Selective resonance reading from double-layer recording magnetization using a spin-torque oscillator

Taro Kanao, Hirofumi Suto, Koichi Mizushima, and Rie Sato
(Corporate Research & Development Center, Toshiba Corporation, Kawasaki 212-8582, Japan)

Three dimensional (or multilayer) magnetic recording which utilizes ferromagnetic resonance (FMR) has been proposed as a method for increasing the recording density [1,2,3]. The recording layers have different FMR frequencies, which enables selective writing or reading of a layer by applying microwave field with a respective frequency. The microwave field is generated by a spin-torque oscillator (STO). This write operation is a multilayer version of microwave-assisted magnetization switching (MAS) [4,5]. The MAS has been investigated because its application for next-generation assisted recording has been expected.

The read operation utilizes changes in the STO oscillation which occur when the STO induces FMR excitation in a recording layer. This method is thus called resonance reading. The layer-selective FMR excitation has been shown in magnetic multilayer films by using a signal generator [6,7]. The resonance reading using the STO has been demonstrated on a sample where the STO and a recording magnetization are fabricated close [8]. By using micromagnetic simulation, transient magnetization dynamics during the resonance reading (from a single recording layer) has been studied and a response within a time scale of 1 ns has been shown[9]. Based on the obtained waveform of the STO, detection methods for the resonance reading have been proposed[10,11].

Recently, we have demonstrated the selective resonance reading from double-layer recording magnetizations using the STO in micromagnetic simulation[12]. Figure 1 shows schematic of the STO and the recording magnetizations with double recording layers. The STO consists of a perpendicular free layer and in-plane fixed layer[13]. Each recording layer consists of a soft layer and a hard layer, which have lower and higher perpendicular anisotropies, respectively. The soft layers are used in the read operation, while the hard layers keep written data. The magnetizations of the soft and hard layers are directed in opposite perpendicular directions by interlayer antiferromagnetic coupling. The magnetization states of the recording layers are called up or down states depending on the magnetization direction of the soft layers. For the recording magnetizations (RMs) an external perpendicular field H_z^{RM} is applied, which makes the FMR frequencies different for the up and down states. Parameters are chosen so that following two conditions are met. The first condition is that the response of the STO for the FMR excitation in the soft layer 2 is large enough. The second condition is that the FMR frequency of the soft layer in one recording layer is unaffected by the magnetization state of the other recording layer.

Figure 2 shows the waveforms of the magnetizations obtained in the micromagnetic simulation where the STO is moved over an array of 6 recording magnetizations with staggered magnetization configuration. The time evolution of the y-components of the magnetizations are shown. The y-component of the STO corresponds to a signal by the magnetoresistive effect since the magnetization of the fixed layer is in the y-direction. The STO oscillation frequency is set near to the FMR frequency of the soft layer 2 in the down state. In Fig. 2(a), when the STO approaches the soft layer 2 in down state, the magnetization oscillation is excited. At the same time, the STO oscillation amplitude decreases owing to increased effective damping. When the STO is near the soft layer 2 in the up state, the amplitude recovers. From this difference in the oscillation of the STO, the magnetization states in the recording layers 2 can be detected. In Fig. 2(b), the magnetization directions of the recording layer 1 are opposite to those in Fig. 2(a). It is found that the waveforms are almost the same. This result means that the magnetization directions of the recording layers 2 can be detected independent of those of the recording layer 1. The independent detection of the magnetization direction in a recording layer enables the layer-selective reading as if there are two single-layered discs on one medium. In the presentation, future problems on the layer-selective resonance reading will be discussed, such as effects of stray fields between the recording magnetizations.

This work was supported by S-Innovation program from the Japan Science and Technology Agency, JST.

Reference

1) G. Winkler *et al.*, Appl. Phys. Lett. **94**, 232501 (2009).

2) S. Li *et al.*, J. Appl. Phys. **105**, 07B909 (2009).
3) H. Suto *et al.*, Jpn. J. Appl. Phys. **55**, 07MA01 (2016).
4) J.-G. Zhu *et al.*, IEEE Trans. Magn. **44**, 125 (2008).
5) S. Okamoto *et al.*, J. Phys. D: Appl. Phys. **48**, 353001 (2015).
6) T. Yang *et al.*, J. Magn. Magn. Mater. **332**, 52 (2013).
7) T. Yang *et al.*, J. Appl. Phys. **114**, 213901 (2013).
8) H. Suto *et al.*, Nanotechnology **25**, 245501 (2014).
9) T. Kanao *et al.*, J. Appl. Phys. **123**, 043903 (2018).
10) Y. Nakamura *et al.*, AIP Advances, **8**, 056512 (2018).
11) Y. Nakamura *et al.*, to appear in IEEE Trans. Magn. (2018).
12) T. Kanao *et al.*, T. Magn. Soc. Jpn. (Special Issues) **2**, 10 (2018).
13) H. Kubota *et al.*, Appl. Phys. Express **6**, 103003 (2013).

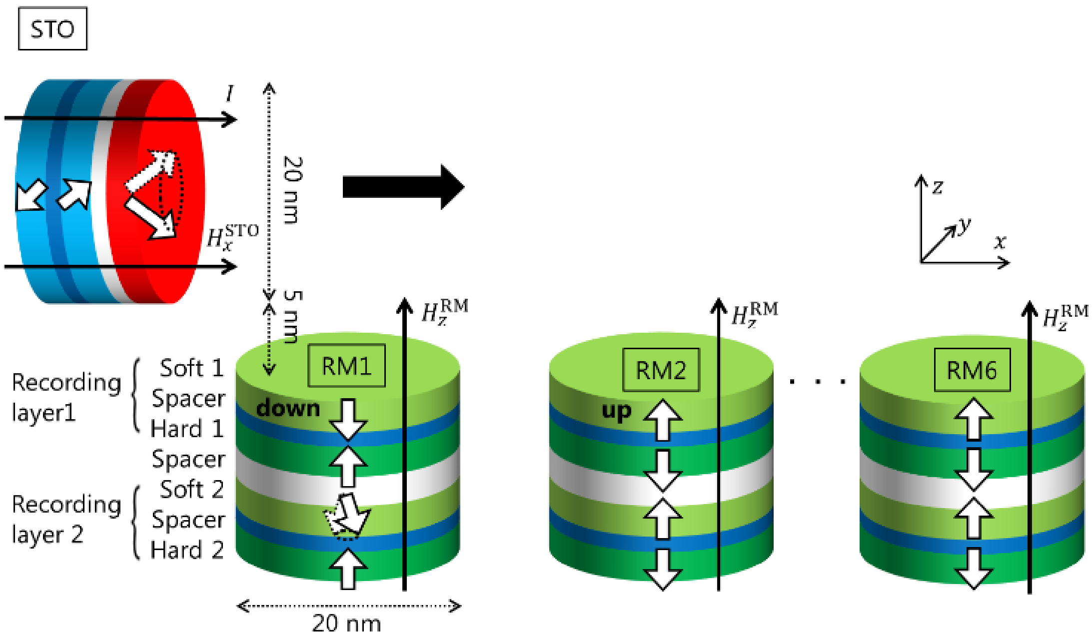

Fig. 1. Schematic of a spin-torque oscillator (STO) and recording magnetizations with two recording layers (RMs).

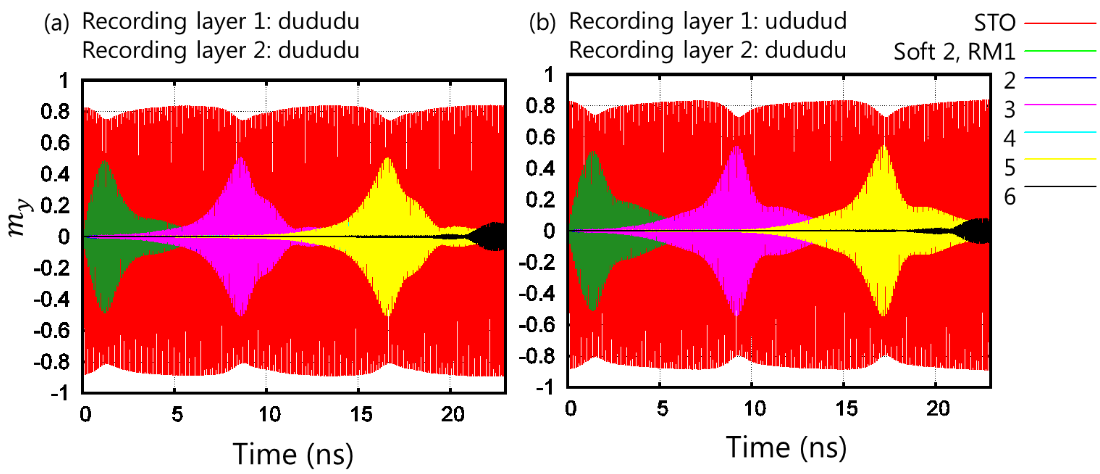

Fig. 2. Time evolution of y-components of magnetizations. In (b), magnetization directions of recording layer 1 are opposite to those in (a). Letters “u” and “d” denote up and down states of the recording layers.

Signal processing for STO reading in three dimensional magnetic recording

Y. Nakamura[1], M. Nishikawa[1], Y. Okamoto[1], T. Kanao[2], and R. Sato[2]
[1]Graduate School of Science and Engineering, Ehime University, Matsuyama 790-8577, Japan
[2]Corporate Research and Development Center, Toshiba Corporation, Kawasaki 212-8582, Japan

1. Introduction

Three-dimensional magnetic recording with antiferromagnetically coupled (AFC) medium[1)] has been proposed as a candidate of the prospective recording technologies, and it uses a spin-torque oscillator (STO)[2)] as a reading sensor as well as a write-assisting device for the microwave assisted magnetic recording (MAMR)[3)]. The reproducing waveform in the reading process using the STO is given as temporal dynamics of magnetization calculated by the micromagnetic simulation[2)]. However, the amount of data obtained by the simulation is too short to evaluate signal processing schemes. We proposed the envelope model to develop the data detection scheme for the temporal magnetization dynamics of a resonantly interacting STO flying over bit patterned media.

2. Reading based on interaction between magnetic medium and STO

The reproducing waveform in the reading process using the STO is given as temporal dynamics of magnetization calculated by the micromagnetic simulation[2)] shown in Fig. 1. We assumed that the relative velocity between the medium and the STO, the dot diameter and pitch are 20 m/s, 20 nm and 25 nm[2)], respectively. The dashed line and cross symbols show the temporal magnetization dynamics normalized by the saturation level of the STO magnetization, A and the sampled envelope with each dot interval, respectively. The horizontal axis shows the time normalized by the channel dot interval T_c. The recorded data pattern is "000111000111" as shown in bottom of Fig. 1, and the STO reacts to the recorded dots for “0”. As can be seen from the figure, the normalized amplitude of STO oscillation waveform decreases as the STO comes close to the recorded dots for “0”. On the other hand, as it leaves from the recorded dot of “0”, the amplitude increases again. Here, we focus the change of the amplitude between the detection target and the previous dot. If "0" is recorded, the difference of amplitude is negative. On the other hand, if “1” is recorded, the difference is positive. Therefore, the recording pattern can be detected by the differential amplitude of the envelope.

3. Read/Write channel model for signal processing

The amount of data obtained by the micromagnetic simulation is too short to evaluate signal processing systems. We proposed the envelope model to develop the data detection schemes[4)]. The envelope model is obtained by the convolution operation of the attenuation functions for the dots of “0” and “1” shown in Fig.2 according to the data pattern. Under observation of the envelope, we noticed that the partial response channel was applicable to improve the performance. We evaluate the performances of the differential detection for the envelope and a soft-output Viterbi algorithm (SOVA)[5)] detection for partial response class-I (PR1)[6)] channel. In addition, we apply the idea of adding another STO with the opposite behavior to the PR channel in order to improve the reading performance. We add another STO which reacts to the recorded dot of “1”. Thus, we employ the dual STO with the reaction to “0” and “1”.

4. Performance evaluation

Figure 3 shows the bit error rate (BER) performance for the system noise (SNR_S) [4)]. The symbols of square, triangulate, and circle show the performances of the differential detection, the SOVA detection with single STO, and the SOVA detection with dual STO, respectively. The vertical and horizontal axes show the BER performance and SNR_S. As can be seen from the figure, the differential detection cannot achieve the BER of 10^{-2} at SNR_S = 30 dB. However the SOVA detections show better BER performance than the differential detection. Moreover, the SOVA detection with dual STO achieves the BER of 10^{-4} at the required SNR_S of 25.2 dB, while the SOVA detection with the single STO needs the SNR_S of about 28.0 dB. Therefore, the SOVA detection with dual STO improves the SNR_S by about 2.8 dB compared with the SOVA detection with single STO.

Acknowledgements

This work is supported by Strategic Promotion of Innovative Research and Development from Japan Science and Technology Agency, JST.

Reference

1) H. Suto, T. Nagasawa, K. Kudo, K. Mizushima, and Rie Sato, *Nanotechnology*, **25**, 245501 (2014).
2) T. Kanao, H. Suto, K. Kudo, T. Nagasawa, K. Mizushima, and R. Sato., *J. Appl. Phys.*, **123**, 043903 (2018).
3) J. Zhu, X. Zhu, and Y. Tang, *IEEE Trans. Magn.*, **44**, 125 (2008).
4) Y. Nakamura, M. Nishikawa, H. Osawa, Y. Okamoto, T. Kanao, and R. Sato, *AIP Advances*, **8**, 056512 (2018).
5) J. Hagenauer and P. Hoeher, P*roceedings of IEEE GLOBECOM*, 1680 (1989).
6) E. R. Kretzmer, IEEE Trans. Commun. Technol. **COM-14**, 67 (1966).

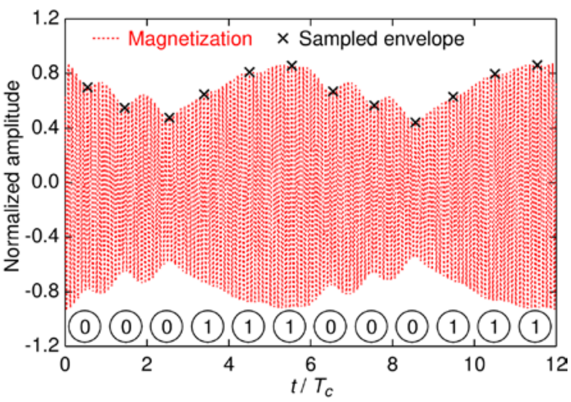

Fig. 1 Magnetization of STO and sampled envelopes.

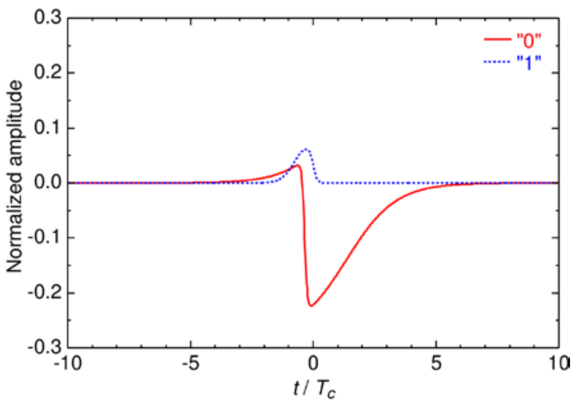

Fig. 2 Attenuuation function for STO.

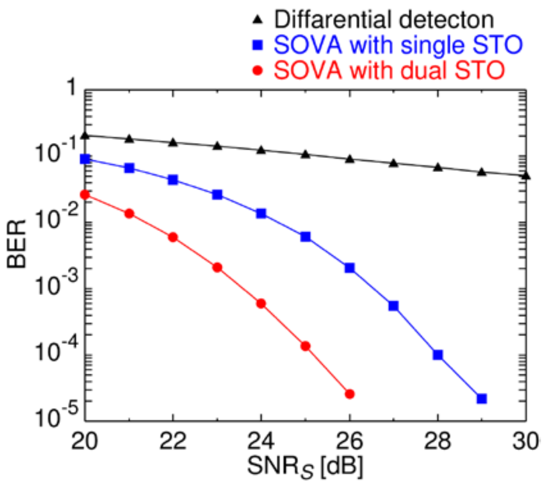

Fig. 3 BER performance.

Microwave assisted magnetic recording on media with multiple, discrete recording layers

S. J. Greaves [1], Y. Kanai [2] and H. Muraoka [1]

[1] Research Institute of Electrical Communication, Tohoku University, Sendai, Japan
[2] IEE, Niigata Institute of Technology, Kashiwazaki, Japan

Introduction

Microwave assisted magnetic recording (MAMR), in which a spin torque oscillator (STO) is used to locally reduce the switching field of a recording medium, allowing information to be recorded on high anisotropy media, is actively being developed for use in future hard disk drives.

If a recording medium has two discrete recording layers it is possible to use MAMR to selectively record on one layer or the other by tuning the frequency of the STO to the resonance frequency of the target recording layer. Given that the spacing between the two recording layers must be small, e.g. 1 - 3 nm, magnetostatic interactions between the layers become a problem. In this work we examine the requirements for multiple layer recording and possible options to reduce the effect of magnetostatic interactions between layers, and between grains within the same layer.

AFC media

Antiferromagnetically coupled (AFC) media were originally developed for longitudinal recording [1], however, it is also possible to make perpendicular AFC media [2]. In such structures, consisting of two magnetic layers separated by a material such as Ru or Ir, an anti-parallel alignment of the magnetisation is favoured, reducing the stray magnetic field emanating from the structure.

In addition to reducing magnetostatic interactions between AFC structures, interactions between grains in the same structure are also reduced. This results in much higher signal to noise ratios (SNR) for tracks written at high linear densities as a result of lower transition jitter [3]. An example of this is shown in fig. 1, which shows the positions of 600 transitions written on AFC and single layer (SL) media. Fits with error functions show the reduction in transition jitter when using AFC media.

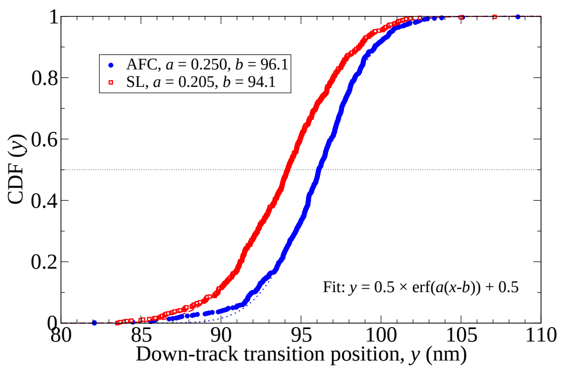

Fig. 1: Positions of 600 transitions written on AFC and single layer (SL) media. 30 nm bit length.

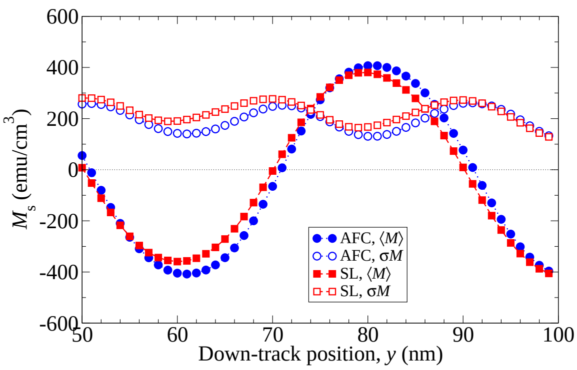

Fig. 2: Average magnetisation and standard deviation of the magnetisation of two 20 nm-long bits written on AFC and SL media. Magnetisation of AFC hard layer is shown.

A second reason for the higher SNR of AFC media is a reduction in magnetisation fluctuations within written bits. Fig. 2 shows the average magnetisation of bits written on AFC and SL media. The magnetisation of the hard layer of the AFC media is shown. The bits written on AFC media had slightly higher average magnetisation, but the standard deviation of the magnetisation was lower, resulting in lower noise during readback.

Media with two discrete recording layers

To select the properties of each layer in a medium containing two discrete recording layers an analysis similar to that shown in fig. 3 is carried out. For a given head field and high frequency (HF) field generated by a STO the maximum switchable H_k of grains in recording layers 1 and 2 (RL1 and RL2) is calculated. Subsequently, H_{k1} is chosen such that a grain in RL1 can be switched by a HF field of frequency f_1, but cannot be switched by f_2. H_{k2} is chosen in a similar manner.

Having determined the H_k and HF field frequencies, tracks can be written on each layer. Magnetostatic interactions between layers favour a parallel alignment of the magnetisation in RL1 and RL2 which can degrade the recording performance. To counteract this a small amount of antiferromagnetic exchange coupling, J_{IL}, can be introduced between RL1 and RL2. Fig. 4 shows the SNR of tracks written in RL1 and RL2 with and without antiferromagnetic exchange [4]. The SNR was increased when antiferromagnetic exchange was used. An alternative approach is to use AFC structures in RL1 and RL2. However, this will not completely eliminate magnetostatic interactions between the layers.

Fig. 4 also shows a strong dependence of the SNR on the write head velocity. The main cause of the SNR reduction at higher head velocities was a decrease in the magnetisation switching probability. This suggests that there is some critical part of the HF field that initiates magnetisation reversal.

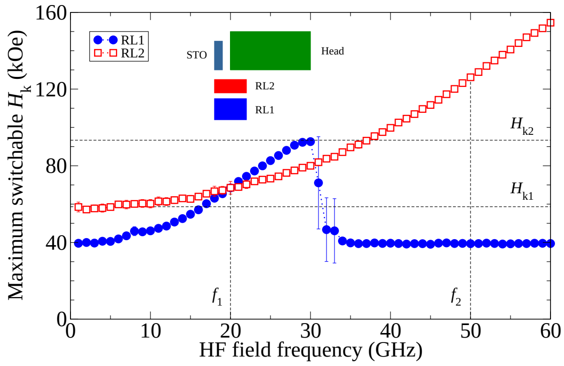

Fig. 3: Maximum switchable H_k of grains in RL1 and RL2 as a function of HF field frequency. Structure is: 7 nm RL1 / 2 nm IL / 5 nm RL 2 / 3.5 nm Air / Write head

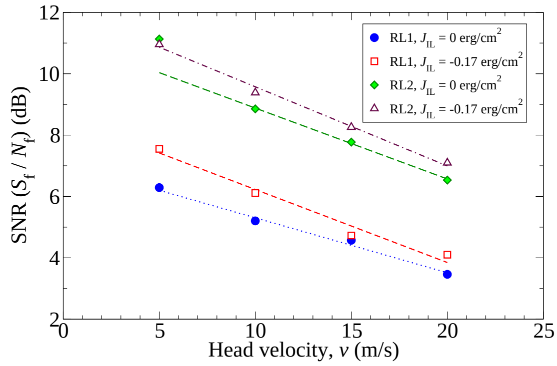

Fig. 4: SNR vs. write head velocity for 847 kfci tracks written on RL1 and RL2 with and without antiferromagnetic coupling between RL1 and RL2.

References

[1] N. Abarra, A. Inomata, H. Sato, I. Okamoto, and Y. Mizoshita, "Longitudinal magnetic recording media with thermal stabilization layers," *Appl. Phys. Lett.*, vol. 77, pp. 2581–2583, 2000.

[2] Y. Nakayama, Y. Kusanagi, T. Shimatsu, N. Kikuchi, S. Okamoto, and O. Kitakami, "Microwave-assistance effect on magnetization switching in antiferromagnetically coupled CoCrPt granular media," *IEEE Trans. Magn.*, vol. 52, pp. 3201203–1–3, July 2016.

[3] S. J. Greaves, Y. Kanai, and H. Muraoka, "Antiferromagnetically coupled media for microwave-assisted magnetic recording," *IEEE Trans. Magn.*, vol. 54, pp. 3000111–1–11, Feb. 2018.

[4] S. J. Greaves, T. Kikuchi, Y. Kanai, and H. Muraoka, "Optimising dual layer recording using antiferromagnetic exchange coupling," *IEEE Trans. Magn.*, (accepted).

Theory of Microwave Assisted Magnetization Reversal

Tomohiro Taniguchi
Spintronics Research Center, National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8568, Japan

Microwave assisted magnetization reversal (MAMR) has been attracted much attention from viewpoints of both fundamental physics and practical application such as a high-density magnetic recording. The basic idea of MAMR is that microwave having the frequency close to ferromagnetic resonance (FMR) frequency efficiently excites an oscillation of the magnetization around the easy axis and assists the magnetization reversal by a small direct field[1)]. A quantitative analysis on a relation between the switching field and microwave frequency has been made by using the Landau-Lifshitz-Gilbert (LLG) equation in a rotating frame[2)]. In the rotating frame, the microwave field is converted to a direct field proportional to the microwave frequency. This additional field in the rotating frame has been considered as an origin of the reduction of the reversal field[3)]. We should, however, point out that this theoretical view is insufficient to understand the mechanisms of MAMR. According to this physical picture, the reversal field is expected to be monotonically decreased with increasing the microwave frequency because the magnitude of the additional field is proportional to the frequency. The numerical simulation of MAMR, however, revealed the existence of a critical frequency, where the reduction of the reversal field is observed only for the frequency lower than the critical value[1)]. As can be seen in this example, it seems that the physical mechanism of MAMR is still not fully understood yet.

In this work, we present a theory of MAMR based on the LLG equation in the rotating frame[4,5)]. We notice that the microwave field in the rotating frame provides not only the direct field but also a torque pointing in the direction of the damping torque. Interestingly, this damping-like torque prevents the switching. In addition, this torque can be mathematically regarded as a spin-transfer torque[6)]. Using this analogy between MAMR and spin-transfer phenomena, we derived equations determining the switching fields in both low and high frequency regions separated by the critical frequency[4)]. A quantitative agreement between our theory and macrospin simulation guarantees the validity of our study. The analytical formula of the critical frequency is also obtained as[5)]

$$f=\frac{\gamma}{2\pi}H_{\mathrm{K}}\frac{\left(H_{\mathrm{ac}}/H_{\mathrm{K}}\right)^{2/3}}{\sqrt{1-\left(H_{\mathrm{ac}}/H_{\mathrm{K}}\right)^{2/3}}}\left[2-\frac{5}{3}\left(H_{\mathrm{ac}}/H_{\mathrm{K}}\right)^{2/3}\right], \tag{1}$$

where γ, H_{ac}, and H_{K} are the gyromagnetic ratio, magnitude of the microwave field, and magnetic anisotropy of the recording bit. The present works[4,5)] provide a comprehensive picture of MAMR, and will be useful for designing magnetic devices utilizing MAMR.

Reference

1) J. G. Zhu, X. Zhu, and Y. Tang, IEEE Trans. Magn. **44** (2008) 125.
2) G. Bertotti, A. Magni, I D. Mayergoyz, and C. Serpico, J. Appl. Phys. **89** (2001) 6710.
3) S. Okamoto, M. Igarashi, N. Kikuchi, and O. Kitakami, J. Appl. Phys. **107** (2010) 123914.
4) T. Taniguchi, Phys. Rev. B **90** (2014) 024424.
5) T. Taniguchi, D. Saida, Y. Nakatani, and H. Kubota, Phys. Rev. B **93** (2016) 014430.
6) J. C. Slonczewski, J. Magn. Magn. Mater. **159** (1996) L1.

Design and development of all-in-plane spin-torque-oscillator for microwave assisted magnetic recording

H. Sepehri-Amin, W. Zhou, S. Bosu, Y. Sakuraba, S. Kasai, and K. Hono
Research Center for Magnetic and Spintronic Materials, National Institute for Materials Science, Tsukuba 305-0047, Japan

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) specific to the MAMR application, has not been established. The STO device for MAMR should have a diameter smaller than 40 nm, total thickness smaller than 25 nm, and a capability to generate large magnetic flux, $\mu_0 H_{ac}$ > 0.1 T, with a frequency over 20 GHz at a small current density J<1.0×10^8 A/cm^2 [1]. We have recently demonstrated experimentally mag-flip STO, that can oscillate with resonance frequency of 21-25.5 GHz and produce an $\mu_0 H_{ac}$ of 0.15 T [2,3]. 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 [3]. In this study, we numerically demonstrate the potential of the all-in-plane STO, 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.

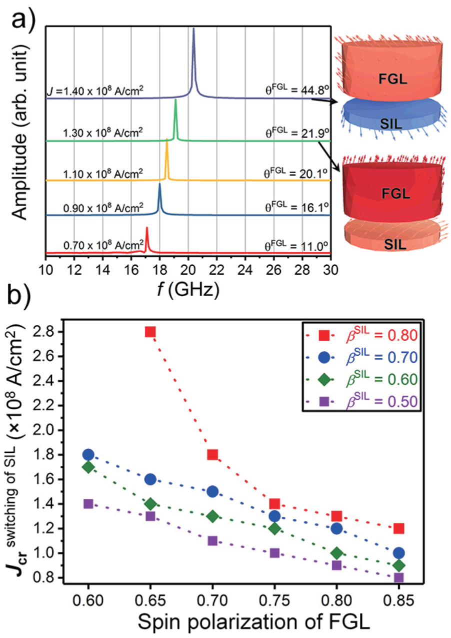

Figure 1: (a) RF spectrums calculated from $\boldsymbol{M_x}$ oscillation of FGL for β^{SIL} = 0.80 and β^{FGL} = 0.75 for different J. The oscillation cone angle of FGL is also shown. (b) Critical current density required for the magnetization switching of SIL as a function of β^{FGL} and varied β^{SIL}.

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 use of spin-transfer-torque that results in oscillation of FGL with a large cone angle at a reduced J. An example is shown in Fig. 1 (a) in which when the current density increases from 1.3×10^8 A/cm^2 to 1.4×10^8 A/cm^2, magnetization of SIL switches opposite to the applied magnetic field direction. Thereafter, increase of resonance frequency to 20GHz and increase of oscillation cone angle to ~45°. We designed SIL to reduce the critical current density, J_{cr}, required for the magnetization switching of SIL. The materials with a smaller $\mu_0 M_s$ and spin polarization (β) in SIL results in reduction of J_{cr} and enables STO to oscillate with frequency of above 20 GHz with a large out-of-plane oscillation cone angle of 45-50°. The validity of this finding was studied experimentally by developing STO with different SIL materials; Heusler $Co_2Fe(Al_{0.5}Si_{0.5})$ and $Fe_{67}Co_{33}$. The former showed B2 crystal structure with a large spin polarization and latter has A2 crystal structure with smaller spin polarization. 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. We also found that large β of FGL is beneficial to reduce J_{cr} as shown in Fig. 1 (b). 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. We will discuss how the magnetization switching of SIL lead to an increase of oscillation cone angle of FGL, reduction of J for oscillation of STO, and an increase of oscillation frequency.

Acknowledgement: This work was in-part supported by Grant-in-Aids for Young Scientific Research B (17K14802).

References: [1] Takeo A. *et al*., Intermag Conference 2014 (AD-02). [2] Bosu S. *et al.,* Appl. Phys. Lett. **108**,072403 (2016). [3] Bosu S. *et al.,* Appl. Phys. Lett. **108**,072403 (2017).

Microwave assisted switching on CoCrPt based granular media

N. Kikuchi[1,2], K. Shimada[3], S. Kikuchi[3], K. Sato[1], S. Okamoto[1,2], O. Kitakami[1,2], T. Shimatsu[2,3,4]
([1]IMRAM, Tohoku Univ, [2]CSRN Tohoku Univ, [3]FRIS Tohoku Univ, [4]RIEC Tohoku Univ.)

Microwave assisted magnetic recording (MAMR) is one of the candidate technologies to realize further recording density [1]. In MAMR, magnetization switching field is reduced by radio-frequency (rf) field with GHz frequency range so that media with higher thermal stability can be used. Magnetization switching behavior under rf field, so-called microwave assisted switching (MAS), has been widely studied experimentally and theoretically [2-5]. Analytical and numerical studies based on the macrospin model have predicted that the switching field linearly decreases with increase of rf field frequency (f_{rf}) up to the critical frequency, at which assistance effect vanishes [2,3]. Experimental results on isolated nanostructures also follows the theoretical prediction, indicating that the MAS behavior can be well described by the macrospin model in isolated structures [4]. From practical point of view, it is important to study MAS behavior of CoCrPt granular media, in which there exist intergranular exchange/magnetostatic interaction and distribution of crystalline/magnetic properties. Experimentally reported MAS behavior of CoCrPt granular media shows different tendency from that of the macrospin model, for instance smaller assistance effect and broader frequency dependence [5]. Numerical studies on granular media have suggested that rf field with sufficiently large amplitude is required to realize large switching field reduction. Recently we have reported that MAS effect in granular media shows strong field amplitude dependence, and the coercivity reduction ratio can reach to 50 % by applying linearly polarized rf field with amplitude close to 1 kOe [6].

In this study, we present experimental results of MAS behavior on CoCrPt granular media quantitatively evaluated by detecting anomalous Hall effect (AHE). Figure 1 shows schematic structure of the prepared sample. CoCrPt granular film of 15 nm in thickness was patterned into a rectangular shape of 1.0 × 3 μm^3, with four terminal electrodes for AHE measurement. A gold line of 1.0 μm in width for rf field application was fabricated underneath the structure separated by a SiO_2 layer of 100 nm in thickness. In-plane linearly polarized magnetic field was generated by applying rf pulsed current with frequency f_{rf} = 2 – 25 GHz to the gold line. The maximum field amplitude was evaluated to be 950 Oe at the sample position. The rf field was applied as pulses with fixed duration of 20 ns to minimize heating effect due to Joule heating. All AHE curves were measured by detecting AHE as a function of dc field along film normal. Figure 2 shows normalized AHE curves measured as a function of dc field H_{dc}. Coercivity decreases with increase of rf field frequency, without significant change of the slope of AHE curves. The coercivity reaches minimum value of 2.4 kOe at f_{rf} = 18 GHz, which is almost half of the coercivity for without rf field (4.7 kOe).

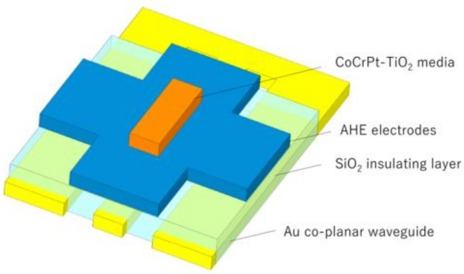

Fig. 1 Schematic illustration of fabricated sample

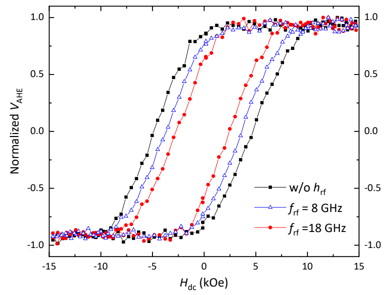

Fig. 2 AHE curves of CoCrPt media measured with rf field (f_{rf} = 8, 18 GHz) and without rf field.

Reference

1) J.-G. Zhu, *et al.*, *IEEE Trans. Magn.* **44**, 125 (2008).
2) G. Bertotti, *et al.*, *Phys. Rev. Lett.* **86**, 724 (2001).
3) S. Okamoto, *et al.*, *J. Appl. Phys.* **107**, 123914 (2010)
4) M. Furuta, *et al.*, *APEX* **6**, 053006 (2013).
5) S. Okamoto, *et al.*, *Appl. Phys. Lett.* **103**, 202405 (2013).
6) K. Shimada *et al.*, MORIS 2018 Technical Digest, Tu-P-01 (2018)

Microwave-Field-Induced Magnetization Excitation and Magnetization Switching of an Antiferromagnetically Coupled Magnetic Bilayer with Perpendicular Magnetization

H. Suto, T. Kanao, T. Nagasawa, K. Mizushima, and R. Sato
(Corporate Research & Development Center, Toshiba Corporation, Kawasaki, Japan)

I. Background

Antiferromagnetically coupled (AFC) media that consists of two antiferromagnetically coupled magnetic layers has been explored for magnetic recording [1]. Because the AFC media reduces the dipolar interaction, it improves the reliability of writing and the stability of data. In microwave-assisted magnetic recording (MAMR), which is a candidate for next-generation magnetic recording [2,3], the dipolar interaction raises other concerns. MAMR utilizes large-amplitude ferromagnetic resonance (FMR) excitation in media magnetization to assist writing, and the dipolar interaction leads to the distribution in FMR frequency and the collective magnetization excitation in multiple grains. In this respect, AFC media is considered to be advantageous for MAMR [4,5]. In this study, we fabricate an AFC magnetic dot consisting of two Co/Pt multilayers and investigate magnetization excitation and switching in a microwave field.

II. Experimental setup

Figure 1 shows the experimental setup. A magnetic film consisting of two Co/Pt multilayers with a Ru layer between them is deposited. The two magnetic layers are designed to have different anisotropy by controlling the Co thickness, and the one with higher anisotropy is referred to as a hard layer and the one with lower anisotropy is referred to as a soft layer. This magnetic film is then patterned into dots of two different size (a larger dot for magnetization excitation and a smaller dot for magnetization switching). Magnetization excitation and switching of the magnetic dot is studied by applying a z-direction magnetic field (H_z) from an external electromagnet and an in-plane circularly polarized microwave field from two coplanar waveguides fabricated on top of the magnetic dot. The detailed experimental setup is described in Ref [6].

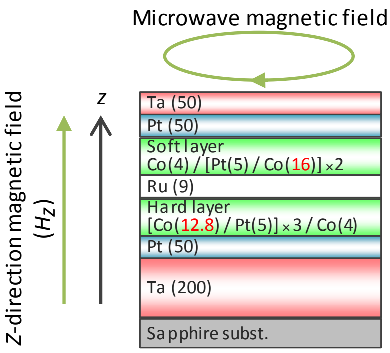

Fig. 1. Stacking structure of the magnetic film consisting. Thicknesses are given in angstroms

III. AHE-FMR measurement of the AFC magnetic dot

Figure 1 shows the anomalous Hall effect (AHE) voltage of the AFC magnetic square dot with a side length of 500 nm. In the remanent state, an antiferromagnetic configuration is realized. By applying a microwave field, an increase or decrease of the AHE voltage appears, indicating that the FMR excitation of the magnetic dot occurs. For the counterclockwise (CCW) microwave field, the decrease of the AHE voltage due to the FMR excitation of the soft layer appears at H_z = 0 and + 4 kOe because CCW is the rotation direction of the FMR excitation of the +z-direction magnetization. The dip is wider in the antiferromagnetic configuration at H_z = 0 kOe than in the ferromagnetic configuration at H_z = + 4 kOe. The different width may be attributed to the interaction between the hard and soft layers. For the clockwise (CW) microwave field, the increase of the

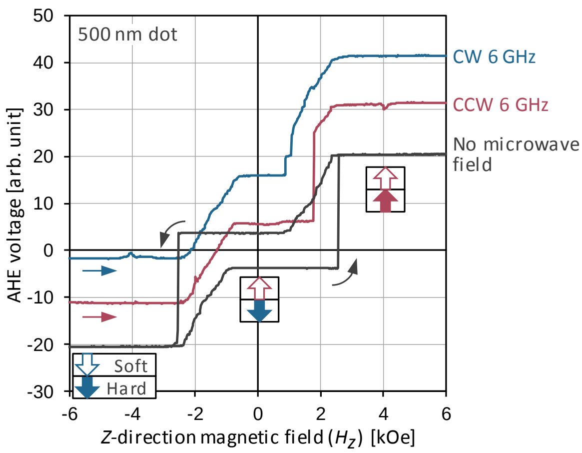

Fig. 2. AHE voltage versus H_z obtained without a microwave field and with a microwave field rotating CCW and CW.

AHE voltage due to the FMR excitation of the soft layer at H_z = – 4 kOe and assisted switching of the hard layer occurs at H_z = + 1 kOe.

IV. Microwave-assisted magnetization switching of an AFC magnetic dot

Figure 3 shows the switching field of the hard layer (H_{sw}) as a function of the microwave field frequency (f_{rf}) obtained for an AFC magnetic circular dot with a diameter of 80 nm. The rotation direction of the microwave field is mostly CW except for the plot depicted by cross in which the rotation direction is CCW. For the microwave field amplitude (H_{rf}) range of 43 – 170 Oe, H_{sw} decreases almost linearly as f_{rf} becomes higher and suddenly increases at a critical frequency. As H_{rf} increases, the microwave assistance effect increases, and a large H_{sw} decrease to approximately 1 kOe is demonstrated. For H_{rf} = 213 Oe and f_{rf} = 12 – 14.5 GHz, a part of the hard layer reverses, resulting in a magnetic domain configuration. This switching behavior is similar to that reported for a single layer perpendicular magnetic dot [3,6]. When the microwave field rotates CCW, FMR excitation of the soft layer is expected. However, no significant change in H_{sw} is observed, showing that the soft layer excitation has little effect on hard layer switching. The H_{sw} decrease for CCW and f_{rf} = 3 – 5 GHz shows the f_{rf} dependence similar to that in the CW microwave and is attributed to the fact that the polarization is not perfectly circular and a small CW component exists. These results show that the large microwave assistance effect is obtained for the AFC bilayer, which is not hindered by the additional soft layer.

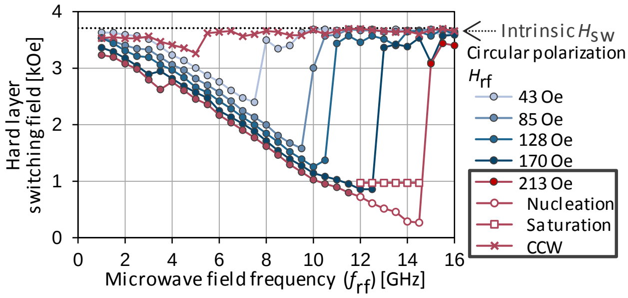

Fig. 3. H_{sw} versus f_{rf} obtained by applying a circularly polarized microwave field.

<u>Reference</u>

[1] E. E. Fullerton, et al., "Antiferromagnetically coupled magnetic media layers for thermally stable high-density recording", Appl. Phys. Lett. 77, 3806 (2000).

[2] J.-G. Zhu, et al., "Microwave assisted magnetic recording", IEEE Trans. Magn. 44, 125 (2008).

[3] S. Okamoto, et al., "Microwave assisted magnetic recording technologies and related physics", J. Phys. D: Appl. Phys. 48, 353001 (2015).

[4] S. Greaves, at al., "Antiferromagnetically coupled media for microwave-assisted magnetic recording", IEEE Trans. Magn. 54, 3000111 (2018).

[5] Y. Nakayama, et al., "Microwave-assistance effect on magnetization switching in antiferromagnetically coupled CoCrPt granular media", IEEE Trans. Magn. 52, 3201203 (2016).

[6] H. Suto, et al., "Subnanosecond microwave-assisted magnetization switching in a circularly polarized microwave magnetic field", Appl. Phys. Lett. 110, 262403 (2017).

This work is supported by Strategic Promotion of Innovative Research and Development from Japan Science and Technology Agency, JST.