様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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

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

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研究成果の概要（和文）：マイクロ波アシスト磁気記録（MAMR）は、ハードディスクドライブの面密度の向上が停滞していることを克服するための有望な技術である。しかし、その最も重要な部分であるスピントルク発振器（STO）は実現されていない。ここでは、小さなバイアス電流密度で40GHz以上の周波数で発振する、MAMRに望まれる新しいSTOを設計・開発した。

研究成果の学術的意義や社会的意義
This work provided guidelines toward realization of next generation magnetic recording technology with a great impact in academia and data storage industries. This study will has paved a way to increase the data storage capacity of hard disks which is important factor for realization of society 5.0

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 (HDD). However, its most essential part, “spin-torque-oscillator (STO)”, has not been realized. We succeeded in development of a novel STO satisfying the requirement of MAMR. We employed advanced micromagnetic simulations and designed a novel STO; all-in-plane (AIP)-STO. The designed STO was fabricated experimentally. We successfully studied the complex magnetization dynamics of AIP-STO by developing a new analysis method using injection locking to an external microwave field. The second fold of this research is design and development of media material for next generation recording technology. We developed TEM image based micromagnetic simulator enabling high throughput evaluation of nanodefects and micromagnetic parameters of media. Our achievements had a great impact in academia as well as HDD industries.

研究分野：応用物性関連

キーワード：Magnetic Recording　Spin torque oscillator　Recording media　Micromagnetic simulation　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 (Fig. 1). In order to increase the areal density of HDD beyond 2 Tbit/in^2, a new recording technology should be introduced. 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}). 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 $J<1.0\times10^{12}$ A/m^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 this project, we will combine a novel micromagnetic simulation, device fabrications/analysis, and advanced structure/interface characterizations to design material/geometry for the STO devices that generate a large AC magnetic field with frequency above 20 GHz at a small bias current density. This is to increase the areal densities of HDD to 2Tb/in^2 using CoCrPt-SiO_2 media. The second goal of this project is design of media materials for so called energy assisted magnetic recording, which can include microwave assisted magnetic recording or heat assisted magnetic recording, to increase the areal densities beyond 2 Tb/in^2.

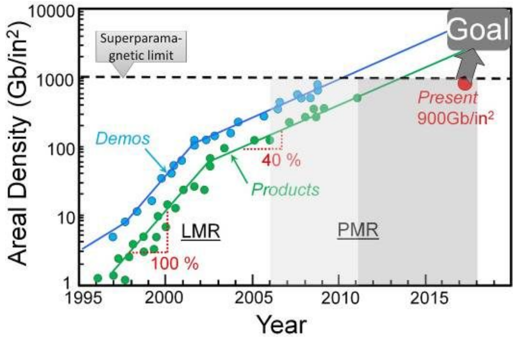

Figure 1: Worldwide areal density increase of hard disk drives (HDD) showing a saturated state and goal of this proposal.

２．研究の目的

The first goal of this research is to design and develop STO that can oscillate with a frequency above 20 GHz in a small current density with a large oscillation cone angle. The oscillation behavior of the STO depends on the material and thickness of the SIL, FGL, spacer, size and shape of the device. In addition, interface structure/chemistry and spin accumulations at the interfaces are important factors. In this project, we will design novel STO using advanced micromagnetic simulations and demonstrated these STO devices experimentally. Using aberration corrected STEM, the multilayer structures of STO will be evaluated.

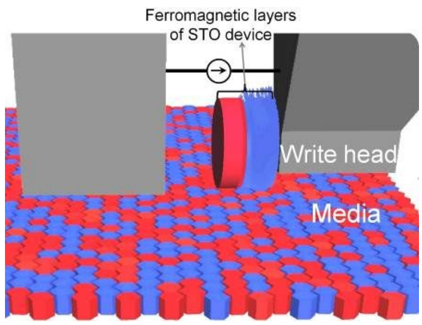

Figure 2: Illustration of application of STO device in MAMR as the next generation of recording technology.

The current research trend of the world on realization of MAMR is focused on employment of STO for CoCrPt-SiO_2 media. However, in order to increase the areal density beyond 2 Tb/in^2, a new media material with a larger K_u needs to be developed to increase the superparamagnetic limit so that grain size can be reduced for a higher areal density recording. However, fundamental investigations are necessary to design the media which can be suited for next generation energy assisted magnetic recording. Our second purpose in this proposal is to design and develop media material for areal densities>2Tb/in^2 for next generation energy assisted magnetic recording; either microwave assisted magnetic recording or heat assisted magnetic recording (Fig. 1). The significance of this research proposal and its originality is its unique combinatorial fundamental research approach; advanced numerical studies, experimental development of device, and nanostructure characterizations that will enable us to demonstrate STO and media materials for the next generation of energy assisted magnetic recording with areal density>2Tb/in^2.

３．研究の方法

We have used a novel micromagnetic simulation method. 3D spin diffusion model coupled to the micromagnetic equations are employed enabling simulation of magnetization and spin diffusion dynamic. Note that unlike the conventional Slonczewski spin-transfer-torque model, solving 3D spin diffusion model in micromagnetic will enable us to study the effect of spin accumulation at the interfaces for accurate design of STO. We use this advanced micromagnetic simulation for a realistic design of STO. In order to further explore the simulation results experimentally, the designed STOs are developed experimentally with different materials used in spin-injection-layer and field-generating-layer. Epitaxial thin films were grown on a (001) MgO single crystalline substrate in an ultra-high vacuum magnetron sputtering chamber. The MR ratios were measured by 4 point probe measurement with an applied magnetic field along the film normal. Oscillation performance of STO devices were investigated by measuring the power spectral density (PSD). A bias DC voltage (*U*) was applied to the STO device through a bias-tee. The generated signal was amplified by a low noise amplifier, and captured by a commercial spectrum analyzer. The microstructure of the films was studied using a Titan G2 80-200 probe aberration corrected microscope.

４．研究成果

(1) Design of all-in-plane spin-torque-oscillator

A new type of spin-torque-oscillator (STO), all-in-plane STO, is introduced as a new candidate for microwave assisted magnetic recording (MAMR) that consist of a spin-injection-layer (SIL) and a field-generating-layer (FGL) with an effective in-plane easy axis due to the shape anisotropy separated with a metallic spacer [1,2]. The magnetization behavior of the all-in-plane STO is schematically shown in Fig. 3 (a), that is designed in this case as SIL(3nm)/Ag(5nm)/FGL(14nm) with a device diameter of 30 nm [1].

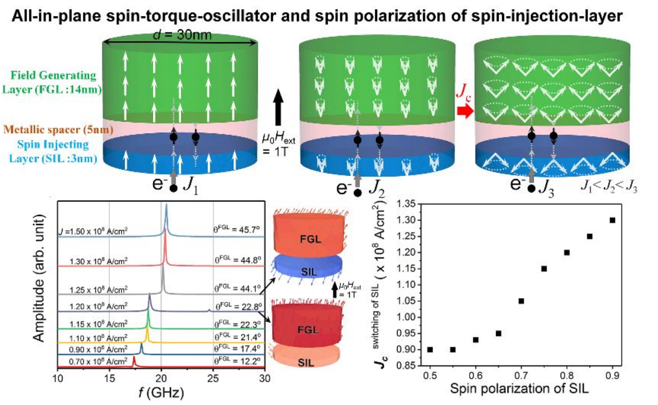

Figure 3: Schematic demonstration of critical current density required for the magnetization swithing of SIL and oscillation of FGL. Power spectra calculated from $\boldsymbol{M_x}$ oscillation of FGL for a 0.85 spin polarization (β) of SIL and β^{FGL} = 0.80. The oscillation cone angle of FGL and applied current density is shown in each spectrum and an example of snap shots of the oscillation of SIL and FGL is shown. Critical current density required for switching of the magnetization of SIL as a function of β^{SIL} is shown. The saturation magnetization of SIL and FGL were kept constant as 1.35 T in these simulations [1].

An external magnetic field of 1 T is applied to saturate the magnetization of the SIL and FGL to out-of-plane direction and electrons are pumped from bottom to top. When the magnetization direction of the layers are pointing upward due to the applied external magnetic field ($\mu_0 H_{ext}$), the up-spin electrons moving from bottom to the top of the device can pass through the spacer/FGL interface while the down-spin electrons get reflected to the SIL. In this simulation, we used a large spin diffusion length of 100 nm for the metallic spacer, Ag. Due to the reflection of down spin electrons from the FGL/spacer interface, a spin-transfer-torque is applied to the magnetization of SIL. When the applied current density is very small, spin-transfer-torque cannot lead to the oscillation of SIL nor FGL. When the critical current density is increased, reflected down-spin electrons lead to a spin-transfer-torque on the magnetic moment of the SIL and transmitted spins apply torque on the magnetization of the FGL, resulting in the oscillation of magnetization in SIL and FGL with the same out-of-plane magnetization direction. When the applied current density is increased further, larger reflected down-spin electrons from the FGL/spacer interface switches the magnetization of the SIL that results in the oscillation of the FGL with a larger cone angle. Compared to the conventional mag-flip STO, the main merit is the reduction of the total device thickness since there is no need for use of materials with perpendicular magnetic anisotropy. We designed SIL to reduce the critical current density, J_c, required for the magnetization switching of SIL (Fig. 3). Materials with a smaller saturation magnetization in SIL reduce J_c. Smaller spin polarization of SIL leads to a larger spin accumulation in SIL with an opposite direction to the magnetization, resulting in a reduction of J_c. This enables magnetization switching of SIL in small J_c followed by oscillation of FGL with frequency above 20 GHz with a large out-of-plane oscillation cone angle of 45-50^o (Fig. 3). we also studied the influence of field-generating-layer (FGL) material on the oscillation of all-in-plane STO. Material with large spin polarization in FGL facilitate the magnetization switching of SIL against external magnetic field by spin transfer-torque that results in the oscillation of STO with frequency above 20 GHz and large oscillation cone angle (Fig. 4). The underlying physics was found to be larger spin accumulation in SIL with opposite direction to the magnetization direction of SIL that originates from reflected electrons from FGL/spacer interface to the SIL. Material with a large saturation magnetization (above 1.8 T) in FGL is needed to have a large ac magnetic field ($\mu_0 H_{ac}$> 0.2 T) out of the STO (Fig. 4).

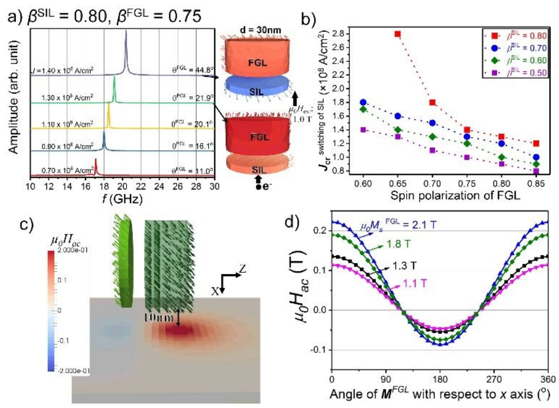

Figure 4: (a) Power spectra calculated from $\boldsymbol{M_x}$ oscillation of FGL for a 0.80 spin polarization (β) of SIL and β^{FGL} = 0.75. The oscillation cone angle of FGL and applied current density are shown in each spectrum. (b) Critical current density required for switching of the magnetization of SIL as a function of β^{FGL}. (c) Simulated ac magnetic field originated from STO with different M_s of FGL maerial as a function of oscilation angle of FGL.

(2) Development of all-in-plane STO

We have developed the designed STO experimentally and evaluated its magnetization dynamics. Using NiFe as spin polarizer and FeCo as FGL, our results from experiment and simulation clearly show the dynamics of the OPP mode oscillation for both layers with different frequency f as f_{NiFe} and f_{FeCo}, respectively (Fig. 5). The dynamics also generated the microwave signal with $f_{MR} = f_{NiFe} - f_{FeCo}$. Based on the macrospin model, θ of the OPP mode oscillation was estimated, and the results suggested a large θ of ~ 70° for the FeCo layer at high f_{FeCo} ~ 16 GHz. With this design, the STO device showed characteristics close to the requirements from application while maintained a thin and simple structure. In addition, the use of only a soft magnetic thin layer as the spin polarizer widens the choice of material for the spin polarizer, which holds potential to further improve the performance of STO and reach the requirements for practical application.

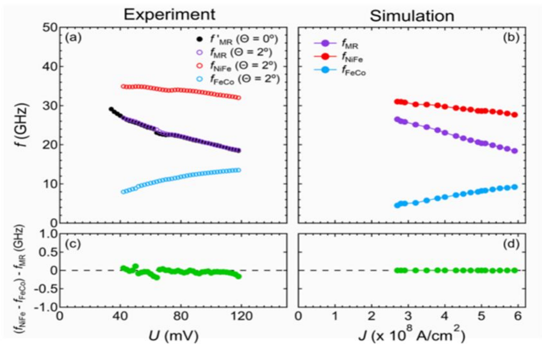

Figure 5: (a) f of some of the microwave signals in PSD from Figs. 2(e) and (f) as a function of U. (b) f of the largest magnitude in the spectra of x components of m_{NiFe} and m_{FeCo} as well as U as a function of J. (c) ($f_{NiFe} - f_{FeCo}$) $- f_{MR}$ from experiment as a function of U and (d) from simulation as a function of J. U = 80 mV in experiment corresponds to $J = 3.3 \times 10^8$ A/cm^2.

The oscillation frequency of FGL is an important parameter in MAMR which greatly affects the The oscillation frequency of FGL is an important parameter in MAMR which greatly affects the MAMR efficiency. Conventionally, the oscillation frequency has been estimated by measuring a high-frequency electrical signal (STO signal) originating from the resistance change due to the magnetoresistance (MR) effect. However, the STO signal from the AIP-STO exhibits multiple peaks corresponding not only to the oscillation of FGL, but also to that of SIL and the difference between these frequencies because magnetization dynamics are induced in both SIL and FGL. Although the multiple peaks can be explained by simulations, an experimental technique capable of analyzing the complex STO signal is desired [3,4]. In this work, we study the magnetization dynamics of an AIP-STO by using injection locking to an external MW magnetic field (H_{MW}). Figure 6 shows an example of experimentally measured oscillation behavior of all-in-plane STO. We have successfully realized

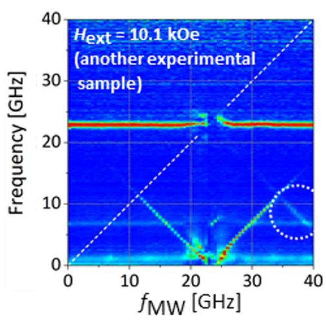

Figure 6: PSD of the STO signal versus f_{MW} obtained from an experimental sample for P_{MW} = 12 dBm; I_{STO} = 4 mA; H_{ext} = 10 kOe.

an oscillation frequency of over 20 GHz in FGL of all-in-plane STO.

(3) TEM image based micromagnetic simulator for media characterizations

The areal density of the heat-assisted magnetic recording (HAMR) technology has a potential to reach 4 Tb/in^2. However, the bimodal grain size distribution and structural defects that are unavoidable in actual FePt-X nanogranular media must be minimized for further reduction of jitter noise [5-7]. This work has demonstrated a new TEM image based micromagnetic approach for structural optimization of FePt-X heat-assisted magnetic recording media. Its key concept is to construct a finite element model that replicates the nanostructure of granular media based on high-resolution transmission electron microscopy images (Fig. 7) [7]. The approach enables the evaluation of micromagnetic parameters and the volume fractions of defects in FePt grains by the precise micromagnetic approximation of experimental hysteresis loops. This method was applied to MgO(6 nm)/FePt-BN(1 nm)/FePt-(C,SiO_2)(7 nm) granular thin films, for which the micromagnetic approximation yielded the volume fractions of {111} twins and [200] misaligned grains, which are in excellent agreement with those determined by synchrotron XRD. The demonstrated TEM image based micromagnetic modelling is an efficient method to evaluate structural defects in nanostructured magnetic materials, enabling high-throughput optimization of the FePt-X media for HAMR. Moreover, the proposed approach can be expanded to any other nanostructured magnetic systems.

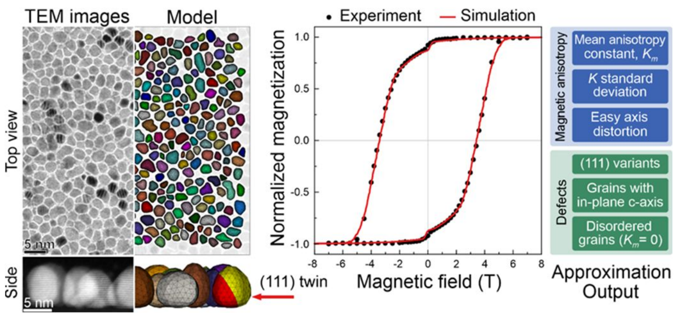

Figure 7: TEM image based micromagnetic simulator, high throughput evaluation of micromagnetic parameters and nano-defects in the granular media [7].

In summary, we have employed advanced micromagnetic simulator and designed new type of spin-torque-oscillator (STO), all-in-plane STO, as a new candidate for microwave assisted magnetic recording (MAMR) for next generation of magnetic recording technology. The new STO consists of a spin-injection-layer (SIL) and a field-generating-layer (FGL) with an effective in-plane easy axis due to the shape anisotropy separated with a metallic spacer. The required materials for SIL and FGL along with device geometry was designed aiming at oscillation of STO at the frequencies above 20 GHz with a large oscillation cone angle under a small current density. We have successfully developed the designed all-in-plane STO experimentally and its complex oscillation performance was evaluated experimentally. We demonstrated the developed STO oscillate at the frequencies above 20 GHz required for practical application. Moreover, we have demonstrated a novel method for high throughput characterization of granular media for the next generation energy assisted magnetic recording technology. As a case study, we have shown the developed TEM image based micromagnetic simulations can directly link nanostructure of the FePt-X media to magnetic properties, boosting the optimization of the media toward realization of HDD with a areal density beyond 2 Tbit/in^2.

Publication list

[1] H. Sepehri-Amin *et al.* "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.

[2] W. Zhou, H. Sepehri-Amin *et al.* "Inducing out-of-plane precession of magnetization for microwave-assisted magnetic recording with an oscillating polarizer in a spin-torque oscillator", Appl. Phys. Letters 114 (2019) 172403.

[3] H. Suto, H. Sepehri-Amin *et al.* "Analysis of an all-in-plane spin-torque oscillator using injection locking to an external microwave magnetic field", Appl. Phys. Express 14 (2021) 053001.

[4] N. Asam, H. Suto, S. Tamaru, H. Sepehri-Amin, *et al.* "Analysis method of a spin-torque oscillator using dc resistance change during injection locking to an external microwave magnetic field", Appl. Phys. Letters 119 (2021) 122405.

[5] J. Wang, H. Sepehri-Amin, *et al.* "Magnetic in-plane components of FePt nanogranular film on polycrystalline MgO underlayer for heat-assisted magnetic recording media", Acta Mater. 177 (2019) 1-8.

[6] I. Suzuki, S. Kubo, H. Sepehri-Amin, Y. K. Takahashi, "Dependance of growth mode in epitaxial FePt films on surface free energy", ACS Appl. Mater. Interfaces 13 (2021) 16620.

[7] A. Bolyachkin, H. Sepehri-Amin, *et al.* "Transmission electron microscopy image based micromagnetic simulations for optimizing nanostructure of FePt-X heat-assisted magnetic recording media", Acta Mater. 227 (2022) 117744.

５．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　6件／うち国際共著　6件／うちオープンアクセス　1件）

１．著者名 Suzuki Ippei、Kubo Shoichi、Sepehri-Amin Hosein、Takahashi Yukiko K.	４．巻 13
２．論文標題 Dependence of the Growth Mode in Epitaxial FePt Films on Surface Free Energy	５．発行年 2021年
３．雑誌名 ACS Applied Materials & Interfaces	６．最初と最後の頁 16620～16627
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acsami.0c22510	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 該当する

１．著者名 Suto Hirofumi、Sepehri-Amin Hossein、Asam Nagarjuna、Zhou Weinan、Bolyachkin Anton、Takagishi Masayuki、Narita Naoyuki、Tamaru Shingo、Nakatani Tomoya、SAKURABA Yuya	４．巻 14
２．論文標題 Analysis of an all-in-plane spin-torque oscillator using injection locking to an external microwave magnetic field	５．発行年 2021年
３．雑誌名 Applied Physics Express	６．最初と最後の頁 053001-1～5
掲載論文のDOI（デジタルオブジェクト識別子） 10.35848/1882-0786/abf667	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 該当する

１．著者名 Zhou W.、Sepehri-Amin H.、Taniguchi T.、Tamaru S.、Sakuraba Y.、Kasai S.、Kubota H.、Hono K.	４．巻 114
２．論文標題 Inducing out-of-plane precession of magnetization for microwave-assisted magnetic recording with an oscillating polarizer in a spin-torque oscillator	５．発行年 2019年
３．雑誌名 Applied Physics Letters	６．最初と最後の頁 172403～172403
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/1.5086476	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 該当する

１．著者名 Wang J.、Sepehri-Amin H.、Takahashi Y.K.、Ohkubo T.、Hono K.	４．巻 177
２．論文標題 Magnetic in-plane components of FePt nanogranular film on polycrystalline MgO underlayer for heat-assisted magnetic recording media	５．発行年 2019年
３．雑誌名 Acta Materialia	６．最初と最後の頁 1～8
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.actamat.2019.07.017	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 該当する

1．著者名	4．巻
Asam Nagarjuna、Suto Hirofumi、Tamaru Shingo、Sepehri-Amin Hossein、Bolyachkin Anton、Nakatani Tomoya、Zhou Weinan、Kubota Hitoshi、Sakuraba Yuya	119
2．論文標題	5．発行年
Analysis method of a spin-torque oscillator using dc resistance change during injection locking to an external microwave magnetic field	2021年
3．雑誌名	6．最初と最後の頁
Applied Physics Letters	142405～142405
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
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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	該当する

1．著者名	4．巻
Bolyachkin A.、Sepehri-Amin H.、Suzuki I.、Tajiri H.、Takahashi Y.K.、Srinivasan K.、Ho H.、Yuan H.、Seki T.、Ajan A.、Hono K.	227
2．論文標題	5．発行年
Transmission electron microscopy image based micromagnetic simulations for optimizing nanostructure of FePt-X heat-assisted magnetic recording media	2022年
3．雑誌名	6．最初と最後の頁
Acta Materialia	117744～117744
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1016/j.actamat.2022.117744	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）	該当する

〔学会発表〕　計1件（うち招待講演　1件／うち国際学会　0件）

1．発表者名
H. Sepehri-Amin
2．発表標題
Realizing oscillation of all-in-plane spin-torque-oscillator for microwave assisted magnetic recording
3．学会等名
The Japan Society of Applied Physics, The 80th Autumn Meeting, 2019（招待講演）
4．発表年
2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

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