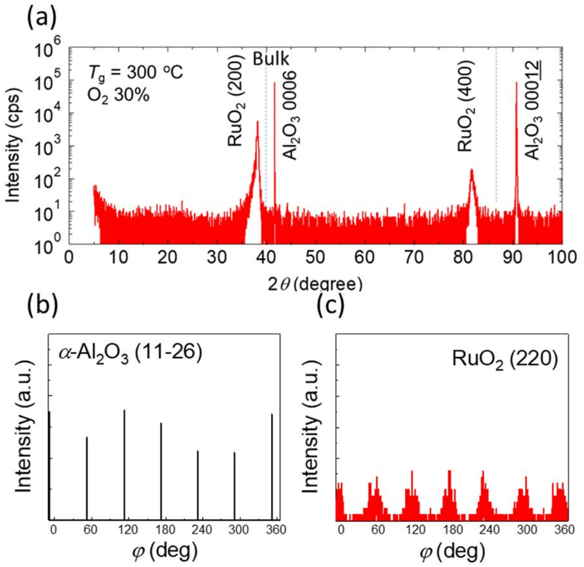

Fig. 1: (a) XRD patterns of RuO_2 film. XRD φ scans for (b) 11-26 peaks of Al2O3 substrates and (c) 220 peaks of RuO_2(100) epitaxial thin films.

peaks in the φ scan along with the 11-26 peaks of α-Al_2O_3 (Fig. 1 (b) and (c)). This result indicated the formation of triple domain structures in the films with the in-plane epitaxial relationships of RuO_2[010]// α-Al_2O_3 [11-20], [1-210], [-2110], as previously reported.

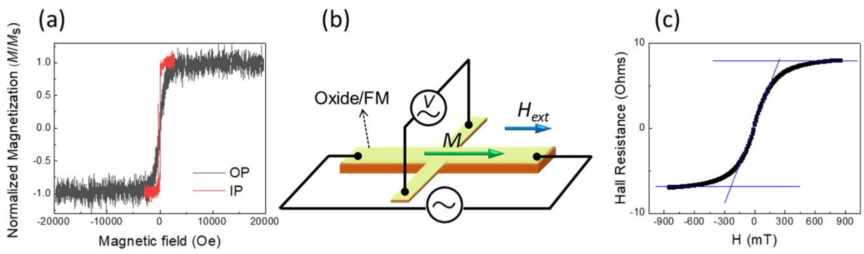

Fig. 2: (a) Magnetization curves for Ru(O)/Co-Fe-B bilayer. (b) Schematic image of a Hall device for harmonic Hall measurement under a rotated magnetization field H_{ext}. (c) anomalous Hall resistance curve for SOT device.

The RuO_2/Co-Fe-B bilayer with an in-plane magnetic anisotropy was prepared (Fig. 2 (a)) and the SOT device was fabricated using this bilayer. Fig. 2 (b) shows the schematic image of a Hall device for harmonic Hall measurement under a rotated magnetization field H_{ext}, and Fig. 2 (c) shows the typical experimental data of Hall resistance (R_{Hall}) versus out-of-plane field H_z for the SOT device. The symmetry analysis of the spin Hall conductivity in RuO_2 (100) was also conducted where the main origin was attributed to the spin-split effect. The analysis results showed that the application of current to both [1-100] and [11-20] directions of α-Al_2O_3 substrate will result in the similar value of spin current along z direction, i.e., the normal direction of the sample surface. Figures 3 (a), and 3 (b) show the in-plane magnetic field angle θ dependence of the first ($R_{1\omega}$) and second ($R_{2\omega}$) harmonic Hall resistances for different H_{ext} where I_c⫽[1-100]$_{Sub}$. Based on these results, the effective SOT fields, including the Slonzewski-like field H_{SL} and the field-like field H_{FL} were evaluated. Figure 3 (c) shows the current density (J) dependence of H_{SL}, H_{FL} for the case I_c⫽[1-100]$_{Sub}$ (squares), in comparison with those for the case I_c⫽[11-20]$_{Sub}$ (dots). Both $|H_{SL}|$ and $|H_{FL}|$ increase with J, implying a current-induced origin for the observed behavior. The close values of $|H_{SL}|$ and $|H_{FL}|$ for both cases at the corresponding values of current density were observed, which is consistent with the suggestion from the symmetry analysis. This research is important for the further research on the current-induced magnetization switching using functional oxides.

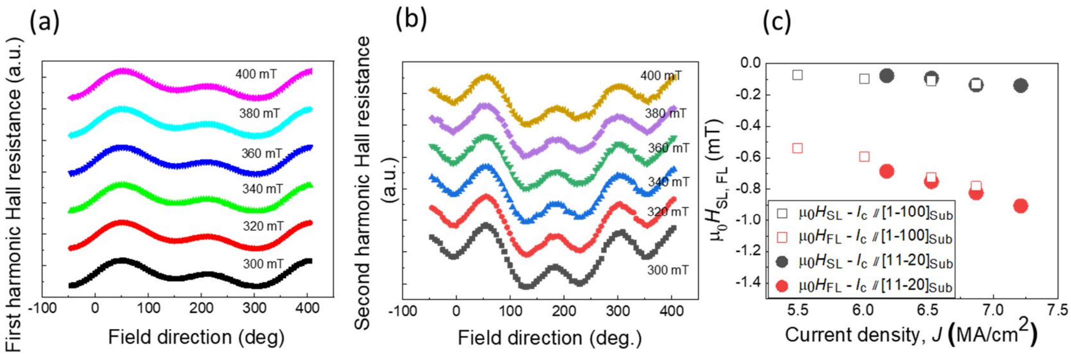

Fig. 3: The first (a) and second harmonic Hall resistance curves (b) for SOT device. (c) Current density (J) dependence of H_{SL}, H_{FL} for SOT devices under the different direction of current applied to device.

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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　1件）

1．著者名	4．巻
T. V. A. Nguyen, Y. Saito, H. Naganuma, S. Ikeda, T. Endoh, Y. Endo	12
2．論文標題	**5．発行年**
Effect of oxygen incorporation on dynamic magnetic properties in Ta-O/Co-Fe-B bilayer films under out-of-plane and in-plane magnetic fields	2022年
3．雑誌名	**6．最初と最後の頁**
AIP Advances	035133(1-5)
掲載論文のDOI（デジタルオブジェクト識別子）	**査読の有無**
10.1063/9.0000297	有
オープンアクセス	**国際共著**
オープンアクセスとしている（また、その予定である）	－

〔学会発表〕　計6件（うち招待講演　0件／うち国際学会　2件）

1．発表者名
T. V. A. Nguyen, Y. Saito, H. Naganuma, S. Ikeda, T. Endoh, Y. Endo
2．発表標題
Dependence of dynamic magnetic properties on the Co-Fe-B layer thickness for Ta/Co-Fe-B and Ta-O/Co-Fe-B bilayers
3．学会等名
The 69th JSAP Spring Meeting 2021
4．発表年
2022年

1．発表者名
T. V. A. Nguyen, S. DuttaGupta, Y. Saito, K. V. De Zoysa, S. Fukami, S. Ikeda, T. Endoh, Y. Endo
2．発表標題
Study on the current distribution in Ta-O/Co-Fe-B stack films with the presence of interfacial scattering
3．学会等名
令和3年度スピニクス特別研究会
4．発表年
2021年

1．発表者名
T. V. A. Nguyen, Y. Saito, S. Ikeda, T. Endoh, Y. Endo
2．発表標題
Effect of surface treatment on damping constant in Ta-O/Co-Fe-B heterostructures
3．学会等名
2022 Joint MMM - Intermag conference（国際学会）
4．発表年
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1．発表者名 T. V. A. Nguyen, S. DuttaGupta, Y. Saito, K. V. De Zoysa, S. Fukami, S. Ikeda, T. Endoh, Y. Endo
2．発表標題 Evaluation of resistivity in Ta-O/Co-Fe-B multilayers with the presence of interfacial scattering
3．学会等名 The 82nd JSAP Autumn Meeting, 2021;
4．発表年 2021年

1．発表者名 T. V. A. Nguyen, S. DuttaGupta, Y. Saito, K. V. De Zoysa, S. Fukami, S. Ikeda, T. Endoh, Y. Endo
2．発表標題 Spin-orbit torque in naturally oxidized Ta-O/Co-Fe-B/Mg-O/Ta structures
3．学会等名 IEEE International Magnetics Conference, 2021（国際学会）
4．発表年 2021年

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2．発表標題 Investigation of spin-orbit torque induced magnetization switching in Ta-O/Co-Fe-B heterostructures
3．学会等名 The 68th JSAP Spring 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

共同研究相手国	相手方研究機関