Damping Constant Influence on Spin Dynamics in Field Generating Layer of STO for MAMR Writing Head

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Abstract. For Microwave Assisted Magnetic Recording (MAMR), large amplitude of ac stray field and coherent motion of magnetization and also low driving power are necessary as a performance of spin torque oscillator for writing head. The damping constant is characterized by both the dynamical motion of magnetization and critical current for the precession-motion. The damping constants for Fe$_x$Co$_{1-x}$ dot were investigated by a network analyzer-ferromagnetic resonance measurement. From these results, suitable material for the oscillator and the effect of finite magnetic element size are discussed.

1. INTRODUCTION

As the recording bit density of hard-disk drive becomes higher and higher, the volume of a bit becomes still smaller with larger media anisotropy energy to keep thermal stability. As a result, a required magnetic field is approaching a physical limit of the magnetic field generated by writer. Microwave Assisted Magnetic Recording (MAMR)\textsuperscript{1} is a promising candidate for solving a writability problem in future hard-disk drives. It is an important issue to realize a writing head generating a high frequency ac magnetic field superimposed on dc field. In STO (Spin Torque Oscillator), magnetic material for Field Generating Layer (FGL) is needed to have a high saturation magnetization ($M_s$) and a low damping constant ($\alpha$) for a large ac field and a low driving power. What’s more, the lower $\alpha$ value should be needed in a nano-sized dot shape to generate a coherent ac field in STO element. Therefore, understanding the mechanism responsible for magnetic damping in dot-materials has become an important issue.

Among the high frequency techniques, ferromagnetic resonance (FMR) measurement, which provides important parameters for magnetic dynamics, such as Gilbert damping constant and magnetic anisotropy, is especially crucial. Network analyzer-ferromagnetic resonance (NA-FMR) techniques \textsuperscript{2,4} have been developed. In standard FMR the used frequency is fixed by the employed microwave cavity. NA-FMR measurements on a coplanar waveguide (CPW) can help resolve this: The impedance of the CPW can be chosen such that the usable frequency range extends to several tens of gigahertz. In contrast to classical FMR, frequency and magnetic field can both be varied continuously.

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In this paper, the suitable material of FGL for MAMR was searched from the viewpoint of $\alpha$ and $M_s$. Furthermore, the size effect on $\alpha$ i.e. coherent motion of FGL was also investigated.

2. EXPERIMENTAL PROCEDURE

![Diagram of the measurement system](image)

Fig 1. Schematic diagram of the network analyzer-ferromagnetic resonance (NA-FMR) measurement. The sample is deposited on the coplanar waveguide. The mutually right-angled external field ($H_{ex}$) and microwave ac field ($H_{rf}$) are in plane of a dot pattern. (b) SEM image of dot of $30 \times 30$ [$\mu$m$^2$]

The NA-FMR technique allows for operating over a wide frequency band and yields FMR parameters from standard microwave S-parameter measurements as function of frequency under various field. Figure 1 shows a diagram of the measurement system. The microwave drive was provided by CPW excitation structure with the thin film sample deposited across the signal line. The mutually right-angled external field ($H_{ex}$) and the microwave field ($H_{rf}$) were in plane of dot patterned sample. The signal analysis was carried out with a standard network analyzer. The electrically shorted coplanar waveguide transmission line consisting of Sub./Ta(5 nm)/Cu(300 nm)/Ta(25 nm) and dot patterns of Fe$_x$Co$_{1-x}$ are fabricated on quartz substrate by a photolithography, an Ar$^+$ ion milling and a resist removal processes. The CPW and dot pattern were insulated by a 60 nm thick SiO$_2$ film. The widths of signal and ground line of the CPW were 100$\mu$m, 250 $\mu$m respectively. The spacing distance between the ground lines and the signal line was 10 $\mu$m. The characteristic impedance of the CPW evaluated from the relative permittivity of 3.8 for the quartz substrate and the geometrical parameters of CPW was approximately 50 $\Omega$.

Each magnetic dot with a thickness of 20 nm and various lateral sizes, i.e. $30 \times 30$, $30 \times 60$, $30 \times 90$, $30 \times 120$ and $30 \times 150$ [$\mu$m$^2$], were fabricated. The magnetization curves and FMR spectra of the sputtered ferromagnetic films, i.e. Fe$_x$Co$_{1-x}$, were measured by using vibrating sample magnetometer and NA-FMR spectroscopy, respectively. The NA-FMR was measured with an Agilent N5230A network analyzer and 40A-GSG-250 EDP of high frequency probe in the frequency range of 0.01–20 GHz. Two grounded-signal-ground (GSG) pin type wafer probes were in mechanical contact with both ends of the CPW transmission line. Therefore, the ac magnetic field caused by applying microwaves to the CPW and the input power of -15 dBm. The microwave magnetic field ($H_{rf}$) was generated in plane by the ac current through signal line around CPW. $H_{rf}$ was right-angled to the external field ($H_{ex}$). $H_{ex}$ from 0 Oe to 1200 Oe was applied parallel to the signal line during measurement.
3. RESULT

The dynamics of magnetic dots were deduced from the frequencies and linewidths of each FMR spectrum. For a magnetic thin film with an in-plane shape anisotropy and with magnetization direction along with applied $H_{ex}$, the resonance frequency ($f_{res}$) is written as the Kittel formula,

$$f_{res} = \frac{\gamma}{2\pi} \sqrt{(H_{k,||} + H_{ex})(H_{k,\perp} + H_{ex})}$$

(1)

where $H_{k,||}$ and $H_{k,\perp}$ are contribution due to the crystalline and shape anisotropy of in-plane and out-plane respectively. $\gamma$ is the gyromagnetic factor of Fe$_{70}$Co$_{30}$.

Figure 2(a) shows FMR spectra of $\text{Re} [\Delta S_{11}]$ resonance in the 30×150 µm$^2$ size of 20 nm thickness Fe$_{70}$Co$_{30}$ at the various $H_{ex}$ between 300-1200 Oe. (b) Resonance frequency ($f_{res}$) in the 30×150 µm$^2$ size of 20 nm thickness Fe$_{70}$Co$_{30}$ film as a function of $H_{ex}$. Black open circle indicates the experimental result and red solid line indicates the fitting line by the Kittel formula Eq. (1).

Figure 2(a) shows FMR spectra of $\text{Re} [\Delta S_{11}]$ and $f_{res}$ in the 30×150 µm$^2$ size of 20 nm thickness Fe$_{70}$Co$_{30}$. The external field of 300-1200 Oe was applied parallel to the signal line i.e. the easy axis of patterned dot because the external field below 250 Oe are thought to be too weak to saturate the magnetization of specimens. The spectrum measured at 0 Oe was taken as the background signal to renormalize the data. $f_{res}$ shifted to the right side with increasing $H_{ex}$. Figure 2(b) shows the dependence of $f_{res}$ on $H_{ex}$. In Figure (b), black open circle and red solid line show the experimental result and the fitting line by Kittel formula, respectively. The plot posses good linearity and indicates the approximation of Eq. (1) works well. The anisotropies ($H_{k,||}$ and $H_{k,\perp}$) were obtained from the fitting. The obtained parameters for the samples are summarized in Table 1.

Table 1. In-plane and out-plane anisotropy fields ($H_{k,||}$ and $H_{k,\perp}$) of various size Fe$_{70}$Co$_{30}$ dots.

| Size            | $H_{k,||}$ [Oe] | $H_{k,\perp}$ [Oe] |
|-----------------|-----------------|--------------------|
| 30×30 [µm$^2$]  | 276             | 12049              |
| 30×60 [µm$^2$]  | 246             | 13175              |
| 30×90 [µm$^2$]  | 250             | 13378              |
| 30×120 [µm$^2$] | 254             | 13384              |
| 30×150 [µm$^2$] | 247             | 13410              |
In order to study quantitatively, the damping constant ($\alpha$) was obtained from Full-Width-Half-Maximum (FWHM: ($\Delta f$) of FMR spectra and anisotropy fields ($H_k : H_{k,||} + H_{k,\perp}$) of Eq. (1).

$$\alpha = \frac{2\pi \Delta f}{\gamma (2H_{ex} + H_{k,||} + H_{k,\perp})}$$

![Fig 3. Sample-size dependence on the damping constant ($\alpha$), FWHM ($\Delta f$), and $H_k : H_{k,||} + H_{k,\perp}$ for various composition of Fe$_x$Co$_{1-x}$ film-dot with 20nm in thickness.]

The results are summarized in Fig. 3. The damping constant increases with the sample size decrease. $\Delta f$ shows slightly increase with decrease sample size and large decrease of $H_k$ is observed. This variation is regarded to be an influence of dispersion of anisotropy or stray field effect at edge part of the sample. In Table 1, The in-plane anisotropy field ($H_{k,||}$) slightly change almost constant. In contrast, the out of plane anisotropy field ($H_{k,\perp}$) largely decrease with smaller sample size.

The magnetic property of single dot depends on the balance of the spins alignment; the in-plane magnetic anisotropy which favours alignment of spins along a particular direction, and the out of plane demagnetizing field is created by the thickness of the dots. If the shape of the dots is not a rectangular at the edge part, the demagnetizing field is non-uniform. $H_k$ or stray field influenced by the curvature distortion of the dot outline of lithographically defined structures as observed with the size variations (insets SEM image of Fig. 1(b)).

![Fig 4.(a) Fe concentration dependence on damping constant and (b) relations between $M_s$ ans $\alpha M_s$ for Fe$_x$Co$_{1-x}$ 30 $\times$ 150 $\mu$m$^2$ dots.]

Figure 4(a) shows the Fe concentration dependence on $\alpha$ for the Fe$_x$Co$_{1-x}$ film-dots with 30×150 $\mu$m$^2$ size. The damping constant almost linearly decreases with Fe concentration increasing. This behavior of damping constant for Fe$_x$Co$_{1-x}$ film-dots are consistent with published conventional FMR data. But the $\alpha$ value is fairly larger than the reported conventional FMR data which might be attributed to the fact that NA-FMR spectrum also contains the FWHM due to a non-uniformity originating from the rf field.

4. DISCUSSION AND CONCLUSION

In the macrospin approximation, the critical current for spin-torque magnetization reversal of a FGL is given by

$$J_c = \frac{e\alpha}{h\gamma}(H_k + 2\pi M_s)$$  \hspace{1cm} (3)

$$J_c \propto \alpha M_s$$  \hspace{1cm} (4)

where $g$ is the spin polarization of the current. $J_c$, which related to the driving power of STO, is proportional to $\alpha M_s$. Figure 4(b) shows the relation between $\alpha$ and $M_s$. Within the assumptions of Eq. (4), low critical currents can be achieved by reducing the $\alpha M_s$. On the other hand, High $M_s$ material generate large amplitude of $H_{ac}$. Therefore, the material parameters should be locate at upper left side in the Fig. 4(b). So, for Fe$_x$Co$_{1-x}$, Fe is the most suitable material for FGL. Note that the above evaluation does not account $g$ parameter effect of Eq. (3). The $g$ parameter should be accounted from the other experiments of MR effects.

For MAMR, STO is necessary to be nano-dot size for magnetization motion of finite size element. The $\alpha$ increased with smaller dot-size as shown in the Fig. 3, which is regarded to be anisotropy dispersion due to the curvature distortion of the dot outline. As a result, $\Delta f$ increases. Although it is extremely difficult to quantify, this anisotropy dispersion could explain why only size variations alone are not sufficient to explain our experimental data.

In conclusion, both dynamics of processional motion and performance of STO can be evaluated by NA-FMR. Fe rich material is much better than Co rich material in the aspect of $M_s$ and $\alpha M_s$ for FGL generating high $H_{ac}$.

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