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Size Dependence of Ferromagnetic Resonance Frequency in Submicron Patterned Magnet

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We investigated the size effect on ferromagnetic resonance (FMR) in a submicron-wide single permalloy bar. The resonant frequency markedly increased with decreasing bar width to less than 1 µm, since the demagnetizing field is effectively modified by changing the bar width even in thin films. The resonant frequency difference between 100- and 1000-nm-wide bars was over 4 GHz in the absence of a magnetic field. This characteristic is promising for practical microwave devices because the desired resonant frequency can be obtained simply by varying the width of narrow ferromagnetic bars so that it is not necessary to change the material or magnetic field. © 2013 The Japan Society of Applied Physics

1. Introduction

Spintronic devices operating at high frequencies such as microwave-assisted magnetization reversal,[1,2] spin batteries (spin pumping),[3,4] and spin torque diodes,[5] rectifying effect due to time-dependent anisotropic magnetoresistance,[6,7] have been intensively investigated. Additionally, the generation and propagation of spin waves (and magnetostatic waves) in ferromagnetic metals are also important topics in spin current researches.[8–14] These devices are based on the precessional motion of the magnetization so that ferromagnetic resonance (FMR) is an important phenomenon in them. The resonant frequency is an important parameter in their operation, which is generally determined by the Kittel equation. We assume that the sample is a thin film with a bar shape, a static magnetic field is applied to the longitudinal direction of the bar, and an in-plane exciting microwave field is applied perpendicular to the longitudinal direction in plane.

When the crystal anisotropy can be neglected, the resonant frequency can be expressed by

$$f = \frac{\gamma}{2\pi}\sqrt{(B + (N_y - N_x)M_S)(B + (N_z - N_x)M_S)} \quad (1a)$$

$$= \frac{\gamma}{2\pi}\sqrt{(B + B_{a\parallel})(B + B_{a\perp})}, \quad (1b)$$

where γ is the gyromagnetic ratio, B is the static magnetic field, N_x, N_y, and N_z are demagnetization factors, and M_S is the saturation magnetization. The terms of demagnetization factors can be described by the anisotropy fields $B_{a\parallel}$ and $B_{a\perp}$. $B_{a\parallel}$ is in the film plane and $B_{a\perp}$ is perpendicular to the plane. For a thin film, we usually take $N_x = N_y \cong 0$ and $N_z \cong 1$, and then Eq. (1) is deduced to a simple form:

$$f = \frac{\gamma}{2\pi}\sqrt{B(B + M_S)}. \quad (2)$$

Equation (2) shows that the resonant frequency depends only on B and M_S, which means that the thin film of the same material has the same resonant frequency at the same magnetic field. It has been presumed that even if $N_x \neq 0$ and $N_y \neq 0$ in a microfabricated thin film magnet, the resonant frequency is not expected to shift very much because N_x and N_y will be small. When many devices are integrated and microwaves are irradiated over a wide area, several devices will be affected by the irradiation. This will cause controllability problems in future applications. In order to control one particular device, highly localized microwave irradiation is required.

Some recent reports, however, implied the possibility of the resonant frequency shift of FMR in nanoscale magnets. These reports state the field dependence of resonant frequency with offset even at zero field in microwave assisted magnetic reversal,[2] on-chip detection of FMR,[15] and the cone angle measurement of FMR for nanowires.[16,17] The micromagnetic calculation predicted that the resonant frequency shift occurs in nanosize rectangular ferromagnetic stripes.[18] These reports drop a hint that the resonant frequency can be tunable in nanoscale magnets even in the same material because the demagnetization effect cannot be neglected.

Recently, some trials of vector network analyzer ferromagnetic resonance (VNA-FMR) measurement have been reported.[19–22] In this technique, the sample is mounted on top of a coplanar waveguide (CPW) structure on a wafer. Microwaves are injected via the CPW and the S-parameter is determined from the microwave transmission or reflection loss. The VNA-FMR has the advantage that local excitation near the CPW can be realized and it has a higher sensitivity than conventional FMR. For the submicron magnets, however, the FMR characteristics are measured as the average of array of many submicron magnets.[2] It includes the static magnetic interaction between magnets and different from single magnet properties.

In this study, we systematically investigated the size dependences of FMR characteristics in a single submicron bar of permalloy (Py) using a VNA. We found that the resonant frequency can be controlled over a wide range by varying the bar width on a submicron scale.

2. Experimental Procedure

A CPW structure of Cu and a submicron Py bar were fabricated on a Si/SiO_2 substrate using electron beam lithography, electron beam evaporation, and the lift-off technique. Figure 1(a) shows SEM images of the sample. The CPW structure consists of two planes and is designed to have an impedance of 50 Ω, which matches that of the VNA and cables. The CPW is of the signal-ground (SG) type and is terminated by a 2-µm-wide strip at the end of the two planes. The Py bar of 30 nm thickness and 6 µm length was fabricated on a shorted strip. The Py width was varied between 100 and 1000 nm.

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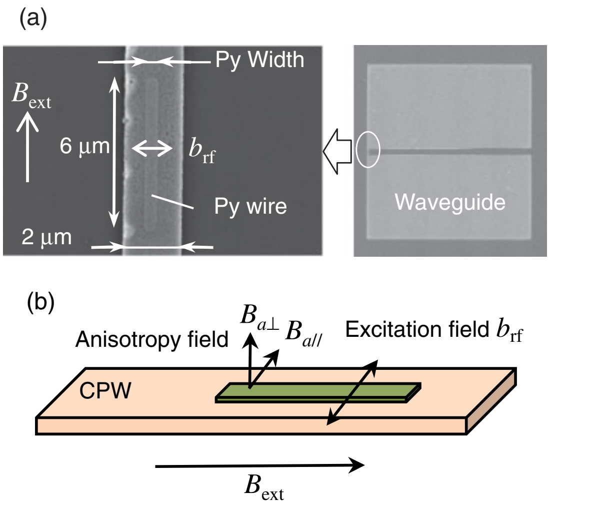

Fig. 1. (Color online) (a) SEM images of Py bar on CPW structure. (b) Magnetic field directions in present measurement. B_{ext} is the static magnetic field, b_{rf} is the excitation microwave magnetic field, and $B_{a\parallel}$ and $B_{a\perp}$ are the anisotropy fields due to the shape anisotropy of the Py bar.

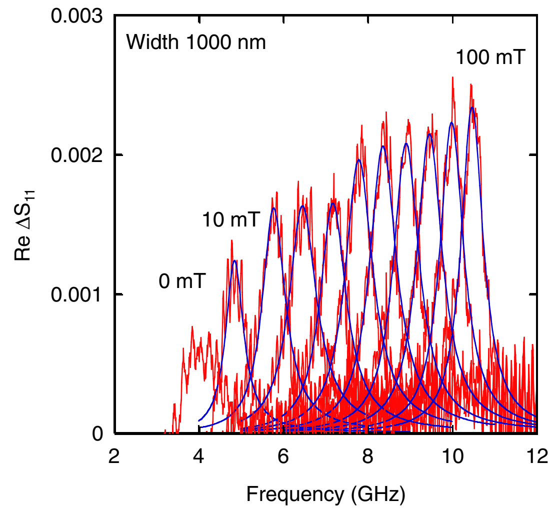

Fig. 2. (Color online) Magnetic field variation of Re ΔS_{11} spectra and their fit curves for bar with $6 \times 1\,\mu m^2$.

FMR measurements were performed using a VNA (HP8510C) and a microprobe station (Cascade Microtech Summit 9000). The stage of the microprobe station was modified to apply an in-plane static magnetic field. As shown in Figs. 1(a) and 1(b), a static magnetic field, B_{ext}, was applied along the longitudinal direction of the bar and an excitation microwave magnetic field, b_{rf}, was applied perpendicular to the longitudinal direction of the bar. $B_{a\parallel}$ and $B_{a\perp}$ are anisotropy fields due to the shape anisotropy of the sample. In this configuration, the excitation spin wave of the Kittel mode (homogeneous rotation mode) is dominant, since the excitation field is applied to the whole bar. We performed one-port reflection measurements and determined the S-parameter (S_{11}). The incident microwave power was 0 dBm, which was confirmed under a linear response regime by the power dependence of the spectra shape. The signals obtained under a static magnetic field were analyzed by subtraction and phase-correction using the background signal, which was obtained under zero magnetic field. Hereafter, we called this subtracted signal ΔS_{11}. The ΔS_{11} response derived from linearized LLG equation in a small excitation field regime is

$$\Delta S_{11} \propto \frac{i\omega_d(\omega_0^2 - \omega^2) + \alpha\omega(\omega_d^2 + \omega^2)}{(\omega_0^2 - \omega^2)^2 + \alpha^2\omega^2(\omega_c + \omega_d)^2}, \quad (3)$$

where $\omega_c = \gamma(B_{a\parallel} + B_{ext})$, $\omega_d = \gamma(B_{a\perp} + B_{ext})$, $\omega_0 = \sqrt{\omega_c\omega_d}$, α is the damping factor, and $\gamma = g\mu_B/\hbar$ (μ_B is the Bohr magneton and g-factor is 2.11, which is a substitute for the Fe value). The resonant frequency, anisotropy fields, and α were estimated by fitting the spectra of the real part of ΔS_{11}. The Py width dependences of these parameters were systematically investigated in detail.

3. Results and Discussion

Figure 2 shows the magnetic field variation of the Re ΔS_{11} spectra and their fit curves for the bar with $6 \times 1\,\mu m^2$. The spectra contain a resonant peak caused by the inductance change of the FMR. The resonant frequency increases with a magnetic field, as expected from the Kittel equation. Note that FMR was observed even at 0 mT, which suggests that the term $(N_y - N_x)M_S$ or the anisotropy field of the width direction ($B_{a\parallel}$) in Eq. (1) cannot be neglected. These spectra were fitted using the real part of Eq. (3) and the parameters α, $B_{a\parallel}$, and $B_{a\perp}$ were extracted. The obtained α can include extrinsic contributions such as two-magnon scattering, which increases the FMR linewidth. This is caused by inhomogeneities and defects at surface and interfaces, and transfers energy from an uniform FMR mode to degenerate short-wavelength spin waves.[23–25] Since this contribution is important in ultrathin films, the obtained α does not represent an intrinsic damping parameter. These are summarized in Figs. 3(a) and 3(b). α was about 0.02, and $B_{a\parallel}$ and $B_{a\perp}$ were about 21 and 916 mT, respectively. These values should be constant because the sample did not change during the measurement. The small deviation of the damping factor could be fitting errors because of noisy signals due to the very small samples. It is known that the damping factor of bulk Py is about 0.007. Our other larger samples prepared by the sputtering deposition of Py on a Si substrate, etching to a bar shape, and CPW deposition on the Py bar, showed an α of about 0.01, which is usually obtained for film samples. In the present case, the Py bar was made *on* a CPW of Cu. The grains of Cu are large. Therefore, we think that the large α was affected by the inhomogeneiteis and roughness of the Py bar.

Figure 4 shows the bar width variation of the Re ΔS_{11} spectra and their fit curves. The resonant frequency markedly increases with decreasing bar width. The peak magnitude decreases since the microwave energy loss is expected to be proportional to the volume of the magnet. In Fig. 5(a), the bar width variation of α except of 100 nm hardly changed, which is reasonable because these samples were prepared at the same time and thus the sample conditions were the same. The α of the 100-nm-wide sample, however, becomes large. We think that the edge roughness in the very narrow bar also largely affects the damping factor. Figures 5(b) and 5(c) show the variation of the anisotropy fields with the bar width and the relationship between the resonant frequency and the bar width. In

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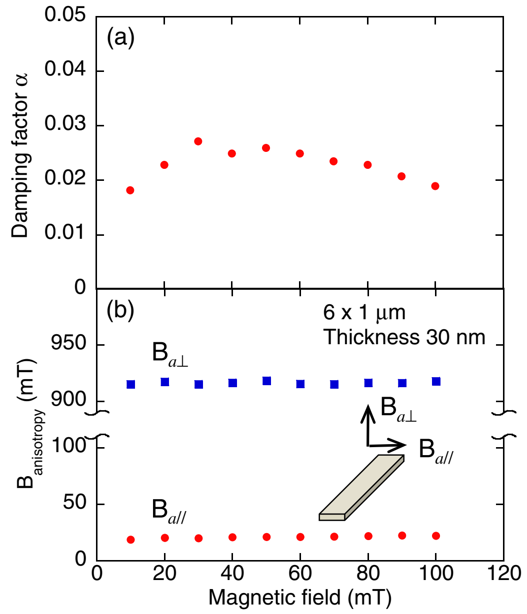

Fig. 3. (Color online) (a) Magnetic field dependence of damping factor α. (b) Magnetic field dependence of anisotropy fields $B_{a\parallel}$, $B_{a\perp}$.

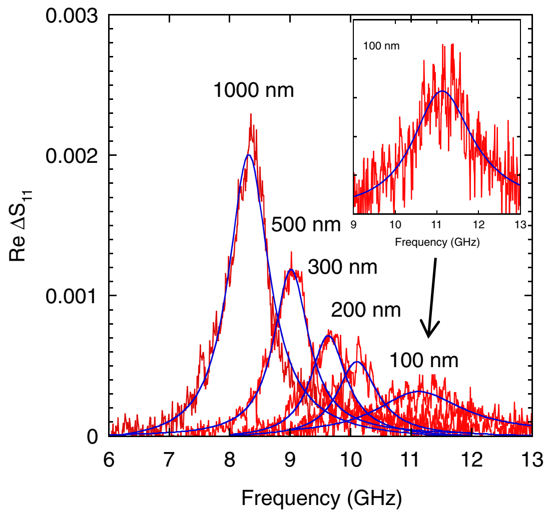

Fig. 4. (Color online) Bar width variation of Re ΔS_{11} spectra and their fit curves with widths of 100–1000 nm.

Fig. 5(b), $B_{a\parallel}$ increases and $B_{a\perp}$ decreases slightly as the bar width decreases below 500 nm. Accompanying these changes in the anisotropy fields, the resonant frequency increases markedly as the bar width decreases below 500 nm [Fig. 5(c)]. The resonant frequency increases by about 2 GHz at 100 mT and more than 4 GHz at 0 mT as the bar width is decreased from 1000 to 100 nm. For the bar narrower than 100 nm, a greater frequency shift is expected. This frequency shift increases as the static field is reduced. Thus, the change in the anisotropy fields is not so large, but the effect on the resonant frequency is large for bars with submicron widths.

Figure 6(a) shows the static magnetic field dependence of the resonant frequency for each width sample. The solid line is a calculated curve using the Kittel equation for a thin film [Eq. (2)]. The resonant frequency of the narrow bars is

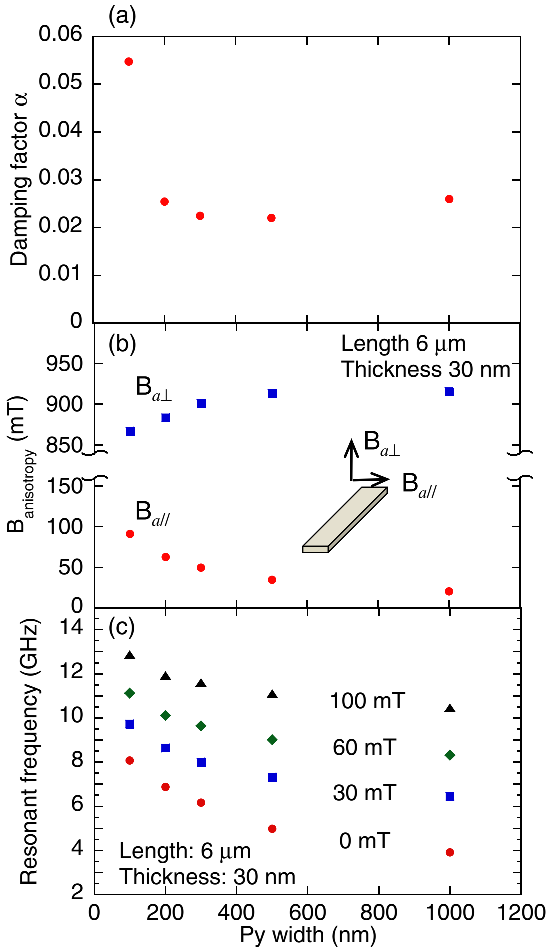

Fig. 5. (Color online) (a) Variation of damping factor α with Py width. (b) Variations in anisotropy fields $B_{a\parallel}$ and $B_{a\perp}$ with Py width. (c) Bar width dependence of resonant frequency at static magnetic fields of 0, 30, 60, and 100 mT.

shifted upward from the solid curve. This frequency shift increases with decreasing bar width. Additionally, there is a resonant peak at 0 T and the frequency shift is largest at 0 T compared with the case under finite fields. Thus, the demagnetization effect of thin films for the ferromagnetic resonance becomes large when the sample width is less than 1 μm. The resonant frequency can be largely controlled by changing the sample width for narrow bars. It is worthwhile to investigate the classical demagnetization factor. The demagnetization factors were estimated by curve fitting using the general Kittel equation [Eq. (1b)]. M_S is 1.08 T and the fitting parameters are N_y and N_z, and N_x is obtained by $N_x = 1 - N_z - N_y$. The dashed lines in Fig. 6(a) are curves obtained by this fitting. Figure 6(b) shows the relationship between the demagnetization factors and the Py width. N_y increases and N_z decreases slightly as the bar width decreases below 500 nm. The estimated anisotropy fields using these demagnetization factors are consistent with the anisotropy field obtained by spectral fitting. We compared the result with the analytically calculated demagnetization factor N_x for rectangular prisms using Aharoni's equation.[26] The range of these values is 0.0040 for the 100-nm-wide sample to 0.0074 for the 1000-nm-wide sample. In the fitting results ($N_x = 0.04$–0.05), there is a weak sample width dependence, and what is much

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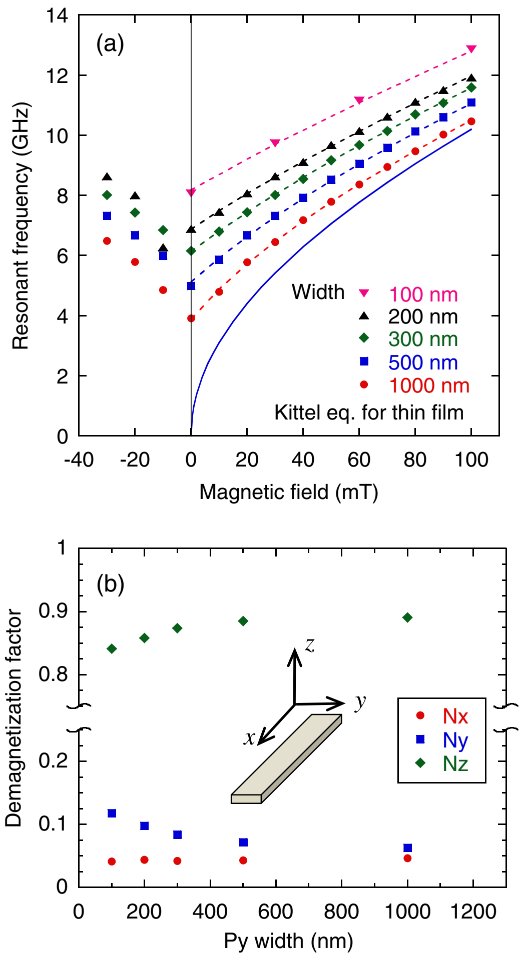

Fig. 6. (Color online) (a) Static magnetic field dependence of resonant frequency for bars with widths of 100–1000 nm. The dashed lines are curves obtained using the general Kittel equation [Eq. (1)], while the solid line is the curve calculated using the Kittel equation for a thin film [Eq. (2)]. (b) Variation in demagnetization factors with Py width.

larger than the calculated results. This discrepancy is attributable to the disturbance of the magnetic moments around the edge and roughness of the bar, which could locally enhance the actual demagnetization factor in the longitudinal direction.

4. Conclusion

We investigated the FMR characteristics of single submicron bars of permalloy (Py) using a VNA and found that the resonant frequency can be controlled over a wide range by varying the bar width on a submicron scale. This originates from the anisotropy field due to the shape magnetic anisotropy. In a nanoscale bar, the demagnetization field in the plane cannot be neglected even in the thin film because the thickness and film width could be comparable. These results provide guidelines for designing microwave devices. Even when the same magnetic material is used for microwave applications, the resonant frequencies of individual submicron magnets on a single chip can be tuned by varying the width of the magnets. If microwaves are irradiated over a wide area, a certain dot or bar can be selected. One additional advantage of a narrow bar is that resonance occurs at 0 mT so that it is not necessary to apply a static magnetic field, and the resonant frequency can be widely changed at a zero magnetic field than at a finite field. This is also very useful for spin pumping because a static magnetic field is not required to generate a spin current. When there are several bars with different widths, the location at which the spin current is generated can also be controlled.

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