Development of microwave interferometer based ultra-high sensitivity ferromagnetic resonance measurement apparatus

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Microwave assisted magnetic recording (MAMR) is one of the promising candidates for increasing the recording density in hard disk drives (HDD). In the MAMR technology, a spin torque oscillator (STO) embedded in the HDD slider generates a microwave field, which is applied to the storage layer of the HDD media to temporally decrease the coercivity during the magnetization switching process. Because this technology takes advantage of the cooperative phenomenon between high frequency magnetic fields and spin dynamics, it is crucial to thoroughly characterize dynamical properties of both the STO and magnetic storage layer. However, the high frequency characterization of the STO is particularly challenging due to its small dimension and multilayer structure that complicate the behavior at high frequencies, thus making it difficult to come up with a clear interpretation of the results obtained by the standard electrical characterization techniques such as oscillation spectrum or thermally excited mag-noise measurements. Therefore, it is desirable to have other means for measuring high frequency dynamics of a magnetic nanostructure as a complementary technique.

For this purpose, we have developed a technique to measure ferromagnetic resonance (FMR) with a high sensitivity based on microwave interferometer, which we named as Interferometric FMR (I-FMR), whose block diagram is shown in Fig. 1 [1]. The basic idea of this technique is as follows. The stimulus signal from P1 is split into two paths, and they destructively interfere with each other such that ideally no stimulus signal exits the power combiner when no magnetic activity is excited. When the FMR condition is met, the stimulus signal of the path going through the coplanar waveguide (CPW) excites FMR on the magnetic element, thus the balance between the two paths is broken. As a result, only the difference signal reflecting the FMR response of the magnetic element exits the power combiner, which is amplified and eventually detected at P2. The first I-FMR demonstration showed a large sensitivity enhancement of as large as about 40 dB (x 100) compared with the conventional vector network analyzer FMR (VNA-FMR) as presented in Fig. 2, which allowed a clear resolution of the Kittel mode FMR signal on a 100 nm diameter and 5 nm thick CoFeB single nanodot.

Following this demonstration, we have developed the second version of the I-FMR apparatus. The main difference between the first and second versions is that the first version required manual adjustments of the interferometer every time when the frequency is changed, which is a very tedious and time consuming step, while this adjustment is fully automated in the second version without largely sacrificing the sensitivity, thus making this system a powerful tool for the high frequency characterization of nano-scale magnetic elements.

In the presentation, I will first give the system overview of the second version of the I-FMR apparatus, then will show some FMR spectra measured on nano-scale magnetic elements under various conditions to shed new lights on the magnetization dynamics.

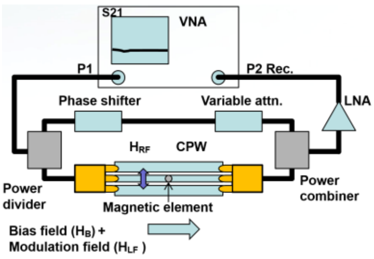

Fig. 1, Block diagram of the I-FMR apparatus

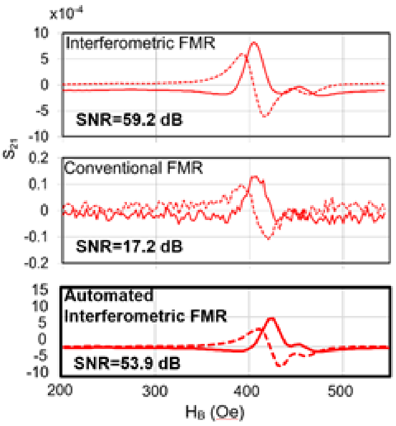

Fig. 2, Comparison of the FMR spectrum measured on a 800 nm diameter and 5 nm thick CoFeB single nanodot taken by the conventional VNA-FMR, first and second versions of I-FMR.

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Magnetization Switching Assisted by Spin Wave Dynamics

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1. Background

Magnetic storage and spintronic devices face a serious challenge in trying to simultaneously achieve ultrahigh-density recording and ultralow power operation. In other words, a nanomagnet with high magnetic anisotropy energy needs to be switched by applying a small external magnetic field. We reported low-field magnetization switching assisted by spin wave dynamics, which is called "spin wave-assisted magnetization switching".[1)] In previous experiments,[1-4)] we employed the in-plane magnetized exchange-coupled bilayers having hard magnetic $L1_0$-FePt and soft magnetic $Ni_{81}Fe_{19}$ (Permalloy), and observed a large reduction in the switching field (H_{sw}) of $L1_0$-FePt by exciting the perpendicular standing spin waves (PSSW) in the Permalloy. From a practical point of view, however, this concept is needed to apply the "perpendicularly magnetized system". In addition, the detailed switching process of spin wave-assisted magnetization switching has not fully been understood yet.

In this talk, we show (i) spin wave-assisted magnetization switching for the exchange-coupled bilayers with perpendicular configuration. In addition to the study on the perpendicular configuration, (ii) the resonant switching behavior of spin wave-assisted magnetization switching is discussed using the in-plane magnetized exchange-coupled bilayers.

2. Spin Wave-Assisted Magnetization Switching in Perpendicularly Magnetized System

We investigated the magnetization dynamics of exchange-coupled bilayers with a perpendicularly magnetized $L1_0$-FePt and a soft magnetic Permalloy. The $L1_0$-FePt (001) layer was epitaxially grown on an MgO (100) single crystal substrate with an Au (001) buffer layer. In order to examine the effect of magnetization dynamics on H_{sw} of the perpendicularly magnetized $L1_0$-FePt, we exploited a nanodot consisting of the $L1_0$-FePt layer and the soft magnetic Permalloy layer having a magnetic vortex. The $L1_0$-FePt layer exhibited H_{sw} = 8.6 kOe without the application of rf magnetic field (H_{rf}). When H_{rf} = 200 Oe with the frequency (f) of 11 GHz was applied, H_{sw} was reduced to 2.8 kOe. By comparing the experimental result with the micromagnetic simulation, we found that the vortex dynamics of azimuthal spin waves in Permalloy effectively triggered the reversed-domain nucleation in $L1_0$-FePt at a low magnetic field (H). Our results demonstrate that the excitation of spin waves in the magnetic vortex leads to the efficient H_{sw} reduction even for the exchange-coupled system having the perpendicularly magnetized $L1_0$-FePt.[5)]

3. Resonant Switching Condition of Spin Wave-Assisted Magnetization Switching

In order to understand the detailed switching condition of spin wave-assisted magnetization switching, we mapped the switching events in the H - f planes for the exchange-coupled bilayers, where $L1_0$-FePt and Permalloy layers showed in-plane magnetization. The magnetization switching was observed only in a limited region following the dispersion relationship of PSSW modes in the Permalloy layer. The experimental result and the numerical simulation indicate that spin wave-assisted magnetization switching is a resonant magnetization process. This is a characteristic behavior and different from the conventional microwave assisted switching. Our results also suggest that spin wave-assisted magnetization switching has the potential to be applied to selective switching for multilevel magnetic recording media.[6)]

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Experimental Study on Microwave-Assisted Magnetization Switching: Circularly Polarized Microwave Field and Varying-Frequency Microwave Field

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I. Background

Applying a microwave magnetic field to a magnet induces FMR excitation, and when this excitation is large enough, it can decrease the switching field. This switching scheme is called microwave-assisted magnetization switching (MAS) and attracts attention for its applications in next-generation magnetic recording such as microwave-assisted magnetic recording and three-dimensional magnetic recording. [1-4] The difficulty of generating a microwave field can be solved by employing a spin-torque oscillator (STO). The STO is a nanodevice, and the one with dimensions less than 30 nm has been reported. [5] By applying a dc current to the STO, the STO magnetization oscillates and generates a microwave field (stray field from the oscillating STO magnetization). This microwave field is confined near the STO, which is beneficial for manipulating magnetization in the nanoscale. In this presentation, for the implementation of the magnetic recording based on MAS, we investigate MAS focusing on two topics: circularly polarized microwave field and varying-frequency microwave field.

II Microwave-assisted magnetization switching in a circularly polarized microwave field

In order to understand MAS, the polarization of the microwave field, e.g. linear polarization (LP) where the field direction alternates in one direction and circular polarization (CP) where it rotates, must be considered. This is because FMR is a precessional motion of the magnetization and is most efficiently induced by a CP microwave field that rotates in the same rotation direction as the natural precession of the magnetization. The microwave field polarization is also important in applications using an STO because the polarization of the microwave field from the STO strongly depends on the oscillation trajectory of the STO magnetization. Here, we investigate MAS behavior of a Co/Pt multilayer perpendicular magnetic nanodot with a diameter of 50 nm in a microwave field with various polarizations. Figure 1 shows the measurement setup. We use a microwave field generated by introducing a microwave signal to the coplanar waveguide (CPW) because the frequency and the amplitude of the microwave field can be easily controlled. The sample has two CPWs crossing at a right angle above the nanomagnet. By introducing microwave signals with a tunable delay to the CPWs, microwave fields with a linear, elliptical, and circular polarization can be generated. Switching of the nanomagnet is detected by the anomalous Hall effect.

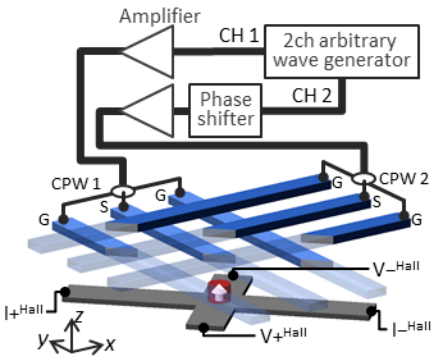

Fig. 1. Experimental setup.

Figure 2 (a) shows the dependence of the switching field on the delay phase between the microwave signals introduced to the two CPWs. When the delay phase is around 90°, the CPWs generate a CP microwave field rotating clockwise in the *x*-*y* plane. This microwave field reduces the switching field only when the nanomagnet reverses from the −*z* to +*z* direction because the rotation directions of the microwave field and the magnetization precession coincide. At around 270°, the microwave field rotates in the opposite direction and MAS occurs only when the nanomagnet reverses from the +*z* to −*z* direction. Next, we fix the phase delay to 90° to examine MAS in a CP microwave field. Figure 2(b) shows the dependence of the switching field on the microwave field frequency. The switching field decreases almost linearly with increasing the frequency and suddenly increases to the value without MAS. This kind of switching behavior is typical of MAS. [3] A large switching field decrease from 7.1 kOe to 1.5 kOe is demonstrated. In comparison with MAS in an LP microwave field, a CP microwave field induces the same MAS effect with half the microwave field amplitude (data not shown), thereby showing that a CP microwave field is efficient in MAS.

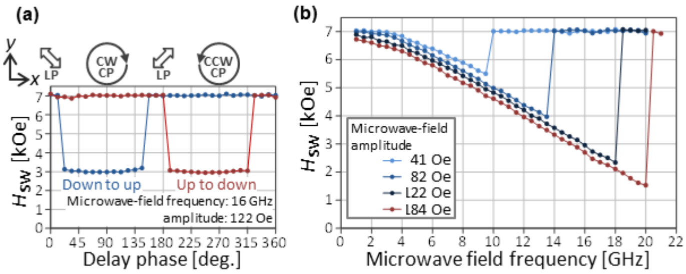

Fig. 2. (a) Switching field versus delay phase of the signal in CPW 1 with respect to that in CPW 2. (b) Switching field versus microwave field frequency in the CP microwave fields from CPWs 1 and 2.

III Microwave-assisted magnetization switching in a varying-frequency microwave field

The FMR frequency of a magnet is not constant but varies with the magnetization trajectory because of nonlinearity. When the magnet has a perpendicular anisotropy, the FMR frequency decreases as the FMR excitation evolves. This suggests that applying a microwave field with time-varying (decreasing) frequency induces larger FMR excitation because the frequency follows the varying FMR frequency, which is expected to enhance MAS effect. Recently, the use of varying-frequency microwave field was suggested by a micromagnetic simulation study, which reported that, in a certain configuration, an STO spontaneously changes its frequency to match the FMR frequency of a magnet because of the mutual stray fields. [6] Here, we investigate MAS in a varying-frequency microwave field. The experimental setup is similar to that shown in Fig. 1 except that only one CPW is used to generate an LP microwave field and that the anisotropy of the nanomagnet is smaller.

Figures 3(a) shows the dependence of the switching field on the microwave field frequency for constant-frequency MAS (CF-MAS). Switching behavior typical to MAS is obtained. Figures 3(b) shows the result for varying-frequency MAS (VF-MAS). The horizontal axis is the start frequency of the microwave field, and the frequency gradually changes to 0.02 GHz over a 10 ns time period. VF-MAS differs from CF-MAS in the following two aspects. (1) VF-MAS can achieve smaller switching field with the same microwave field amplitude, thereby showing that a varying-frequency microwave field enhances MAS effect. (2) After the abrupt increase, switching field becomes almost same as the minimum switching field of CF- MAS, which differs from CF-MAS where switching field increases to the value without MAS. The latter can be explained as follows. As the start frequency increases, the frequency changes at a higher rate, and when the magnetization excitation cannot follow the frequency change, the enhancement of MAS by a varying-frequency microwave field no longer occurs. When the enhancement disappears, switching occurs in the same manner as CF-MAS when the frequency decreases and matches the frequency at which CF-MAS occurs. Therefore, switching field becomes almost same as the minimum switching field of CF-MAS.

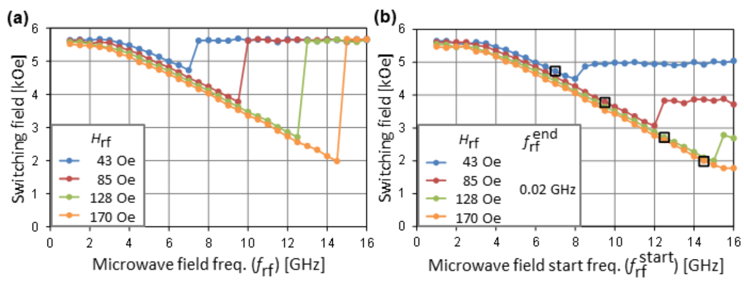

Fig. 3. (a) Switching field versus microwave field frequency for CF-MAS. (b) Switching field versus microwave field start frequency for VF-MAS. Open squares are the maximum microwave field frequency at which CF-MAS occurs, and corresponding switching field.

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Microwave assisted magnetic recording on ECC and AFC media

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Introduction

Microwave assisted magnetic recording (MAMR) is a possible technology for use in future hard disk drives [1]. The simultaneous application of a DC field from a write head and a high frequency (HF) field from a spin torque oscillator (STO) can locally reduce the switching field of media in the vicinity of the STO, leading to a higher effective head field gradient and improved SNR. In this work we present results of simulations of two types of media: exchange coupled composite (ECC) and antiferromagnetically coupled (AFC) and consider their behaviour in a MAMR system.

ECC media

The use of ECC media in a MAMR system offers advantages such as a reduced resonance frequency and enhanced MAMR effect. Fig. 1 shows the switching fields of the hard layers of 4 nm hard + x nm soft ECC grains subjected to a 500 Oe HF vector field rotating in the plane perpendicular to the easy axis. Without the HF field the switching field was about -16.5 kOe for all grains. With the HF field the switching field decreased rapidly once the soft layer thickness exceeded 4 nm. The switching field changed sign for soft layer thicknesses between 6 nm and 8 nm, i.e. the hard layer magnetisation switched before the applied field reached zero, as shown by the inset hysteresis loop for a grain with a 7 nm soft layer.

The same effect can be realised in a recording medium. A static planar write head with a STO was used to write single bit footprints on AC-erased ECC media. The average change of magnetisation is shown in fig. 2 as a function of down-track position, together with the vertical component of the head field at each point. It can be seen that the magnetisation switched in the opposite direction to the head field, with peaks under the edges of the STO (position indicated by the darker shaded region).

When the head field was zero no magnetisation switching was observed, but [2] describes conditions in which the HF field alone can switch the magnetisation direction. Tuning the STO and medium properties may enable this effect to be realised.

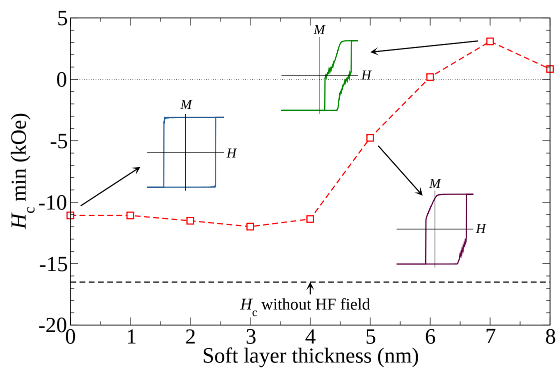

Fig. 1: Minimum switching field of hard layer on descending part of hysteresis loop vs. soft layer thickness. 500 Oe in-plane HF field.

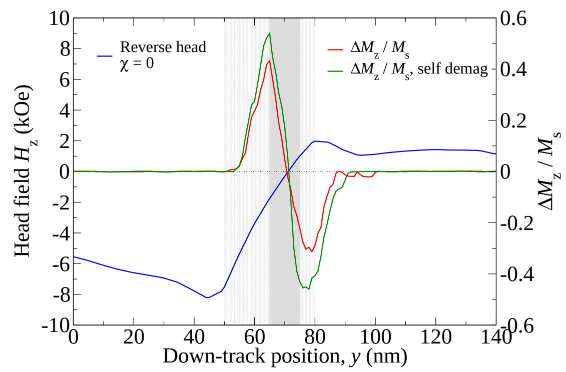

Fig. 2: Change of medium magnetisation, ΔM, as a function of down-track position for footprints written by a planar head and HF field from a STO.

AFC media

Another advantage of MAMR is the possibility to realise multiple layer recording [3]. Selective recording of each layer in a medium with two or more recording layers is possible if the layers have different resonance frequencies. However, the spacing between the recording layers cannot be large as the HF field and head field rapidly decrease in strength with distance from the ABS. As a result there can be strong magnetostatic interactions between the recording layers. To mitigate these interactions the use of AFC media has been proposed [4].

Fig. 3 shows hysteresis loops of single layer (SL) and AFC media. The thickness of both media was 11 nm and the AFC medium had the structure 4 nm hard / 1 nm Ru / 6 nm soft. The saturation magnetisation of the hard layer was 600 emu/cm^3 and that of the soft layer was 400 emu/cm^3. In zero field antiferromagnetic coupling between the hard and soft layers of -1 erg/cm^2 led to an anti-parallel magnetisation state and almost zero remanence. The hard layer of the AFC medium had the same switching field, 20 kOe, as the SL medium. In contrast to ECC media, switching of the soft layer in AFC media did not initiate reversal of the hard layer due to the large difference in switching fields between the two layers.

Tracks were written on SL and AFC media at various linear densities. At low densities the SNR was similar or slightly higher for the SL media. However, as the linear density increased the SNR of the SL media decreased whilst the AFC media SNR was almost unchanged. Fig. 4 shows averaged readback signals of ten tracks written on SL and AFC media at 1693 kfci (15 nm bit length). Although the signal from the AFC media was lower due to the anti-parallel magnetisation, the noise was much reduced, as evidenced by the smaller fluctuations in peak height and much lower transition jitter. Other properties of AFC media will be discussed in the talk.

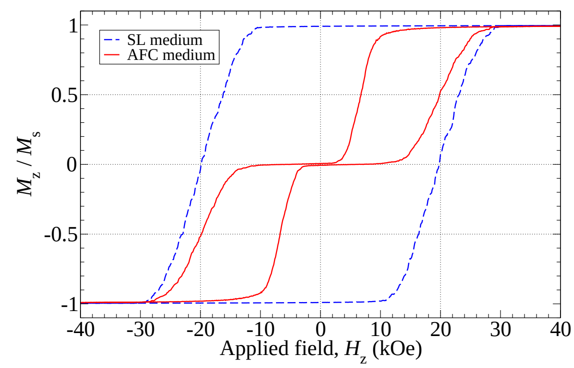

Fig. 3: Hysteresis loops of single layer (SL) and AFC media. K_u hard / SL = 8×10^6 erg/cm^3.

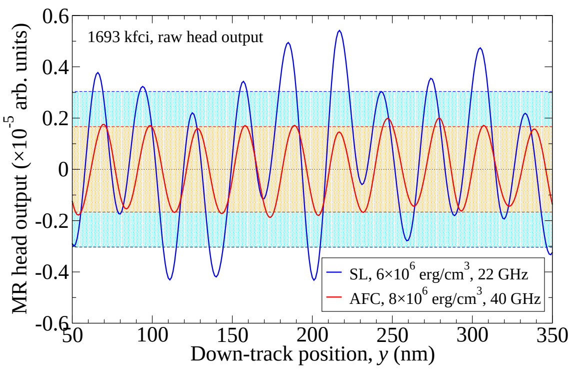

Fig. 4: MR head output signal for 1693 kfci tracks written on SL and AFC media.

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