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研究課題名（和文）Laser-induced deterministic magnetization switching for next-generation magnetic recording

研究課題名（英文）Laser-induced deterministic magnetization switching for next-generation magnetic recording

研究代表者

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研究成果の概要（和文）：A novel magnetization manipulation approach was proposed and demonstrated by unprecedently utilized the interconversion between heat (phononic), light (photonic), and spin (spintronic) for ultrafast manipulation of magnetization reversal in magnetically hard L10-ordered FePt thin films.

研究成果の学術的意義や社会的意義
The new physics behind the results will promote a new field of academic enquiry concerned with the interconversion between heat (phononic), light (photonic), spin (spintronic), and nanomagnetism and furthermore provide new insight into the R&D of the next-generation hard-disk drive (HDD) industry.

研究成果の概要（英文）：Nowadays, the question of how, and how fast, magnetization can be reversed is attracting great practical interest in hard disk drive (HDD) community. In this project, we successfully demonstrate a clearly enhanced all optical magnetic switching (AOS) in magnetic hard L10-ordered FePt continuous/nanogranular films deposited on yttrium iron garnet (YIG) single crystal substrate. The enhancement was confirmed by comparing with similar FePt thin films deposited on gadolinium gallium garnet single crystal substrate. The enhancement was considered due to a thermal-induced spin-transfer torque via the spin Seebeck effect in YIG substrate with a tremendous temperature gradient induced by the laser exposure. For practical application, the quantification of the enhancement and optimization of the thin film (especially the nanogranular film) microstructure will be necessary to achieve a laser-induced deterministic magnetization switching in magnetically hard FePt nanogranular film.

研究分野：応用物性（磁性材料）

キーワード：エネルギーアシスト磁化反転　FePt媒体　光誘起磁化反転　熱流スピン流変換　超高密度磁気記録

１．研究開始当初の背景

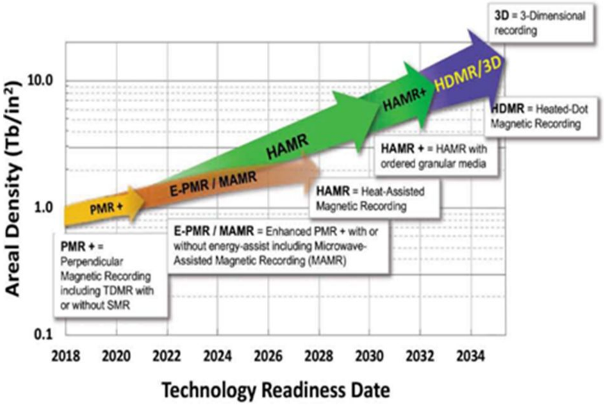

Fig. 1. Advanced Storage Technology Consortium roadmap for the future hard disk drive areal density [1].

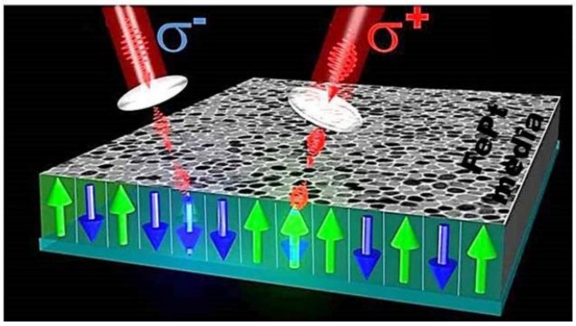

Fig. 2. Schematic of AOS techniques with FePt media [2].

Modern science and technology developments related to *Big Data*, *Artificial Intelligence*, and *Internet of Things* have become the cornerstones of future services and societal systems, known as "***Society 5.0***". Consequently, the endless explosion of digital data universe is now pushing the world toward a data storage capacity crisis. What's worse, the energy consumption of data storage devices is increasing exponentially, which will cause serious energy and environmental issues in the near future. Therefore, **revolution of current data storage technologies is urgently desired.** To solve these challenges, **FePt nanogranular film-based heat-assisted magnetic recording (HAMR)** media which can offer an ultrahigh recording areal density of ~4 Tbit/in^2 (*4 times larger than the current hard disk drive (HDD) recording media*) (**Fig. 1**) has been proposed and intensively studied [1]. However, its write/read process is quite energy inefficient and slow. On the other hand, circularly polarized laser was recently proved that it can induce helicity dependent magnetization reversal in a magnetic material (**Fig. 2**), which is termed as **all-optical switching (AOS)** [2]. The merits of the AOS technique come from its ultrafast (*1000 times faster than magnetic field pulse*) magnetization switching control in a remarkable energy-efficient manner ($\leq$2.5 aJ/nm^3) [3]. It can bring revolutionary impact on HDD industry if integrate AOS technique into HAMR which allow the ultra-high recording areal density, ultra-fast switching speed, and energy-efficient device. However, to date, deterministic (100%) AOS is only reported in soft magnetic materials (*e.g.*, GdFeCo or [Co/Pt]$_n$ films [3]). There is no report of deterministic AOS in hard magnetic materials like $L1_0$-ordered FePt nanogranular recording media which hinder its practical application.

２．研究の目的

This research project aims to study and utilizes the interconversion between heat (phononic), light (photonic), and spin (spintronic) for ultrafast manipulation of magnetization reversal. Specifically, based on the applicant's previous four-years R&D work on FePt-based HAMR, the applicant in this work proposal and explore a new magnetic recording technique by realizing laser-induced deterministic magnetization switching in magnetically hard FePt nanogranular film. The magneto-optical interaction in FePt thin films on different substrates will be compared to investigate the thermal contribution beside the conventional thermal demagnetization. The new physics behind the results will attract interests from related academic community and even bring revolutionary impact on the next-generation HDD development.

３．研究の方法

As demonstrated in **Fig. 3**, by introducing magnetic insulator(s) (MI) as underlayer and/or segregant for FePt nanogranular media, the applicant proposes to utilize the laser-induced thermal gradients, J_Q in the magnetic insulator to triggering a pure spin current (spin wave), J_S via the spin Seebeck effect (SSE). Subsequently, this spin current will be pumped into the adjacent FePt nanograins and acts as a spin transfer torque (STT). This induced STT can act as additional driving force combined with AOS and will finally lead to the deterministic magnetization switching of the FePt nanograins. This integration of the spin caloritronics effect and AOS within the HAMR technique is *an unprecedented approach* for achieving 100% AOS of magnetically hard materials which *have been studied independently so far*.

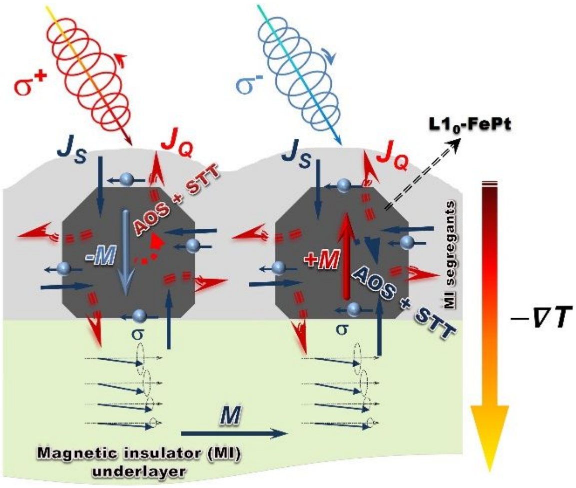

Fig. 3. Conceptual diagram of the laser induced STT for 100% AOS in FePt nanogranular media.

４．研究成果

To demonstrate the concept and subtracted the pure thermal-induced STT as illustrated in **Fig. 3**, there are two main challenges: a) Two comparable magnetic insulators, one with large while the other with negligible small spin Seebeck coefficient; b) The microstructure (morphology, crystallography) and magnetic properties (Saturation magnetization, M_S and coercivity, H_C) of the FePt thin film deposited on both magnetic insulators should be similar to ensure a reasonable comparison. Considering on these two critical requirements, the applicant propose the comparison of continuous FePt thin films deposited on yttrium iron garnet (YIG) and gadolinium gallium garnet (GGG) single crystal substrates. YIG with a composition of $Y_3Fe_5O_{12}$ is a well-known ferrimagnet used for spintronics [4] and magnonics [5] applications since it exhibits large spin Seebeck effect, low damping, and good thermal stability. On the other hand, GGG with a composition of $Gd_3Ga_5O_{12}$ usually presents neglectable small spin Seebeck effect, but it ensures a similar microstructure (morphology, crystallography) and magnetic properties (Saturation magnetization, M_S and coercivity, H_C) of the deposited FePt thin film as YIG substrates since quite similar lattice parameters between YIG and GGG. **Figure 4** presents the characterization results of $L1_0$-ordered FePt continuous thin film deposited on YIG and GGG (001) single crystal

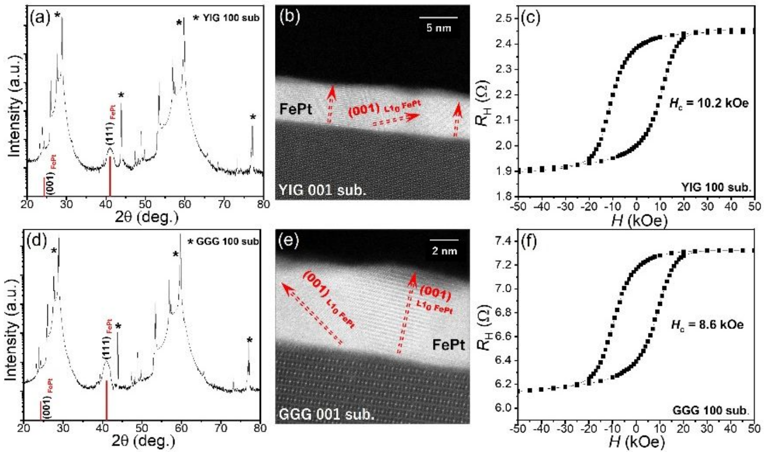

Fig. 4. X-ray diffraction patterns (**a & d**), high-resolution HAADF-STEM images (**b & e**), and corresponding anomalous Hall resistance R_H (**c & f**) of 6 nm-thick-continuous FePt thin films deposited on yttrium iron garnet (YIG) 100 (**a-c**) and gadolinium gallium garnet (GGG) 100 (**d-f**) single crystal substrates.

substrates (SCS). As the results indicated, both FePt thin films deposited on YIG and GGG (001) SCS show similar crystal texture (mixture of (001) and (111) textures in **Figs. 4a** and **4d**), similar morphology (6-nm-thick FePt continuous films with cross-sectional HAADF-STEM images of **Figs. 4b** and **4e**), and comparable coercivity (10.2 vs 8.6 kOe from anomalous Hall resistance loops of **Figs. 4c** and **4f**). The successful preparation of similar FePt thin films on both YIG and GGG (001) SCSs ensure a valid comparison and final demonstration of the proposed new concept.

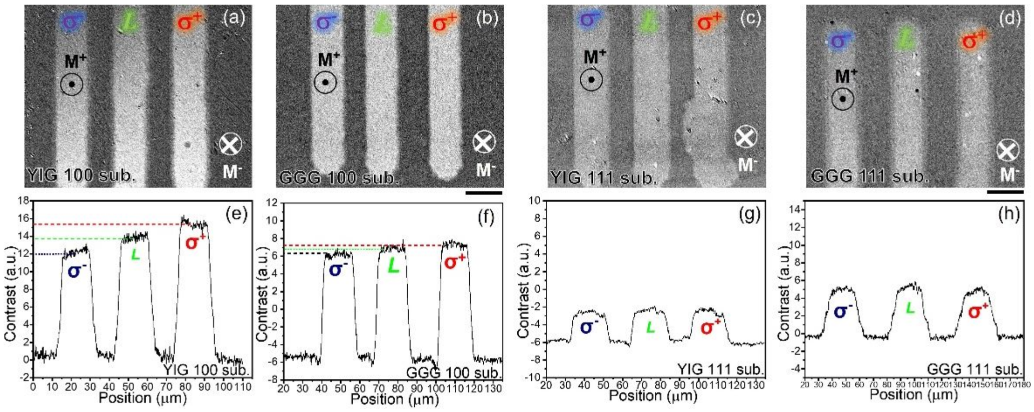

Fig. 5. Subtracted MOKE images and corresponding contrast line profile for circular polarized light (helicities left to right: left $\sigma-$, linearly *L*, and right $\sigma+$ polarized laser) induced magnetization switching in $L1_0$-ordered FePt continuous thin film deposited on yttrium iron garnet (YIG) 100 (**a & e**), 111 (**c & g**) and gadolinium gallium garnet (GGG) 100 (**b & f**), 111 (**d & h**) single crystal substrates. All the thin film samples were initially magnetic saturated by applying an external magnetic field of 70.0 kOe along film normal direction 'down'. The circular polarized laser with a diameter about 20.0 μm was swept on the thin film surface at a repetition rate of 10.0 kHz. The average laser power onto the sample was 3.0 mW (49.2 mJ cm^{-2} per pulse). The laser beam was swept on the surface of FePt thin film at a slow velocity of ~3.0 μm s^{-1}. Note that the subtracted image obtained from before and after applying the laser exposure. The scale bar stands for 20.0 μm.

Figure 5 shows the MOKE images of the helicity-dependent (left σ^-, linearly *L*, and right σ^+ polarized laser) all-optical magnetic switching in $L1_0$-ordered FePt continuous thin films deposited on YIG (100) (**Fig. 5a**), (111) (**Fig. 5b**) SCSs and GGG (100) (**Fig. 5c**), (111) (**Fig. 5d**) SCSs. The brighter/dark contrast in the subtracted MOKE image standing for the magnetic moments pointing out/ inside of the film plane. The results indicate that the laser can introduce thermal demagnetization in all the sample. However, according to the corresponding cross sectional contrast profiles, the YIG (100) SCS/FePt sample (**Fig. 5e**) clearly show an enhanced helicity-dependent AOS than GGG (100) SCS/FePt sample (**Fig. 5f**). The results successfully prove the validity of the proposed concept, *i.e.*, the thermal-induced STT can assisted the magnetization reversal and enhance the final AOS in the YIG (100) SCS/FePt sample. On the other hand, the absent of such enhancement in the YIG (111) SCS/FePt sample is considered due to a weak exchange interaction between the magnetic moment from $L1_0$-ordered FePt film and YIG (111) SCS when considering the YIG (111) SCS holds an in-plane magnetic easy axis.

With increasing the laser power (fluence), one can expect a linear enhancement of the AOS effect in the YIG SCS/FePt samples since it induces higher temperature gradient, *i.e.*, larger thermal-induced STT through SSE. Thus, we also measured the laser power (fluence) dependence of AOS in all the YIG and GGG SCSs/FePt samples. The laser power of applied right circular polarized laser, σ^+ was linearly increased from 16.9 to 69.6 mJ/cm^2 which cover a range from a threshold AOS emerging fluence to a strong damageable laser (black Scorched region in MOKE images). As **Fig. 6** indicated, all the samples show a linearly weak increasement of the AOS contrast in the MOKE and corresponding cross contrast profiles. There is no remarkable laser power dependence of AOS in the YIG (100) SCS /FePt sample.

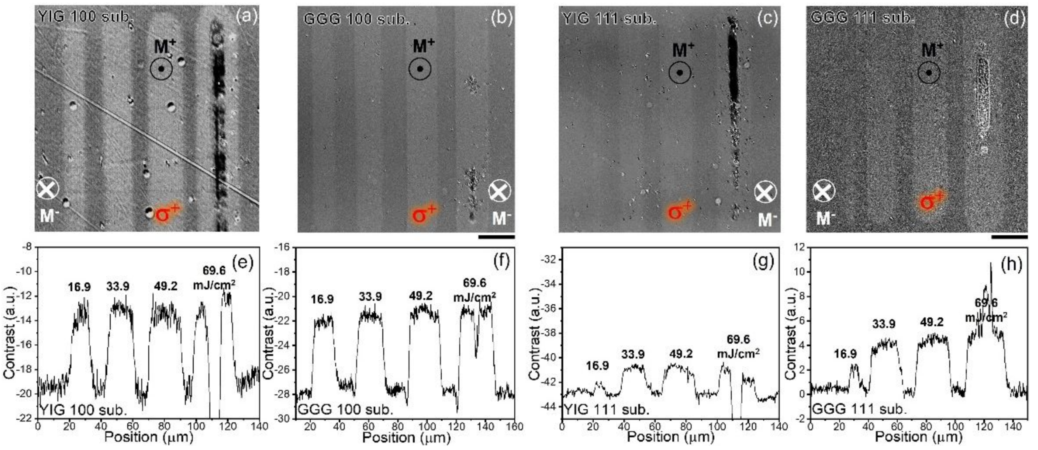

Fig. 6. Subtracted MOKE images and corresponding contrast line profile after sweeping the $L1_0$-ordered FePt continuous thin film with various laser power (left to right: 16.9, 33.9, 49.2, and 69.6 mJ/cm^2) for the thin film deposited on yttrium iron garnet (YIG) 100 (**a & e**), 111 (**c & g**) single crystal substrate and gadolinium gallium garnet (GGG) 100 (**b & f**) and 111 (**d & h**) single crystal substrate.

However, we can observe a positive laser dependence of AOS in YIG SCSs/FePt-C nanogranular films (data will be published later). It reveals that both strong ferromagnetic exchange coupling and favorable in-plane thermal diffusion in the continuous film does not favor the thermal-induced STT contribution from the YIG SCSs.

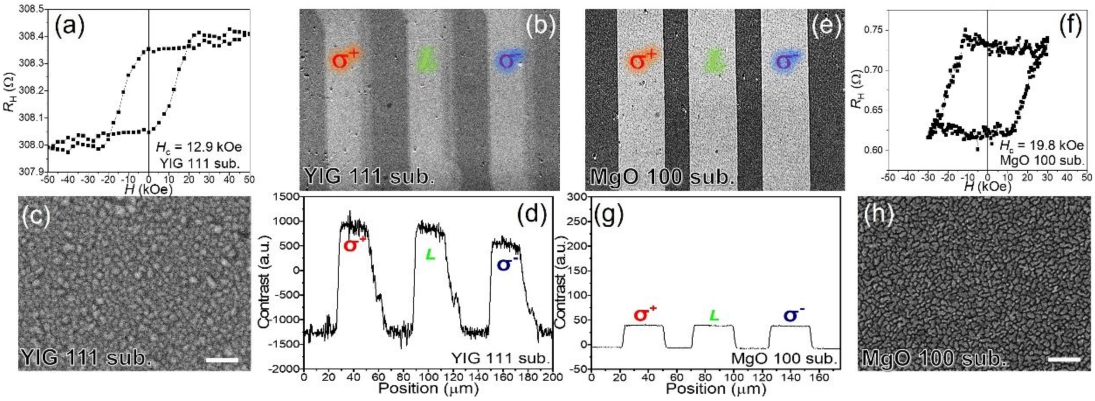

Fig. 7. Magnetic field dependence of AHE loops (**a & f**), subtracted MOKE images (**b & e**), corresponding contrast line profile for circular polarized light (laser helicities left to right: left $\sigma-$, linearly L, and right $\sigma+$ polarized laser) induced magnetization switching (**d & g**), , and in-plane SEM images (**c & h**) of $L1_0$-ordered FePt-C nanogranular films deposited on yttrium iron garnet (YIG) 1111 (**a-d**) and MgO 100 (**e-h**) single crystal substrates.

Compared with $L1_0$-ordered FePt continuous thin film, the enhanced helicity-dependent AOS was also detected in the $L1_0$-ordered FePt-C nanogranular films (see **Fig. 7**). Unlike the continuous films, after introducing carbon as segregant, the $L1_0$-ordered FePt nanograins become physical/thermal isolated and magnetic decoupled from their neighbors which can further favor the proposed concept (data will be published later). With similar nanogranular feature in MgO (100) SCS/FePt-C sample, we could not detect the enhanced helicity-dependent AOS which again prove the positive contribution from magnetic insulator YIG substrate.

References

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５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　2件／うちオープンアクセス　1件）

１．著者名 Jian Wang, Yong‐Chang Lau, Weinan Zhou, Takeshi Seki, Yuya Sakuraba, Takahide Kubota, Keita Ito, Koki Takanashi	４．巻 8
２．論文標題 Strain-Induced Large Anomalous Nernst Effect in Polycrystalline Co2MnGa/AlN Multilayers	５．発行年 2022年
３．雑誌名 Advanced Electronic Materials	６．最初と最後の頁 2101380
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/aelm.202101380	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Hitoshi Makino, Jan Rusz, Jian Wang, Diego Turenne, Masahiro Ohtsuka, Yukiko K Takahashi, Hermann A Durr, Shunsuke Muto	４．巻 558
２．論文標題 A study on the relationship of magnetic moments orientation in L10 FePt network nanostructured film by electron energy-loss magnetic chiral dichroism using semi-core excitation spectra	５．発行年 2022年
３．雑誌名 Journal of Magnetism and Magnetic Materials	６．最初と最後の頁 169522
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jmmm.2022.169522	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 Diego Turenne, Alexander Yaroslavtsev, Xiaocui Wang, Vivek Unikandanuni, Jian Wang (30th) et al.	４．巻 8
２．論文標題 Nonequilibrium sub-10 nm spin-wave soliton formation in FePt nanoparticles	５．発行年 2022年
３．雑誌名 Science Advances	６．最初と最後の頁 1-10
掲載論文のDOI（デジタルオブジェクト識別子） 10.1126/sciadv.abn0523	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

〔学会発表〕　計0件

〔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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