Magnetization Reversal of Single Co/Pd Multilayer Nanodot by Nanoseconds Pulse Field

Y Suyama, Y Murayama, N Kikuchi, S Okamoto, and O Kitakami

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan

E-mail: suyama.y@mail.tagen.tohoku.ac.jp

Abstract. Magnetization switching experiments on nanosized [Co(δCo = 0.3 – 0.8 nm)/Pd (2 nm)]3 multilayer dots with the diameter of D = 240 - 500 nm are carried out using pulse fields with the duration of 1.6 – 10 ns. The switching fields in the nanoseconds regime are significantly enhanced with respect to the values measured by conventional quasistatic magnetometry. The energy barriers are evaluated from the time-dependence of the switching field based on the Néel-Arrhenius law and are found to be proportional to the Co layer thickness.

1. Introduction

Magnetic recording technology has shown continuous progresses in both density and operation speed for last decades. For development of further advanced devices using nanomagnets as memory elements, such as bit patterned media (BPM) and magnetoresistive random access memory (MRAM), understanding of the magnetization behavior of nanoscale structures becomes more important. Dynamic magnetization behavior is also a key issue since their operation frequency is supposed to be of the order of GHz being comparable with the magnetization precession frequency. A number of studies on magnetization dynamics [1] with the time resolution of femtoseconds have been reported [2]. However, few studies have been reported on irreversible switching of hard magnetic materials [3], due to difficulty in large pulse field generation. In the previous work, we have reported the pulse field generator with the maximum field of 3 kOe and investigated the magnetization switching behavior of a single Co/Pt multilayer dot of 300 nm in diameter [4, 5]. In this study, we present experimental results on magnetization switching of nanosized Co/Pd multilayer dots with the Co layer thickness of δCo = 0.3 – 0.8 nm by nanoseconds pulse fields.

2. Experimental

A series of Co/Pd multilayers were deposited on quartz substrates by dc magnetron sputtering at room temperature. The base pressure before deposition was 5.0 × 10⁻⁵ Pa and Ar gas pressure during deposition was 2.0 Pa. The film structure was Ta (2 nm)/Pd (2 nm)/[Co (δCo nm)/Pd (2 nm)]3. The Co layer thickness δCo was varied from 0.3 to 0.8 nm. The saturation magnetization Ms was measured by vibrating sample magnetometry (VSM). The effective uniaxial magnetic anisotropy constant Keff and the effective anisotropy field Hk eff, which includes demagnetization terms, were evaluated from anomalous Hall effect (AHE) curves using the generalized Sucksmith-Thompson (GST) method [6]. Keff per Co layer was varied from 2.3 × 10⁶ to 2.1 × 10⁶ erg/cc by controlling δCo from 0.3 to 0.8 nm. The multilayer films were patterned into circular dots with the diameter D = 240 – 500 nm by using electron beam lithography and Ar ion etching. Subsequently, a 9 nm thick Pt layer with Ta adhesion layers was deposited onto the dots and then patterned into cross shape electrodes for AHE measurements. Then, an insulating layer of 200 nm in thickness was formed by hardening hydrogen silsequioxane (HSQ) with e-beam. Finally, a Ag coil with the
inner diameter of 6 µm and width of 5 µm for pulse field generation was fabricated by the lift-off technique. Figure 1 shows the SEM image for the device without HSQ insulating layer for SEM observation. Magnetic pulse fields were generated by using an electric pulse generator equipped with a coaxial cable as a capacitor \([4, 5, 7]\). The field amplitude and duration were varied by adjusting charging voltage \(V_0\) and the cable length \(L\), respectively. Figure 2 shows a series of typical pulse profiles for \(V_0 = 400\) V and \(L = 0.1 - 1.0\) m. All the pulses show well rectangular shape with the rise time of less than 0.4 ns. The pulse duration increases from 1.6 to 10.0 ns with increasing \(L\) from 0.1 to 1.0 m. Ideally, the peak voltage in Fig. 2 of the pulse should be \(V_0 / 2 = 200\) V, but the experimentally obtained value is 80 % of the ideal one. This amplitude decay is probably due to electric leakage and/or partial reflection of the pulse due to impedance mismatching. Finite element method calculations revealed that the maximum pulse field reaches 4 kOe at the coil center for \(V_0 = 400\) V.

![Figure 1](image1.png) (a) SEM image for a Co/Pd dot with a cross electrode and a Ag coil. The inner diameter of the coil is 6 µm. (b) Magnified image of the dot.

![Figure 2](image2.png) Pulse waveforms for charging voltage \(V_0 = 400\) V and the coaxial cable length \(L = 0.1 - 1.0\) m.

### 3. Results and Discussion

Pulse field switching experiments were carried out in the presence of the dc bias field \(H_{dc}\). The dot magnetization was negatively saturated by the dc field of -5 kOe before application of each pulse field. The switching probability \(p\) for the dot with \(D = 400\) nm and \(\delta_{Co} = 0.6\) nm is plotted in Fig. 3 (a) as a function of \(H_{dc}\). Here \(p\) is obtained as the average of 10 times measurements. The pulse field duration and charging voltage were \(\tau_p = 10.0\) ns and \(V_0 = 0 - 300\) V, respectively. It was confirmed that the dot was always single-domain both before and after the pulse field application. Note that the switching probability curves shifts toward smaller \(H_{dc}\) with increasing \(V_0\). In Fig. 3 (b) the mean dc field required for switching \(H_{dc^{sw}}\) which gives \(p = 0.5\) in Fig. 3 (a) is plotted as a function of \(V_0\). The linear decrease in \(H_{dc^{sw}}\) for \(V_0 > 150\) V indicates that the magnetization switching occurs when the condition \(H_{dc^{sw}} \leq H_p + H_{dc} = \xi V_0 + H_{dc}\) is satisfied, where \(\xi\) is the proportional coefficient given by \(H_p / V_0\). For \(V_0 < 150\) V, however, \(H_{dc^{sw}}\) remains constant and equals to \(H_c = 0.94\) kOe measured by the quasistatic magnetometry. The reason for this result is explained elsewhere \([4]\). The dotted line in Fig. 3 (b) is the best fitted linear function for \(V_0 > 150\) V. The intersection with the vertical axis \((V_0 = 0\) V\) gives the switching field on the time scale of pulse duration \(\tau_p = 10\) ns.
In Fig. 4, the $H^\text{sw}$ for Co/Pd dots with (a) $\delta_{\text{Co}} = 0.3$ nm, $D = 240$ nm, (b) 0.6 nm, $D = 360$ nm, and (c) 0.8 nm $D = 240$ nm are plotted as a function of the pulse field duration $\tau_p$. The dc coercivity $H_u$ measured by the quasistatic magnetometry is also plotted at $\tau_p = 1$ s. Assuming the single energy barrier for the same magnetization switching over the whole time range examined in the present study, the median switching field $H^\text{sw}(\tau_p)$ can be expressed by the following Sharrock equation based on the classical Néel-Arrhenius law [8],

$$H^\text{sw}(\tau_p) = H_0^\text{sw} \left\{ 1 - \left[ k_B T / E_0 \cdot \ln\left( f_0 \tau_p / 0.693 \right) \right]^{1/\alpha} \right\}, \tag{1}$$

where $f_0$ is the attempt frequency of the order of $10^{10}$ Hz, $E_0$ is the energy barrier height, $H_0^\text{sw}$ is the switching field without thermal agitation, $k_B$ is the Boltzmann constant, $T$ is temperature, $\alpha$ is the constant depending on the magnetization reversal mode, respectively. Here we tentatively assumed $\alpha = 2$ as in the previous work [4]. The best fitted results using eq. (1) are shown as the solid lines in Figs. 4 (a) – (c). For all the $\delta_{\text{Co}}$, the obtained $H^\text{sw}$ was significantly smaller than the anisotropy field $2K_u^\text{eff}/M_s$. This discrepancy might be related with the intrinsic and extrinsic inhomogeneity in the film, and further study to reveal the origin of the nucleation site would be required for more detailed discussion. In Fig. 5, thus obtained energy barrier $E_0$ for all Co/Pd dots is plotted as a function of $K_u^\text{eff}$. Here, the effect of the dot diameter on $K_u^\text{eff}$ is negligibly small since the diameter is considerably larger than the film thickness. Although the data are widely scattered, $E_0$ tends to decrease with $K_u^\text{eff}$ and increase with $\delta_{\text{Co}}$. The median values $E_0$ for $\delta_{\text{Co}} = 0.3$, 0.6, and 0.8 nm are, respectively, 60, 150, and 180 $k_B T$, indicating that $E_0$ is roughly proportional to $\delta_{\text{Co}}$. Now, let us discuss this result in the following. As has been revealed in the previous papers [4, 5, 9], the magnetization reversal in a nanosized magnet proceeds via nucleation of a reversed embryo followed by its rapid expansion. Therefore the nucleation process determines the value of $E_0$. It is considered that a reversed embryo with minimum energy has the dimension of the domain wall width $l_w$. Therefore its energy is roughly estimated to be $\sigma_w l_w^2$, where $\sigma_w$ is the wall density, as suggested by Givord [10]. In the present study, however, since $\delta_{\text{Co}}$ is much smaller than $l_w$, the energy may be reduced to $\sigma_w l_w \delta_{\text{Co}}$. Thus, the $E_0$ may be proportional to $\delta_{\text{Co}}$ as,

$$E_0 \approx \sigma_w \cdot l_w \cdot \delta_{\text{Co}} \sim \sqrt{A K_u} \cdot \sqrt{A / K_u} \cdot \delta_{\text{Co}} \propto \delta_{\text{Co}}, \tag{2}$$

where $A$ denotes exchange stiffness. The above crude discussion roughly explains the $\delta_{\text{Co}}$ dependence of $E_0$ for Co/Pd dots but not for Co/Pt data [9], which exhibit the monotonic increase in $E_0$ with $K_u$. To solve the
contradictory results between Co/Pd and Co/Pt, further intensive studies, such as detailed, magnetic and structural analyses, are obviously required.

4. Summary

Magnetization switching experiments are carried out on nanosized Co/Pd multilayer dots with the Co layer thickness of \( \delta_{Co} = 0.3 \) – 0.8 nm by applying pulse fields with nanoseconds duration. Significant increase of the switching field in the nanoseconds regime is found for all Co/Pd dots prepared in this study. The analysis of the time dependence of the switching field based on the Néel-Arrhenius law has revealed that the energy barrier for magnetization switching monotonically increases with \( \delta_{Co} \). This result is roughly explained by assuming that the nucleation of a reversed embryo has the literal size of the domain wall width and the thickness of the Co layers. However, this crude model fails in explains the experiments of Co/Pt dots of while energy barrier are exclusively dominated by the magnetic anisotropy. This contradictory result between Co/Pd and Co/Pt data obviously needs further intensive studies.

Acknowledgments

This work was partially supported by the “Research and Development for Next-Generation Information Technology” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Grant-in-Aid for Scientific Research from MEXT, and the Storage Research Consortium in Japan.

5. Reference

[1] Hiebert W K, Stankiewicz A, and Freeman M R 1997 Phys. Rev. Lett. 79 1134
[2] Beaurepaire E, Merle J C, Daunois A, and Bigot J Y, 1996 Phys. Rev. Lett. 76, 4250
[3] Weisheit M, Bonfim M, Grechishkin R, Barthem V, Fähler S, and Givord D 2006 IEEE Trans. Magn. 42 3072
[4] Ito A, Kikuchi N, Okamoto S and Kitakami O 2008 IEEE Trans. Mag. 44 3446
[5] Kikuchi N, Okamoto S and Kitakami O 2009 J. Appl. Phys 105 07D506
[6] Okamoto S, Kikuchi N, Kitakami O, Miyazaki T, Shimada Y, Fukamichi K 2002 Phys. Rev. B 66 024413

[7] He L, Doyle W D, Varga L, Fujiwara H, and Flanders P J 1996 J. Magn. Magn. Mater. 155 6; Doyle W D, and He L, 1993 IEEE Trans. Magn. 29 3634

[8] Sharrock M P and Mckinney J T 1981 IEEE Trans. Mag. 17 3020

[9] Okamoto S, Kato T, Kikuchi N, Kitakami O, Tezuka N and Sugimoto S 2008 J. Appl. Phys. 103 07C501

[10] Givord D, Tenaud P, Viadieu T 1988 IEEE Trans. Magn. 24 1921