Thermal spin-torque heat-assisted magnetic recording

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To achieve higher recording density with lower power consumption than the current heat-assisted magnetic recording (HAMR) for next-generation, a more efficient writing with less laser power would be indispensable. An advanced HAMR concept is developed to address such specification, and the writability has been demonstrated in multilayer media stacks comprising the core structures of antiferromagnetic MnPt and ferromagnetic FePt layers with the magnetic easy axis oriented perpendicular to the film plane. The concept is based on two distinct switching mechanisms: thermally activated (TA) and spin-transfer-torque (STT) assisted magnetization switching. The latter is driven by an out-of-plane temperature gradient (ΔT) in the MnPt/FePt multilayer which is referred as thermal spin-torque (TST) HAMR media. Pump-probe measurements reveal significant magnetic coercivity (H_c) modulation by ΔT at the local magnetization of the FePt layer. The hybrid mechanism with TA and STT can be separated by sweeping the delay time between the pump and probe laser pulses, and it is found that the STT dominates the mechanism for H_c modulation in the short delay time regime. Furthermore, the modulation of H_c of the FePt layer is demonstrated to be dependent on the magnitude and the direction of steady state ΔT. These results suggest that lower laser power consumption is achievable owing to the contribution of STT assisted switching in the TST-HAMR media.

***Index Terms*—HAMR, spin-transfer torque, pump-probe MOKE, HDD**

I. Introduction

The hard-disk-drives (HDDs) community has put tremendous efforts to develop revolutionary recording technologies to break records of recording density, providing cost efficient solutions to large volume data storage. Many research and developments have been extensively performed, for example, the material engineering of granular media[1-3] was initialized to reduce the grain diameter to increase the recording areal density.[4] The shrinking size of media grains inevitably leads to a decrease in the thermal stability. To overcome such issue, $L1_0$-ordered FePt granular media has been developed, which achieved a sufficiently high K_u value up to 7 MJ/m^3.[5,6] However, this possesses significant challenge to the conventional magnetic writer to switch FePt grains as the magnetic coercivity (H_c) of granular media increases with K_u. This is referred as *trilemma in HDDs*.

Heat-assisted magnetic recording (HAMR) has been developed as a breakthrough technology to solve the trilemma problem.[4-6] To achieve both high thermal stability and writability in the FePt granular media, laser pulses from writing heads are irradiated right before the moment of writing. The laser pulse raises the temperature of FePt grains to a level above the Curie temperature (T_c), which significantly reduces the switching barrier, enabling the writing with minimal magnetic fields required. Followed by locally field cooling the grains, the high thermal stability resumes, which stores information into FePt media. Therefore, the trilemma problem is solved by utilizing thermal energy to assist switching. And HAMR based HDDs have been shipped to data centers with a 28 TB capacity per drive in 2024, and mass production has been started. In addition, new technology such as multi-level recording in HAMR has been demonstrated to further increase data capacity in the future.[7]

Besides of further increasing recording density, it is desirable to reduce the power consumption to heat FePt grains of the media, which is one of the important factors to be considered for large volume data centers. Here, we focus on utilizing the temperature gradient (ΔT), that is inevitably formed in the HAMR media by the heating of laser pulses, as a driving force of the magnetization switching in addition to the conventional thermally activated (TA) switching. The spin-current, generated by the out-of-plane ΔT originating from the spin Seebeck effect (SSE),[8] would provide the magnetization of FePt grains with spin-transfer torques (STTs) to assist switching, therefore, it is expected that the laser power for the TA switching could be reduced. This is the new concept of magnetic recording based on the hybrid effect of STT and TA, leading to an advanced thermal spin-torque (TST)-HAMR media in the future.[9]

II. Concept of TST-HAMR

The HAMR with hybrid mechanisms of STT and TA, referred to as a TST-HAMR, could achieve both ultra-high efficiency and low power consumption. Figure 1(a) illustrates the principles of TST-HAMR, as compared to the current HAMR. Laser irradiation induces ΔT along the out-of-plane direction. With spin current generated from the antiferromagnets (AFMs) such as the MnPt layer under the FePt layer, the more efficient magnetization switching could be expected owing to the ΔT-driven STT, arising from the SSE.[8] For example, the spin momentum (σ) with -*z* orientation that is represented by the green allows with balls, originating from the possible uncompensated magnetic moment at the AFM/FePt interface ($M_{\mathrm{Mn}}^{\mathrm{UC.}}$), could assist the magnetization switching of the FePt layer from up-to-down, while it is not expected for the conventional system without AFM layer. Figure 1(b) depicts the energy diagram showing the bi-stable magnetic states of the FePt layer separated by an energy barrier of K_uV. The energy barrier can be suppressed by TA with uniform heating, in addition, the STT can serve as an extra driving force for magnetization switching. Figure 1(c) illustrates the expected hysteresis loops impacts from the TA and the STT. The TA is responsible for both H_c reduction and demagnetization, while STT primarily contributes to only H_c reduction, because the SSE induced spin-angular momentum transfer can occur without charge transfer, resulting in no Joule heating or extra power consumption. Thus, demagnetization caused by elevating temperature is unrelated with STT.

AFMs have a potential to achieve more efficient spin generation driven by the ΔT.[10-13] We focus on the MnPt with the same $L1_0$ atomic order and lattice constants as the FePt, and high Néel temperature reaching 970 K.[14] These characteristics allow us to prepare the full epitaxial multilayer samples, and the AFM phase is stable regardless of the representative working temperature by laser pulses of HAMR media around 700 K. Figure 1(d) shows the crystal structure of $L1_0$-MnPt, in which the stable magnetic structure with collinear AFM is indicated by arrows. Although two possible collinear magnetic structures of MnPt were reported, with Néel vectors pointing in out-of-plane and in-plane directions,[14] the Néel vector is determined to be parallel to the out of-plane direction in the present MnPt layer by controlling its atomic composition, as revealed by the enhanced H_c of the top FePt layer.

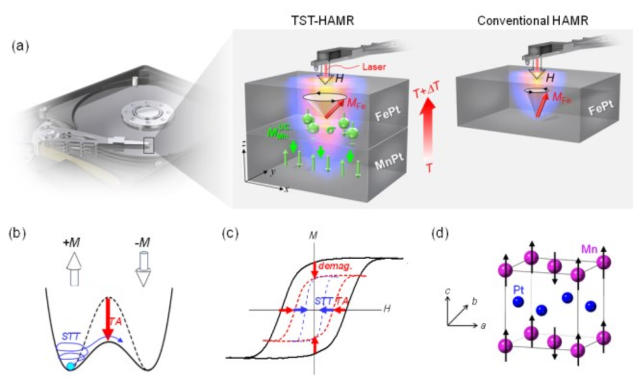

Fig. 1. (a) Concept of the thermal spin-torque heat-assisted magnetic recording (TST-MAHR) with the $L1_0$-MnPt / $L1_0$-FePt bilayer system, together with the conventional HAMR. The green arrows at the MnPt/FePt interface represent the uncompensated Mn moment ($M_{\mathrm{Mn}}^{\mathrm{UC.}}$) induced by the exchange magnetic interaction between Mn and Fe. The green arrows with balls represent the spin angular momentum (σ) that is parallel to the $M_{\mathrm{Mn}}^{\mathrm{UC.}}$. The writing field ($H$) from the HDD-dead is shown by dashed arrow. (b) Energy diagram showing the bi-stable magnetic states of FePt and its change depending on the heating by laser pulses. (c) Possible magnetic hysteresis loops of the FePt layer with temperature gradient by laser pulses. (d) Schematic illustration of $L1_0$-MnPt unit cell.

III. H_C Modulation by Laser Pulses

We verify that the MOKE hysteresis loop without pump pulse (black symbols) agrees with the magnetic hysteresis behavior measured using MPMS. In contrast, the loops are dramatically impacted by pump pulses, showing dependence on the Δt: similar signal with remarkably small H_c at $\Delta t = -1$ ps (red symbols), and remarkably small MOKE signal with large H_c at $\Delta t = +1$ ps (blue symbols), followed by the increase of MOKE signal with the decrease of H_c obtained at $\Delta t = 30$ ps (green symbols). The magnetization measured in the MOKE hysteresis at $\Delta t = -1$ ps corresponds to the magnetic states of the FePt layer at the initial state. Figure 2(b) shows the demagnetization dependence on Δt, which is determined by the ratio of MOKE signal obtained at each Δt to the value measured without pump laser. The magnetization is governed by temperature in general, so that Fig. 2(b) indicates the elevated temperature in the FePt layer. The magnetization decreases by ~75 % of initial value at $\Delta t = +1$ ps, suggesting the highest temperature in the FePt layer induced by the pump laser pulse heating. Then the magnetization starts recovery to the initial magnitude with Δt, suggesting heat dissipation from the FePt layer. It is inferred from the measurement that the magnitude of magnetization is fully recovered before the irradiation of next pump pulse.

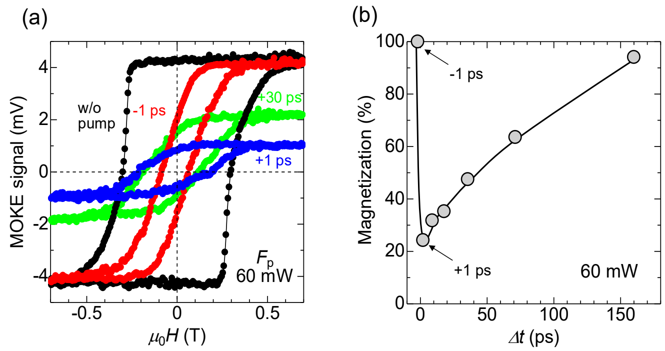

Fig. 2. (a) Magneto optical Kerr effect (MOKE) as a function of magnetic field (H) measured via pomp-probe method with different delay time (Δt) for the multilayer sample, MgO substrate//VN(10 nm)/MnPt(10 nm)/FePt(10 nm). (b) Demagnetization as a function of Δt.

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References

[1] D. Reinsel, et al., The digitization of the world from edge to core, Framingham: Int. Data Corp. 16 (2018) 1.
[2] V. Ozdemir, N. Hekim, Birth of industry 5.0: making sense of big data with artificial intelligence, "the internet of things" and next-generation technology policy, Omics J. Integr. Biol. 22 (2018) 65.
[3] G. Albuquerque, et al., HDD reader technology roadmap to an areal density of 4 Tbpsi and beyond, IEEE Trans. on Magn. 58 (2021) 1.
[4] D. Weller, et al., Review Article: fePt heat assisted magnetic recording media, J. Vac. Sci. Technol. B 34 (2016), 060801-1-10.
[5] K. Hono, et al., Heat-assisted magnetic recording media materials, MRS Bull. 43 (2018) 93–99.
[6] D. Weller, et al., L10 FePtX–Y media for heat-assisted magnetic recording, Phys. Status Solidi A 210 (2013) 1245–1260.
[7] P. Tozman, et al., Dual-layer FePt-C granular media for multi-level heat-assisted magnetic recording, Acta Mater. 271 (2024), 119869-1-8.
[8] K. Uchida, et al., Observation of the spin Seebeck effect, Nature 455 (2008) 9.
[9] S. Isogami, et al., Thermal spin-torque heat-assisted magnetic recording, Acta Materialia 286 (2025) 120743.
[10] S. Seki, et al., Thermal generation of spin current in an antiferromagnet, Phys. Rev. Lett. 115 (2015), 266601-1-5.
[11] S. Wu, et al., Antiferromagnetic spin Seebeck effect, Phys. Rev. Lett. 116 (2016), 097204-1-5.
[12] I. Gray, et al., Spin Seebeck imaging of spin-torque switching in antiferromagnetic Pt/NiO heterostructures, Phys. Rev. X 9 (2019), 041016-1-10.
[13] S. Rezende, et al., Theory of the spin Seebeck effect in antiferromagnets, Phys. Rev. B 93 (2016) 014425.
[14] R. Umetsu, et al., Magnetic and electrical properties, and mechanism of exchange bias-field of γ-phase and $L1_0$-type antiferromagnetic Mn alloys, Trans. Magn. Soc. Japan 3 (2003) 59.