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Microwave-assisted magnetization reversal in a Co/Pd multilayer with perpendicular magnetic anisotropy

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Microwave-assisted magnetization reversal in a rectangle of a Co/Pd multilayer with a perpendicular magnetic anisotropy is examined using vector network analyzer ferromagnetic resonance (FMR) spectroscopy. A microwave field is applied along the in-plane direction of the rectangle together with a negative dc easy-axis field smaller than the coercive field. Broadening or splitting of the peak profile in the FMR spectrum suggesting the formation of multidomain structure appears after the microwave field is applied. The dominance of microwave-assisted nucleation of magnetization is supported by the frequency dependence of the probability with which the multidomain structure appears. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3213559]

Microwave-assisted magnetization reversal (MAMR) is a promising candidate for solving a writability problem in future hard-disk drives (HDDs) that use a magnetic medium with a very strong perpendicular magnetic anisotropy. The earliest MAMR experiment was performed by Thirion *et al.*,[1] for an hcp-Co particle 20 nm in diameter, where frequency-dependent suppression of the switching field was clearly observed in the asteroid curve using a microsuperconducting quantum interference device. Thereafter, MAMR experiments on ferromagnets with a thin film geometry were performed by many groups.[2–8] Although MAMR on ferromagnetic thin films with perpendicular magnetic anisotropies is significant for practical application to future HDDs, all experiments nevertheless focused on patterned ferromagnetic thin films with in-plane magnetic anisotropies.

In this paper, an experimental study of MAMR in a perpendicularly magnetized Co/Pd multilayer is presented. A change in the magnetic domain structure of the Co/Pd multilayer after the application of ac magnetic fields was observed from the variation in the shape of ferromagnetic resonance (FMR) spectra measured using vector network analyzer (VNA) FMR spectroscopy. Furthermore, frequency dependence of the probability with which this variation appeared was examined to verify the evidence supporting the realization of MAMR in the Co/Pd multilayer.

A ferromagnetic multilayer consisting of $[\mathrm{Co}(0.17\ \mathrm{nm})/\mathrm{Pd}(0.8\ \mathrm{nm})]_{20}$ was deposited on a glass substrate by tandem-type magnetron sputtering with a multicathode system (Anelva SPC-350). Background pressure was below 5.0×10^{-7} Torr, and the Ar pressure during deposition was fixed at 20 mTorr. Sputtering rates for Co and Pd were 0.10 and 0.036 nm/s, respectively. The Co/Pd multilayer was then shaped into a rectangle with a lateral size of $100\times10\ \mu\mathrm{m}^2$ by a conventional lift-off process. Finally, an electrically shorted coplanar waveguide (CPW) consisting of Ti(10 nm)/Au(100 nm) was fabricated on the patterned Co/Pd multilayer by another lift-off method using electron-beam lithography. Both Ti and Au films were prepared using electron-beam evaporation with a background pressure of 5.1×10^{-6} Torr. The CPW and Co/Pd multilayer were separated by a 100-nm-thick SiO_2 film. The center conductor of the CPW was aligned along the long axis of the Co/Pd multilayer. The center conductor was 1.0 μm wide, which is much narrower than the ground plane (230 μm). Therefore, the ac magnetic field caused by applying microwaves to the CPW was mainly concentrated just below the center conductor. The direction of the ac field was along the in-plane short axis of the rectangle. The spacing distance between the ground planes and the signal conductor was 0.6 μm. The characteristic impedance of the CPW evaluated from the relative permittivity of 6.7 for the glass substrate and the geometrical parameters of CPW was approximately 50 Ω. The magnetization curve and FMR spectrum of the sputtered Co/Pd multilayer were measured using vibrating sample magnetometry and VNA-FMR spectroscopy, respectively.

MAMR operation proceeded as follows. Initially, the magnetization was saturated perpendicular to the film plane by applying a magnetic field of 5 kOe. Then a dc test field was applied in the direction opposite to the initial magnetization direction. The amplitude of the test field was less than that of the coercive field of the Co/Pd multilayer. Next a 100-μs-long microwave impulse was applied to the CPW using a radio-frequency (rf) signal generator. After that the FMR spectrum of the Co/Pd multilayer was measured from the frequency variation in the microwave reflection coefficient S_{11} of the CPW. The FMR frequency (f_{FMR}) is expected to increase when the magnetization switches because the relative orientation of the magnetization with respect to the test field changes from antiparallel to parallel.[7]

In the MAMR experiment, the rf signal from the generator is mostly reflected at the electrically shorted point of CPW. The interference between the transmitted and reflected rf signals leads to the formation of a standing wave. The antinode of the amplitude of electrical current that generates the ac field is formed at the shorted point. The wavelength λ of the standing wave decreases with increasing the frequency although the position of the antinode is fixed at the shorted point. When the frequency of rf signal is 30 GHz that is used for the MAMR experiment, λ of the standing wave is approximately evaluated to 3.9 mm. The rectangle of Co/Pd multilayer with a lateral size of $100\times10\ \mu\mathrm{m}^2$ are placed very close to the shorted point ($\sim$20 μm). These dimensions are much less than the wavelength of the standing wave.

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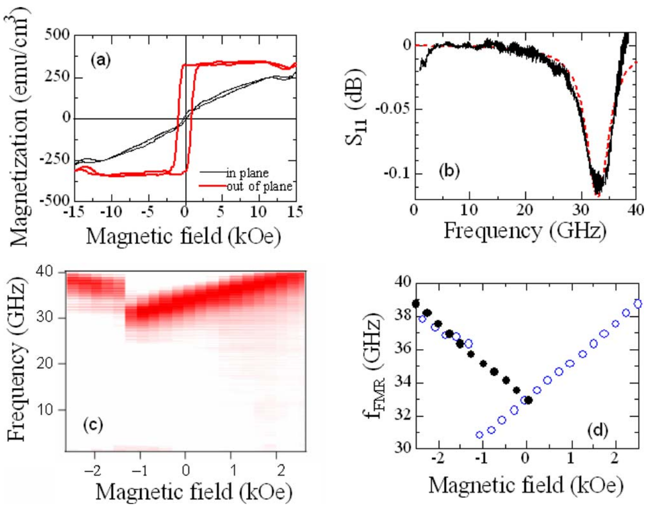

FIG. 1. (Color online) (a) Magnetization curves for $[\mathrm{Co}(0.17\ \mathrm{nm})/\mathrm{Pd}(0.8\ \mathrm{nm})]_{20}$ film fabricated on a glass substrate. Thin and thick solid curves represent in-plane and out-of-plane magnetization, respectively. (b) Frequency variation in the microwave reflection coefficient S_{11} of the CPW fabricated on a rectangle of Co/Pd multilayer with a lateral size of $100\times 10\ \mu\mathrm{m}^2$. The measurement was performed at remanent state after saturating the magnetization of the Co/Pd multilayer along the out-of-plane direction. S_{11} is normalized to the high-field saturated value. The dashed curve shows the result of Lorentzian fitting. (c) Gray scale plot of S_{11} measured while sweeping the dc magnetic field from +2.5 to −2.5 kOe along the out-of-plane direction. (d) Variation in the ferromagnetic resonance frequency of the Co/Pd multilayer during a field sweep from +2.5 to −2.5 kOe (open circles) and from −2.5 kOe to 0 (closed circles).

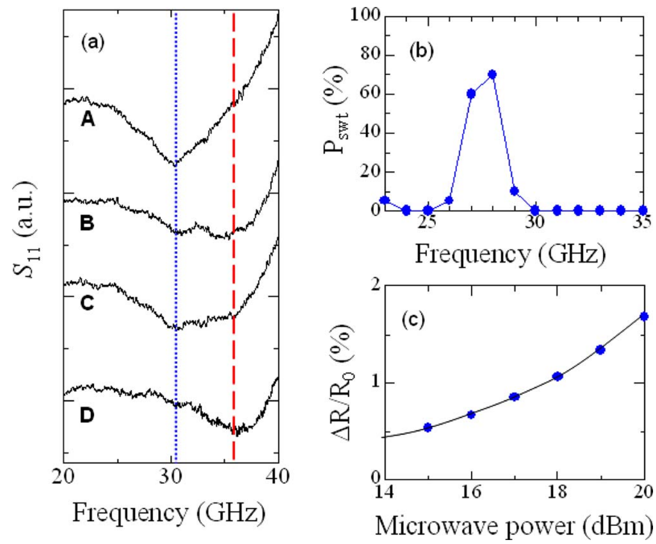

FIG. 2. (Color online) (a) Frequency variations in S_{11} measured after application of microwave impulse with a power of 20 dBm and frequency of 28 GHz. The length of the impulse was fixed at 100 μs. A dc magnetic field of −1 kOe was simultaneously applied with the microwaves. Dotted and dashed lines represent FMR frequencies for unswitched and switched states, respectively. (b) The probability that complete or partial magnetization switching appears as a function of the frequency of the microwave field. (c) The rate of increase of electrical resistance with respect to the room temperature value as a function of the power of microwaves continuously applied to the CPW.

Therefore, the amplitude of ac field is almost uniform along the center conductor of CPW.

Figure 1(a) shows magnetization curves of the Co/Pd multilayer. Thin and thick solid curves represent in-plane and out-of-plane magnetization, respectively, and a perpendicular magnetic anisotropy is clearly observed in the Co/Pd multilayer. The remanent magnetization perpendicular to the film plane is 3.2×10^2 emu/cm^3, which is almost similar to the saturation value. The coercive field H_c of the Co/Pd multilayer is 1.2 kOe, and the anisotropy field evaluated from the magnetic field saturating the magnetization in the in-plane direction is 18 kOe. The steeper slope of the in-plane M-H curve observed between −2.5 and +2.5 kOe suggests a weak in-plane anisotropy. The perpendicular anisotropy in the Co/Pd multilayer results from the hybridization of the d-shell electrons at the interfaces between Co and Pd layers.[9] The roughness and/or the interlayer mixing of the multilayer causes an easy axis distribution around the direction normal to the film plane.

Figure 1(b) shows S_{11} of the CPW fabricated on the Co/Pd multilayer as a function of frequency. S_{11} was measured at the remanent state of the Co/Pd multilayer. Note that S_{11} was normalized to the high-field saturated data at 5 kOe along the out-of-plane direction. As a consequence, the influence of field-independent losses such as conduction loss, radiation loss, dielectric loss, and Eddy current loss can be removed. However, a positive peak of S_{11} corresponding to FMR absorption at 5 kOe appears in the normalized S_{11} shown in Fig. 1(b). The dashed curve in Fig. 1(b) shows the result of Lorentzian fitting. Microwave absorption caused by FMR in the Co/Pd multilayer appears at 33 GHz. The deviation from the Lorentzian curve on the high-frequency side is attributed to the appearance at 44 GHz of the positive peak in the normalized S_{11} mentioned above. The value of damping constant α evaluated from the linewidth of the FMR spectrum ranges from 0.06 to 0.08. The amplitude of microwaves used for S_{11} measurement was always −20 dBm. The ac field amplitude caused by applying microwaves of −20 dBm is approximately 5 Oe, which is numerically estimated by assuming an ideal CPW without any microwave losses. Thus, FMR caused by −20 dBm microwaves is expected to be within a linear response regime.

Figure 1(c) shows a gray scale plot of S_{11} as a function of the microwave frequency and amplitude of the dc magnetic field perpendicular to the film plane. The dc field was swept from 2.5 to −2.5 kOe. The contrast indicates the appearance of a large FMR absorption. From this plot, the variation in f_{FMR} during magnetization reversal can be obtained, as shown in Fig. 1(d). Open circles in Fig. 1(d) show FMR frequencies measured while sweeping the dc magnetic field from 2.5 to −2.5 kOe. A rapid increase in f_{FMR} is clearly observed at −1.2 kOe. This is attributed to the change in the relative orientation of magnetization with respect to the dc field. Indeed, the field amplitude showing this sudden increase is identical to H_c of the Co/Pd multilayer. Closed circles in Fig. 1(d) are FMR frequencies measured while sweeping the dc field from −2.5 kOe to 0. Hysteresis of f_{FMR} below the coercive field is obvious. Consequently, magnetization switching with respect to the direction of the dc field can be detected by measuring f_{FMR} at a dc field smaller than H_c.

The MAMR experiment was performed at a dc test field of −1 kOe, which is 200 Oe smaller than H_c. If the magnetization switches after the ac field is applied, f_{FMR} of the Co/Pd multilayer will increase from 31 to 35 GHz. Four curves in Fig. 2(a) are typical examples of FMR spectra measured after microwave application. The microwave power is 20 dBm, corresponding to an ac field amplitude of 480 Oe.

The frequency is 28 GHz, which is 3 GHz lower than the FMR frequency at a dc field of −1 kOe. Dotted and dashed lines represent FMR frequencies for unswitched and switched states, respectively. As shown in Fig. 2(a), complete magnetization switching is observed in case "D." However, the obvious shift in the peak profile indicating complete switching was rarely observed. In most cases, e.g., cases "B" and "C," the peak profile broadened or split into two peaks corresponding to switched and unswitched states. Therefore, it is expected that a multidomain configuration formed preferentially after microwave application. The domain nucleation during the reversal process is attributed to the inhomogeneous ac field distribution and/or the scattering of magnetic anisotropy in the Co/Pd multilayer observed in the in-plane M-H curve.

Figure 2(b) shows the frequency dependence of the probability with which the magnetic domain configuration changes after microwave application. Note that to evaluate the probability, 30 measurements of the FMR spectrum after microwave injection were carried out at each frequency. The power level of the rf signal generator must be adjusted at each frequency to keep the amplitude of the ac field from varying because the efficiency of ac field generation in the CPW generally depends on the frequency. To find an adequate level of microwave power at each frequency, we performed the following experiment before the MAMR experiment. The ac field amplitude is believed to be proportional to the current flowing through the CPW, which increases the electrical resistance of the CPW due to Joule heating. Initially, the increase in electrical resistance while applying continuous microwaves with a power of 20 dBm was measured at 20 GHz. The dc bias voltage used to measure the electrical resistance was applied using a bias tee. Then we found microwave power levels showing the same increase in electrical resistance at different frequencies. The microwave power required to generate the same Joule heating monotonously increases with increasing frequency. This suggests that losses other than Joule heating increase monotonously with the frequency. MAMR experiments in Fig. 2(b) were performed using the adjusted microwave power at each frequency. As shown in the figure, the probability is maximized at 28 GHz, which is 3 GHz lower than f_{FMR} at −1 kOe with a small ac field.

To examine the effect of Joule heating on magnetization reversal after microwave application, we measured the increase in the electrical resistance of the CPW caused by continuous microwave application. Figure 2(c) shows the rate of increase of the electrical resistance as a function of power level. R_0 is the electrical resistance of the CPW at room temperature, and ΔR is the difference between the electrical resistance before and after applying the microwaves. The frequency was fixed at 20 GHz. The electrical resistance increases by only 1.7% at 20 dBm, which is similar to the power used for the MAMR experiment. This suggests that the temperature increase due to Joule heating is only a few Kelvin. In the case of the Co/Pd multilayer used for the MAMR experiment, it has been confirmed that the temperature increase required to reduce the switching field from H_c to 1 kOe is approximately 30 K.[10] Furthermore, it has also been found that the temperature increase is monotonously reduced with increasing frequency. In contrast, the probability that the change in the magnetic domain configuration appears is maximized at a particular frequency of 28 GHz. Therefore, thermally assisted reduction of the switching field due to Joule heating of the CPW is expected to be negligible in our MAMR experiments. Note that resonant absorption of microwaves by the magnetic element could also lead to a frequency-dependent temperature increase in the magnetic element (ΔT). However, it is difficult to measure ΔT in the Co/Pd multilayer from the increase of electrical resistance in the CPW because the multilayer and CPW are separated by a 100-nm-thick SiO_2 layer. Furthermore, it is also difficult to numerically evaluate ΔT in the high power FMR experiment because nonlinear effects such as resonance saturation effect and Suhl spin wave instability processes must be considered.[11,12] To clarify the influence of temperature increase caused by FMR absorption on MAMR, it is significant to demonstrate the MAMR experiment at different temperatures. ΔT can be systematically controlled by the thermal conductivity of the substrate because ΔT is inversely proportional to the thermal conductivity.[4]

In conclusion, we demonstrate that the formation of multidomain structure in a perpendicularly magnetized Co/Pd multilayer can be assisted by applying a microwave field along the in-plane direction. The probability of nucleating the inversed magnetic domain is maximized at a particular frequency a few gigahertz lower than the FMR frequency of the Co/Pd multilayer. Furthermore, the reduction of the switching field due to Joule heating of the CPW during microwave application is much smaller than the microwave-assisted effect. The experimental result of MAMR in a perpendicularly magnetized film will encourage realization of successful recording in future HDDs with an areal density exceeding 1 $\mathrm{Tbit/in.}^2$

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