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研究課題名（和文）Design and development of spin-torque-oscillator for microwave assisted magnetic recording.

研究課題名（英文）Design and development of spin-torque-oscillator for microwave assisted magnetic recording

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研究成果の概要（和文）：We proposed and demonstrated a novel spin-torque-oscillator, all-in-plane STO, for microwave assisted magnetic recording, the next generation of recording technology. This work was done by combination of micromagnetic simulations, device fabrication/analysis, and nanostructure characterizations.

研究成果の学術的意義や社会的意義
We successfully proposed and demonstrated a novel design of spin torque oscillator for the next generation of magnetic recording technology. This is important for our society to overcome the data storage capacity crisis. This work had a great impact in academia as well as HDD industries.

研究成果の概要（英文）：Microwave assisted magnetic recording (MAMR) is a promising technology to overcome the stagnated areal density increase of hard disk drives. However, its most essential part, spin-torque-oscillator (STO), has not been realized due to the lack of fundamental studies. In this work, we combined a novel micromagnetic simulation, device fabrications/analysis, and advanced structure/interface characterizations to design material/geometry for the STO devices with desired performance for MAMR. This innovative fundamental research lead to design and experimental demonstration of a new type of STO, all-in-plane STO for MAMR. We experimentally demonstrated the dynamics of the out-of-plane precession (OPP) mode oscillation for field generating layer with oscillation cone angle of 70o and frequency of 16 GHz. This fundamental study not only had a great academic impact but also has attracted a great attention from media industry.

研究分野：Magnetic Materials

キーワード：Spin torque oscillator　MAMR　spin polarization　spin accumulation　Simulations　Microstructure

１．研究開始当初の背景

Increase of areal density of the hard disc drives (HDD) has been stagnated in the last few years as shown in Fig. 1. In order to increase the areal density of HDD beyond 2 Tbit/in^2, a new recording technology should be introduced. This is important for our society that strongly depends on digital information to overcome the data storage capacity crisis. The current problem is the magnetic field produced by the write heads (~1.2 T) cannot switch the magnetization direction of the nano-sized ferromagnetic grains of the media with large magnetocrystalline anisotropy. However, the switching field of the nano-sized magnetic grains can be reduced by introducing an AC magnetic field (H_{ac}) [1-3]. This idea has opened up the concept of microwave-assisted magnetic recording (MAMR) for the next generation HDD. The most critical part of MAMR write head is a "*spin-torque-oscillator*" (STO) that can produce a large H_{ac} (Fig. 2). The STO device for MAMR should have a size of 30-40 nm and be able to generate large H_{ac} with a frequency over 20 GHz at a small current density J<1.0×10^{12} A/m^2 [2]. However, such a device has not been yet realized experimentally due to lack of fundamental understandings on the optimum materials design and structure of the STO. In order to meet the specification of the STO device for MAMR as the new recording technology, comprehensive fundamental studies are necessary to develop STO that oscillates with resonance frequency over 20 GHz at $J < 1.0 \times 10^{12}$ A/m^2.　This has been the main goal of this research.

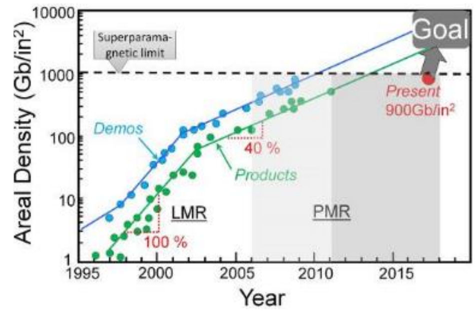

Figure 1: Worldwide areal density increase of hard disk drives (HDD) showing a saturated state to 900 Gb/in^2 and goal of this proposal.

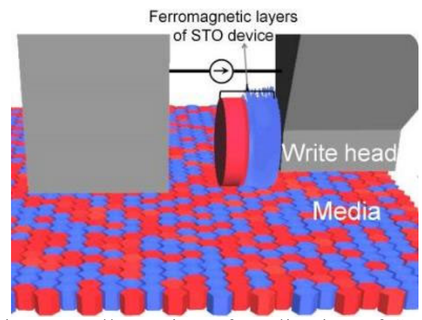

Figure 2: Illustration of application of STO device in MAMR as the next generation of magnetic recording technology.

２．研究の目的

The main purpose of this research is to design and develop STO device with desired oscillation behavior for MAMR, next generation of recording technology for hard disk drives (HDD) with areal density beyond 2Tb/in^2. The oscillation behavior of STO device depends on the design of STO such as materials used in each ferromagnetic and nonmagnetic layers, thickness of pinned and free layers, and size and shape of the device. In addition, interface structure/chemistry and spin accumulations at the interfaces are important factors. However, exploring and optimizing these parameters experimentally is time-consuming and all aspects of materials parameters cannot be investigated. Hence, the first fold of my research was focused on design of STO device theoretically. I employed a novel advanced micromagnetic simulation to design STO-device for MAMR write head that can produce a large H_{ac} with uniform oscillation with a frequency over 20 GHz with small bias current density J < 1.0×10^{12} A/m^2. The second goal of this research proposal is to develop the designed STO device experimentally and to study its oscillation behavior. My expertise in nano-scale microstructure characterizations using aberration corrected scanning transmission electron microscopy enabled me to evaluate the multilayer and interface structures of STO devices with an atomic scale resolution that is important for the material design of STO.

３．研究の方法

We employed a micromagnetic simulation code, *magnum.fe*, which solves the coupled dynamics of the magnetization $\boldsymbol{m}$ and spin accumulation $\boldsymbol{s}$ simultaneously using the 3D spin-diffusion equations and the Landau-Lifshitz-Gilbert (LLG) equation, respectively [4-6]. The used model that is an extension of the well-established Slonczewski model allows to calculate the unknown geometry and material dependent prefactors of the Slonczewski model of the damping like term and predicts a field like term in the metallic multilayers [4-6]. Furthermore, the used model has several advantages that are crucial for the present study. In contrast to the Slonczewski model, the spin-diffusion model relies on bulk material parameters rather than global system properties, which enables systematic parameter studies. Moreover, the spin-diffusion model naturally accounts for the bidirectional spin-torque coupling of the magnetic layers. This enabled us for a realistic design of STO for MAMR. Magnetization dynamics as a function of time are governed by the Landau-Lifshitz-Gilbert equation (LLG):

$$\partial_t \boldsymbol{m} = -\gamma \boldsymbol{m}\times(\boldsymbol{h}_{\text{eff}} + (J/\hbar\gamma M_s)\boldsymbol{s}) + \alpha \boldsymbol{m}\times\partial_t \boldsymbol{m} \quad (1)$$

where $\boldsymbol{m}$ is the normalized magnetization, γ is the reduced gyromagnetic ratio, α is the gilbert damping constant, and $\boldsymbol{h}_{\text{eff}}$ is the effective magnetic field. In our simulation, we consider the effect of spin accumulation by coupling the spin accumulation $\boldsymbol{s}$ to the magnetization using a torque term. In the above equation, J is the exchange strength between the conducting electrons and magnetization and $\hbar$ is Plank constant. The spin accumulation $\boldsymbol{s}$ is computed according to the spin-diffusion model [7]. Using the magnum.fe code, we designed the materials for oscillation of all-in-plane STO with resonance frequency of 20-25 GHz, a large oscillation cone angle, and small bias current density.

We also fabricated two STOs with different SIL material to further explore the simulation results experimentally. Epitaxial thin films were grown on a (001) MgO single crystalline substrate in an ultra-high vacuum magnetron sputtering chamber. The surface of the MgO substrates was first cleaned and flattened by annealing it at 600°C followed by deposition of Cr(10nm)/Ag(100nm) buffer layers deposited at room temperature and post annealed at 400°C. Thereafter, two different films were deposited with the same substrate and buffer layers, the first film was $Fe_{67}Co_{33}$(3nm)/Ag(5nm)/$Fe_{67}Co_{33}$(7nm) and second film was $Co_2FeAl_{0.5}Si_{0.5}$(3nm)/Ag(5nm)/ $Fe_{67}Co_{33}$(7nm) deposited at room temperature followed by post-annealing at 500°C. Based on the micromagnetic simulation results, we also developed STO device using $Ni_{80}Fe_{20}$ as SIL with the same $Fe_{67}Co_{33}$ FGL material. The microstructure of the films was studied using a Titan G2 80-200 probe aberration corrected microscope. The MR ratios were measured by 4 point probe measurement with an applied magnetic field along the film normal.

４．研究成果

In our previous feasibility investigations on design and development of STO, we have demonstrated mag-flip STO in which electrons flow from field generating layer (FGL) to spin injection layer (SIL) while SIL and FGL is magnetized out-of-plane using an external magnetic field. In fact, the oscillation of FGL originates from reflected spins from the SIL/spacer interface toward FGL with opposite direction to the magnetization direction of FGL. We demonstrated that mag-flip STO with 40-60 nm in diameter that can oscillate with resonance frequency of 21-25.5 GHz and produce an $\mu_0 H_{ac}$ of 0.15 T [8,9]. However, the main disadvantage of the mag-flip STO is its large thickness due to the need for ~10 nm out-of-plane magnetized FePt. In addition, the required J for oscillation of mag-flip STO is over 4.3×10^8 A/cm^2 that needs to be substantially reduced for the practical application [8,9]. In this research, we first numerically proposed and demonstrated a novel type of STO, all-in-plane STO device, which composes in-plain magnetized spin-injection layer (SIL) and field-generating layer (FGL), that can possess smaller thickness and driving current density compared to the mag-flip STO. In this device, electrons are injected from SIL to FGL while the magnetization of the SIL and FGL is saturated to the out-of-plane by the external magnetic field of ~1.0 T. How this device works is discussed in detail in our

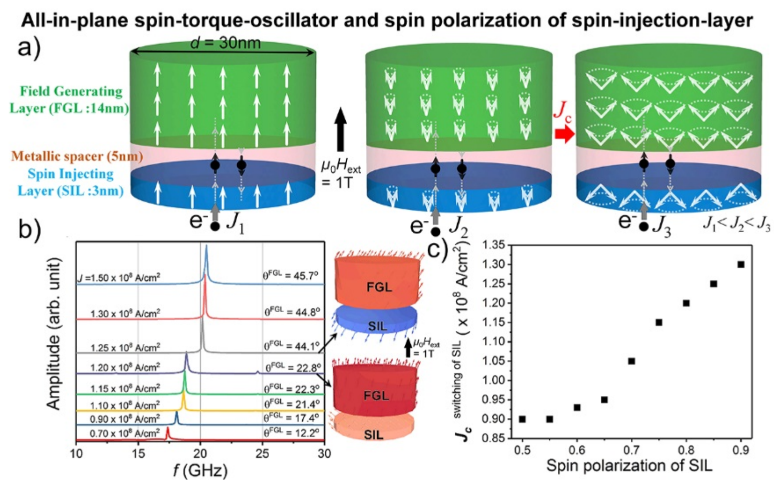

Figure 3: (a) Schematic illustration of all-in-plane STO. Power spectra calculated from $\boldsymbol{M}_x$ oscillation of FGL for a 0.85 spin polarization (β) of SIL and $\beta^{\text{FGL}} = 0.80$. The oscillation cone angle of FGL and applied current density is shown in each spectrum and an example of snap shots of the oscillation of SIL and FGL is shown in (b). Critical current density required for switching of magnetization of SIL as a function of β^{SIL} is shown in (c).

published paper and shown schematically in Fig. 3 (a) [10]. Micromagnetic simulations showed that the magnetization direction of SIL can be switched to the opposite direction to that of the applied external magnetic field by the use of spin-transfer-torque. An example is shown in Fig. 3 (b) in which when the current density increases from 1.2×10^8 A/cm^2 to 1.25×10^8 A/cm^2, magnetization of SIL switches opposite to the applied magnetic field direction due to the spin-transfer-torque. Thereafter, increase of resonance frequency to above 20 GHz and increase of oscillation cone angle to ~45^o can be observed after the magnetization switching of SIL as shown in Fig. 3 (b). Our detail micromagnetic simulation study has shown that all-in-plane STO has merit of reduced thickness compare to that of mag-flip STO, but also smaller current density is required for the oscillation of device due to the larger spin accumulation in FGL after the magnetization switching of SIL [10]. We designed SIL to reduce the critical current density, J_c, required for the magnetization switching of SIL. Unlike the conventional mag-flip STO device, we found that the small spin polarization of SIL play very important role in J_c required for switching of SIL and OOP oscillation of FGL (Fig. 3 (c)). The materials with a smaller $\mu_0 M_s$ and spin polarization (β) in SIL results in reduction of J_c and enables STO to oscillate with frequency of above 20 GHz with a large out-of-plane oscillation cone angle of 45-50^o (Fig. 3 (b,c)). The validity of this finding, in particular the material choice of SIL, was studied experimentally by developing STO with different SIL materials; Heusler $Co_2Fe(Al_{0.5}Si_{0.5})$ and $Fe_{67}Co_{33}$. Figure 4 (a) shows the high angle annular dark field (HAADF) STEM image and micro-beam electron diffraction patterns obtained from $Fe_{67}Co_{33}$(SIL3nm)/Ag(5nm)/$Fe_{67}Co_{33}$(FGL-7nm) film showing epitaxial growth of the layers with a sharp interfaces between spacer and SIL. Both SIL and FGL have the A2 structure. STEM-EDS maps of Fe, Co, and Ag and the concentration line profiles from the STEM-EDS is also shown in Fig. 4 (a) confirming the formation of $Fe_{67}Co_{33}$ in SIL and FGL. Fig. 4 (b) shows HAADF-STEM image and micro-beam electron diffraction patterns from the $Co_2FeAl_{0.5}Si_{0.5}$(SIL-3nm)/Ag(5nm)/$Fe_{67}Co_{33}$(FGL-7nm) film. STEM-EDS maps of Fe, Co, Ag, Al, and Si as well as the concentration line profiles from the STEM-EDS map is also shown in Fig. 4 (b). STEM-EDS line profile and micro-beam diffraction patterns show that SIL has a composition of $Co_2Fe(Al_{0.5}Si_{0.5})$ with the B2 structure. The FGL shows a composition of $Fe_{67}Co_{33}$ with the A2 structure. The magnetization configuration of SIL and FGL in STO with ~60 nm diameter is investigated experimentally based on the field dependent resistance change measured at room temperature and low temperature and discussed based on the micromagnetic simulations. It was found experimentally that the spin polarization of SIL play very important role in the reduction of current density for the magnetization switching of SIL and large cone angle oscillation of FGL, in agreement with the micromagnetic simulation results [10]. We

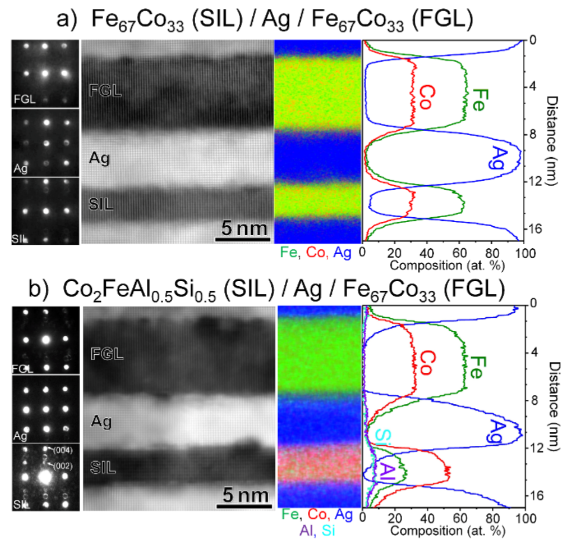

Figure 4: High angle annular dark field (HAADF)-STEM, STEM-EDS maps of constituent elements, composition line profile and microbeam diffractions from SIL, Ag, and FGL of (a) $Fe_{67}Co_{33}$(SIL)/Ag/$Fe_{67}Co_{33}$(FGL) and (b) $Co_2FeAl_{0.5}Si_{0.5}$(SIL)/Ag/$Fe_{67}Co_{33}$(FGL) films.

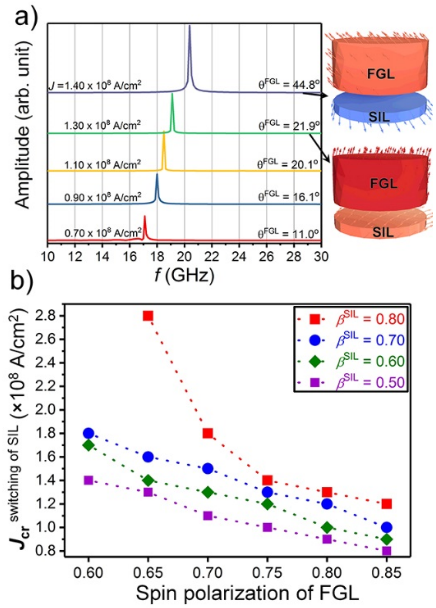

Figure 5: (a) RF spectrums calculated from $\boldsymbol{M_x}$ oscillation of FGL for $\beta^{SIL} = 0.80$ and $\beta^{FGL} = 0.75$ for different J. The oscillation cone angle of FGL is also shown. (b) Critical current density required for the magnetization switching of SIL as a function of β^{FGL} and varied β^{SIL}.

also found that large β of FGL is beneficial to reduce J_{cr} as shown in Fig. 5. We studied the underlying physics for this based on the spin accumulation in SIL for different spin polarization of FGL. By increase of β^{FGL}, more reflected spins from FGL/Ag interface toward to SIL layer with opposite direction to the magnetization of SIL was realized that will be beneficial for magnetization switching of SIL. It was found that by increase of β^{FGL}, we get more reflected negative spins from FGL/Ag interface that will be beneficial for switching of SIL and OOP oscillation of FGL, resulting in smaller J_c. However, large spin polarized materials such as Heusler alloys have limited saturation magnetization of below ~ 1.3 T. This is not beneficial for STO for MAMR since small saturation magnetization of FGL results in a small ac-field that can be generated from FGL on media. In order to increase the ac-field generated by STO, it is necessary to increase the saturation magnetization of FGL. In order to gain large spin polarization of FGL combined with large saturation magnetization in FGL, we propose all-in-plane STO with dual FGL. By use of this model, we can gain large spin accumulation in SIL that is beneficial for the magnetization switching of SIL and second layer of FGL can have a large saturation magnetization with lower spin polarization desired for large ac magnetic field out-put of device. Further study is needed to realize this device experimentally.

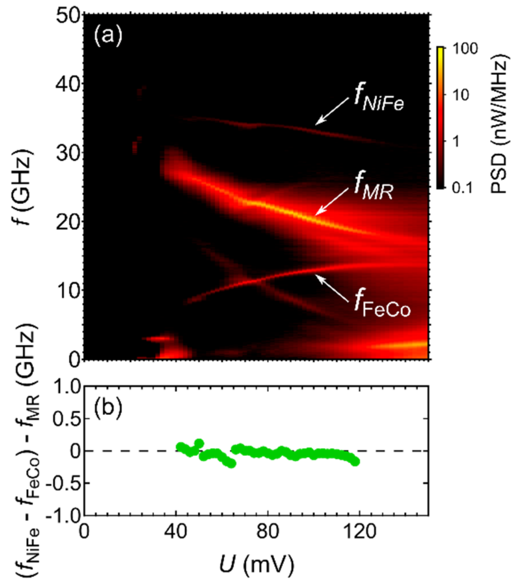

Figure 6: (a) The mapping of PSD under $\mu_0 H = 0.81$ T. (b) $(f_{NiFe} - f_{FeCo}) - f_{MR}$ from (a) as a function of U. U = 80 mV in experiment corresponds to $J = 3.3 \times 10^8$ A/cm^2.

We further reduced the device size to 28nm and investigated the oscillation behavior of all-in-plane STO experimentally. Since both SIL and FGL layers in all-in-plane STO oscillates simultaneously, oscillation behavior analysis by conventional method of measuring resistance change of device would need more comprehensive understanding to correlate the oscillation peaks to SIL or FGL. Hence, we designed materials of all-in-plane STO for this purpose based on micromagnetic simulations. A 7-nm-thick $Fe_{67}Co_{33}$ (FeCo) layer was used as the FGL while a 7-nm-thick $Ni_{80}Fe_{20}$ (NiFe) layer was used as the polarizer, which were separated by 5-nm-thick Ag spacer. The blanket thin film was micro-fabricated into circular shape elements. For characterization of the STO, the resistance (R), dV/dI, and the power spectral density (PSD) of the device were measured with increasing bias DC voltage (U) under a constant H. The positive U was defined as the electrons flowing from the NiFe layer to the FeCo layer. Micromagnetic simulation was also carry out to understand the corresponding dynamics occurred in the STO. Figure 6(a) shows the mapping of PSD under $\mu_0 H = 0.81$ T tilted 2° from the perpendicular direction. Here the strong microwave signal marked f_{MR} is the result of both the FGL and the polarizer in OPP mode oscillation with different f. The microwave signals marked f_{NiFe} and f_{FeCo} in Fig. 6(a) reflect OPP mode oscillation of the NiFe and FeCo layers, together with the relationship of $f_{MR} = f_{NiFe} - f_{FeCo}$, as indicated by Fig. 6(b). Such dynamics were well reproduced by micromagnetic simulation. Exploiting the macrospin model and assuming f of OPP mode oscillation is proportional to the effective field of the layer, we estimated the cone angle (θ) based on f_{NiFe} and f_{FeCo} extracted from the experimental results. The estimation suggested that a large θ of ~ 70° at high f of 16 GHz for OPP mode oscillation of FeCo was realized in the STO [11].

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５．主な発表論文等
〔雑誌論文〕（計　３件）

1- *H Sepehri-Amin*, W Zhou, S Bosu, C Abert, Y Sakuraba, S Kasai, D Suess, K Hono, “Design of spin-injection-layer in all-in-plane spin-torque-oscillator for microwave assisted magnetic recording”, J. Magn. Magn. Mater. 476 (2019) 361-370. (Peer-reviewed and published).
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1- *H. Sepehri-Amin,* W. Zhou, S. Bosu, Y. Sakuraba, S. Kasai, and K. Hono, “Design and development of all-in-plane spin-torque-oscillator for microwave assisted magnetic recording”, Magnetic Society of Japan, September 11-14, 2018, Nihon University, Japan, **Invited talk.**
2- *H. Sepehri-Amin,* C. Abert, D. Suess, K. Hono,” Design of field generating layer in all-in-plane spin-torque-oscillator”, Intermag 24-27 April, 2018, Singapore.
3- *H. Sepehri-Amin***,** S. Bosu, C. Abert, Y. Sakuraba, S. Kasai, M. Hayashi, D. Suess, and K. Hono, “Design and development of spin-torque-oscillator for microwave assisted magnetic recording”, The 28th magnetic recording conference (TMRC2017), August 2-4, 2017, Tsukuba, Japan, **Invited talk.**

〔図書〕（計　　件）

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