Switching Behaviors and its Dynamics of a Co/Pt Nanodot Under the Assistance of rf Fields

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We have studied the switching behavior of a single Co/Pt multilayer dot under the assistance of rf fields. The switching field monotonically decreases with increasing rf frequency up to a critical frequency. It is found that the reduction of the switching field is more significant than the theoretical prediction based on the single macrospin model. In addition, switching field distribution due to thermal fluctuation is also considerably suppressed. The simulation has revealed that these drastic changes are caused by excitation of large amplitude spin waves in the dot.

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Microwave assisted switching (MAS) of magnetization is a newly proposed switching technique as one of the promising candidates for future ultrahigh density magnetic recording technology [1–16]. In the MAS, the magnetization direction can be controlled through large amplitude magnetization precession excited by application of radio frequency (rf) magnetic fields. However, despite the prospective potential of MAS, which can reduce the switching field of a magnetic element as discussed in many simulations [2–4] and analytical calculations [5,6] based on the Landau- Lifshitz-Gilbert (LLG) equation, most of the previous experiments on MAS are limited to soft magnetic materials [7–10] due to the technical difficulty of generating an rf field large enough to realize MAS for a perpendicular nanomagnet. Recently, few MAS experiments on perpendicular magnetic films [11–14] and nanodots [15] have been reported, but the MAS effect is not so significant due to the modest rf field amplitude.

Very recently, we have successfully demonstrated that a significant reduction of the switching field is realized in a dot array of the Co/Pt multilayer (Co/Pt for short) by applying a large rf field but one much smaller than the effective anisotropy field [16]. As well as the significant reduction of the switching field, the broad switching field distribution of the dot array in the absence of the rf field is notably suppressed.

In this Letter, to elucidate the switching process under the assistance of large rf fields, we investigate the MAS on a single Co/Pt nanodot with perpendicular magnetic anisotropy. It is found that the reduction of switching field is much more significant than the theoretical prediction based on the single macrospin model, resulting from a qualitative change in switching process due to a large amplitude of the rf field.

The sample structure used in this Letter is almost identical to that in Refs. [15,16] except for the number of dots and the dot diameter. As shown in the scanning electron microscopy image of Fig. 1(a), the single Co/Pt dot with 120 nm in diameter was fabricated from a Co/Pt film with the layer structure of quartz sub./Pt(20)/$[Co(0.9)/Pt(0.5)]_{10}$ (parentheses in nm) using electron beam lithography and Ar ion etching. The effective anisotropy field of the Co/Pt film $H_{k,\mathrm{film}}$ including the demagnetizing field was evaluated to be 4.5 kOe by the generalized Sucksmith- Thompson method [17]. By taking the average demagnetizing field inside the dot [18] into account, the effective anisotropy field of the dot $H_{k,\mathrm{dot}}$ is estimated to be 7.6 kOe. The Pt buffer layer was patterned into a cross shape as an electrode for anomalous Hall effect (AHE) measurements [19]. The magnetic dot was fabricated at the center of the cross electrode. After covering the dot with an insulating layer, a Cu strip line with 2 μm in width was fabricated just above the dots. A large amplitude transverse rf field was generated by flowing a rf current fed from a signal generator with a microwave amplifier. To avoid Joule heating, the rf current was fed as a pulse train with a 2 μs pulse width/2 ms interval. The magnetization switching in the dot was detected by an AHE curve measurement under a vertical dc field H_{dc} from an

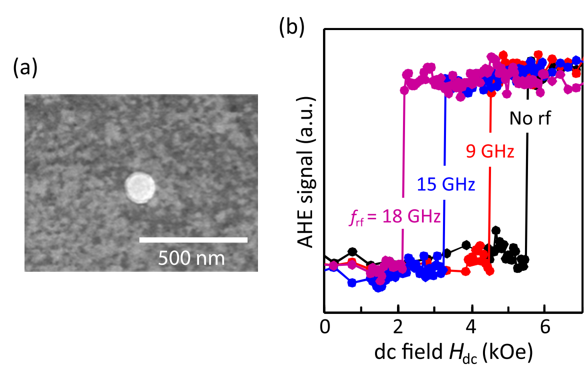

FIG. 1 (color online). (a) Scanning electron microscopy image and (b) AHE curves of a single dot with 120 nm in diameter fabricated from a $[Co0.9\ nm/Pt0.5\ nm]_{10}$ multilayer. AHE curves are measured with and without the assistance of a rf field of $h_{\mathrm{rf}} = 450$ Oe with $f_{\mathrm{rf}} = 9$, 15, and 18 GHz, respectively.

electromagnet. The value of h_{rf} is evaluated by electromagnetic calculation.

Figure 1(b) shows the AHE curves for the single Co/Pt dot with and without the assistance of rf fields with the amplitude $h_{\mathrm{rf}} = 450$ Oe ($= 5.9\%$ of $H_{k,\mathrm{dot}}$) and the frequency $f_{\mathrm{rf}} = 9$, 15, and 18 GHz. The switching field H_{sw} of this Co/Pt dot in the absence of the rf field is 5.5 kOe, which is obviously smaller than the $H_{k,\mathrm{dot}} = 7.6$ kOe. When the rf field is applied, the H_{sw} clearly decreases from 5.5 to 2.1 kOe with increasing the f_{rf}. All AHE curves observed in this study are perfect squares. Figure 2(a) shows the H_{sw} of the single Co/Pt dot as a function of the f_{rf} for various field amplitude h_{rf}. The H_{sw} initially remains almost unchanged below the frequency $f_{\mathrm{rf}} \approx 7$ GHz, then linearly decreases up to the critical frequency ${f_{\mathrm{rf}}}^c$, and finally goes back to the original value abruptly above the ${f_{\mathrm{rf}}}^c$. The ${f_{\mathrm{rf}}}^c$ monotonically increases with increasing the h_{rf}. For $h_{\mathrm{rf}} \geq 280$ Oe, it is found that two small and broad dips are observed at around $f_{\mathrm{rf}} = 10$ and 16 GHz. At present, it is hard to clarify the reason of these broad dips, but this phenomenon would be related to the change of the switching process depending on the f_{rf}. In fact, the f_{rf} at which the switching process begins to change, as will be mentioned later, corresponds to the boundary of these two broad dips.

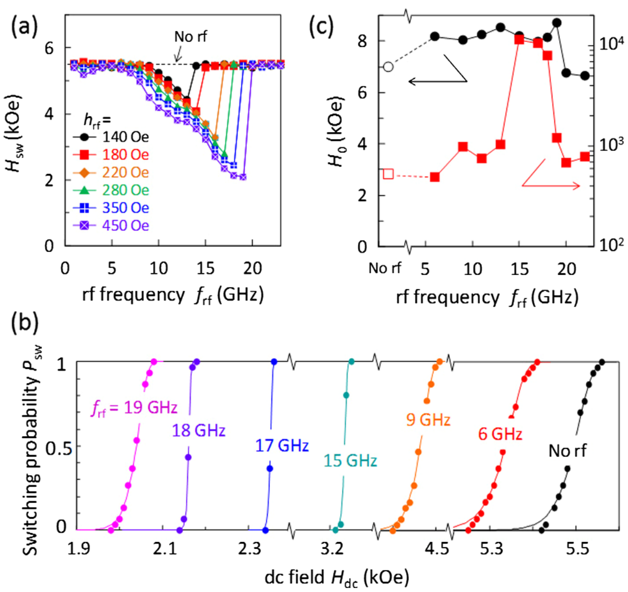

FIG. 2 (color online). Switching behaviors of a single dot of $[\mathrm{Co}0.9\ \mathrm{nm}/\mathrm{Pt}0.5\ \mathrm{nm}]_{10}$ multilayer under the assistance of a rf field. (a) Switching field H_{sw} for various rf fields h_{rf} ranging from 140 to 450 Oe as a function of the rf frequency f_{rf}. Dashed line indicates the H_{sw} in the absence of a rf field. (b) Switching probability P_{sw} with and without the assistance of rf fields of $h_{\mathrm{rf}} = 450$ Oe with various f_{rf} ranging from 6 to 19 GHz. Solid lines indicate the best fit results using Eq. (1) in the text. (c) H_0 (left ordinate) and $E_0/k_{\mathrm{B}}T$ (right ordinate) obtained from the best fit results shown in (b) as functions of f_{rf}. Open marks indicate the H_0 and $E_0/k_{\mathrm{B}}T$ in the absence of a rf field, respectively.

To analyze the switching process of the single Co/Pt dot under the assistance of the rf field, the switching probability P_{sw} was evaluated by 30 successive measurements of the switching field at each rf frequency f_{rf}. Thus obtained P_{sw} is plotted by solid marks in Fig. 2(b). In the absence of the rf field, the P_{sw} clearly exhibits the double exponential curve which can be fitted by the following Néel-Arrhenius law [20],

$$P_{\mathrm{sw}} = 1 - \exp[-t f_0 \exp(-E/K_{\mathrm{B}}T)], \quad (1)$$

where,

$$E = E_0(1 - H_{\mathrm{dc}}/H_0)^n. \quad (2)$$

Here, t is the data acquisition time of 5 s, f_0 is the attempt frequency of $1 \times 10^{10}\ \mathrm{s}^{-1}$, $k_{\mathrm{B}}T$ is the thermal energy composed of the Boltzmann constant k_{B} and ambient temperature $T = 300$ K, E_0 is the energy barrier at $H_{\mathrm{dc}} = 0$, H_0 is the intrinsic switching field without thermal agitation, and the exponential factor $n = 2$ for H_{dc} being in parallel with the magnetic easy axis. Under the assumption that the magnetization of the dot behaves coherently as a single macrospin, E_0 and H_0 should, respectively, equal to $K_{u,\mathrm{dot}}v$ and $H_{k,\mathrm{dot}}$, where $K_{u,\mathrm{dot}}$ is the effective magnetic anisotropy of the dot given by $M_s H_{k,\mathrm{dot}}/2$, M_s is the saturation magnetization of the dot, and v is the dot volume, respectively. The solid lines in Fig. 2(b) are the best fit results using Eq. (1) with two fitting parameters of H_0 and the normalized energy barrier $E_0/k_{\mathrm{B}}T$. Thus, we determined H_0 and $E_0/k_{\mathrm{B}}T$ in the absence of a rf field as 7.0 ± 0.1 kOe and 500 ± 50, respectively. Since the $K_{u,\mathrm{dot}}v/k_{\mathrm{B}}T$ of the dot is estimated to be 1.4×10^4, the activation energy for magnetization switching is only 4% of the $K_{u,\mathrm{dot}}v/k_{\mathrm{B}}T$. This very small activation energy is attributed to the fact that the switching is governed by nucleation of a reversed domain with the dimension of exchange length as discussed in the previous works [21,22]. Thus, the H_{sw} in this switching process is dominated by the magnetic properties of the nucleation site. In contrast, the behavior of P_{sw} drastically changes when the rf field $h_{\mathrm{rf}} = 450$ Oe is applied. In spite of the monotonic decrease in the H_{sw} with increasing the f_{rf} up to the critical frequency f_{rf^c} of 19 GHz as shown in Fig. 2(a), the P_{sw} in Fig. 2(b) exhibits a sudden increase of its slope in the frequency range of 15 GHz $\leq f_{\mathrm{rf}} \leq$ 18 GHz, indicating that the thermal fluctuation during the switching is considerably suppressed. These P_{sw} can be also reproduced very well by using Eq. (1), but the energy formula of Eq. (2) should be slightly modified in the presence of the rf field as follows. When the magnetization precesses with the frequency of f_{rf}, this processional motion is equivalent to the presence of $H_\omega = 2\pi f_{\mathrm{rf}}/\gamma$, where γ is the gyromagnetic ratio $\gamma = 1.944 \times 10^7\ \mathrm{Oe}^{-1}\,\mathrm{s}^{-1}$ for g factor $= 2.21$ of bulk Co. The H_ω is also directly derived through the coordinate transformation from the laboratory frame to the rotating frame [6]. Thus, H_{dc} in Eq. (2) should be replaced by the field $H^R = [(H_{\mathrm{dc}} + H_\omega)^2 + {h_{\mathrm{rf}}}^2]^{0.5}$, which is the effective field acting on the magnetization in the rotating frame [6]. Moreover, since the H^R acting on the magnetization deviates from the magnetic easy axis of Co/Pt in the rotating frame, $n = 3/2$ should be used instead of 2 [23,24]. The data acquisition time t in Eq. (1) is 1/1000 of that used in the absence of the rf field, because the rf excitation time is only 1/1000 of the total data acquisition time. From the best fitted curves in Fig. 2(b), H_0 and $E_0/k_B T$ are summarized in Fig. 2(c). The H_0 is almost constant to be 8 kOe irrespective of f_{fr} (except for the two data points in $f_{rf} \geq 20$ GHz). This value of H_0 agrees very well with the effective anisotropy field of the dot $H_{k,\mathrm{dot}}$. As for the energy barrier $E_0/k_B T$, it is drastically enhanced to $(1.1 \pm 0.15) \times 10^4$ in the same frequency range of $15 \leq f_{rf} \leq 18$ GHz where the P_{sw} becomes very steep. This value also coincides with the $K_{u,\mathrm{dot}} v/k_B T$ of the dot. Outside this frequency range, $f_{rf} < 15$ GHz and $f_{rf} > 18$ GHz, the $E_0/k_B T$ falls down by more than 1 order of magnitude, being almost the same value as that in the absence of the rf field. These behaviors of H_0 and $E_0/k_B T$ lead us to speculate that the magnetization switching process of the dot changes from the nucleation dominant mode toward the uniform switching mode in which the magnetization in the dot behaves as a macrospin under the assistance of rf fields.

This straightforward speculation is examined by computer simulations based on the Landau-Lifshitz- Gilbert (LLG) equation. The simulations were performed by the two different models. One is the single spin model in which all spins behave coherently as a single macrospin. In the other model, the dot with 120 nm in diameter was discretized into prisms of uniformly magnetized cells. Each prism has dimension of $5 \times 5 \times 14$ nm^3 which is smaller than the exchange length $l_{ex} \approx 16$ nm of our Co/Pt dot, which is roughly estimated from the domain wall width $l_{ex} = \pi(A/K_{u,\mathrm{dot}})^{0.5}$ using the exchange stiffness $A = 1 \times 10^{-6}$ erg/cm. Hereafter, this model is referred to as the finite cell model. All the calculation parameters, such as dot shape, magnetic properties, rf field, and so on, are identical to the above experiments. As the rf field in this experiment linearly oscillates around the Cu strip line, it is treated as a linearly polarized wave in the simulations. The Gilbert damping α is assumed to be 0.05 as experimentally evaluated for the Co/Pt film by vector network analyzer based ferromagnetic resonance [25].

Figure 3(a) shows the results for $h_{rf} = 450$ Oe calculated by the above two models. Surprisingly, both the reduction of H_{sw} and the critical frequency $f_{rf}{}^c$ predicted by the single spin model are much smaller than the experiments in Fig. 2(a). This fact indicates that the experimentally obtained MAS effect is much more profound than the prediction by the single spin model. In contrast to the single spin model, the finite cell model seems to reproduce the experimental results very well. Figure 3(b) shows the sequential snapshots of 2D images of magnetization direction inside the dot during magnetization switching at $f_{rf} =$ 20 GHz and $H_{dc} = 1.8$ kOe. From these images, the magnetization switching in the presence of the large rf field

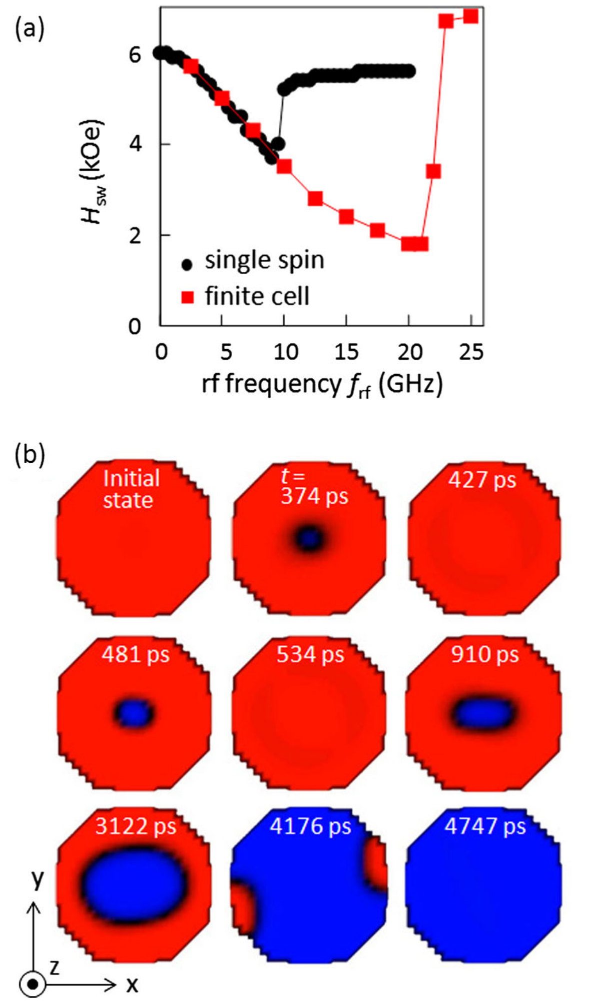

FIG. 3 (color online). Simulation results based on the LLG equation for the rf field of $h_{rf} = 450$ Oe. (a) Switching field H_{sw} calculated by single spin model (black circles) and finite cell model (red squares) as functions of rf frequency f_{rf}. (b) Snapshots of 2D magnetization images of the dot during switching calculated by the finite cell model at $f_{rf} = 20$ GHz and $H_{dc} = 1.8$ kOe. Red and blue colors correspond to the magnetization direction of down and up, respectively. The vertical dc field H_{dc} and linearly polarized transverse rf field is applied along z axis and y axis, respectively. In both single spin and finite cell model calculations, the H_{dc} is applied as a trapezoidal wave with rise and descent of 2 ns and constant region (upper base of trapezoid) of 5 ns, while the h_{rf} is applied continuously. t in (b) is the elapsed time after H_{dc} reaches to be constant.

proceeds in the following manner. At the very beginning, a concentric spin wave (SW) with the fixed end at the dot rim and the antinode at the dot center is excited. The positions of the fixed end and antinode correspond to the regions with the smallest and the largest local demagnetizing fields in the dot, respectively. Therefore, the nonuniform local demagnetizing field in the dot plays an important role to excite the concentric SW [18]. After several large amplitude SW oscillations at the dot center, a reversed domain forms and slowly expands. The energy barrier for this switching process normalized to the thermal energy $k_B T$ is evaluated as 7.4×10^3 from this simulation, which is close to the experimentally obtained value. Thus, we can conclude that the significant reduction of H_{sw} is caused by large amplitude SW excitation in the dot. Since the antinode diameter is larger than the exchange length l_{ex}, it is highly expected that the magnetic properties of nucleation sites, which dominate the switching behaviors in the absence of a rf field [21,22] and under the small amplitude of the rf field [16], do not affect the switching behavior of the SW driven mode. Moreover, in our previous report, we found that the broad distribution of the switching field in an array of Co/Pt dots in the absence of a rf field becomes quite narrow under the assistance of a large rf field [16]. This phenomenon is also easily understood as a consequence of the change from the nucleation dominant switching mode to the SW driven one.

In conclusion, we investigated the switching behavior of a single Co/Pt nanodot under the assistance of large rf fields. We found significant switching field reduction and suppression of thermal fluctuation. This reduction rate of the switching field was much more significant than the theoretical prediction by the single spin model. According to the computer simulations, these switching behaviors were caused by the large amplitude SW excitation in the dot. One may say that this SW driven switching process would not be applicable for a magnetic dot as small as the exchange length. As discussed in the present Letter, spatially nonuniform distribution of local demagnetizing fields in the dot plays an important role for the SW driven switching. Therefore, even though the dot size becomes smaller than the exchange length, various kinds of nonuniformity to excite the SW can be introduced such as a layered structure with hard and soft magnetic materials [26–29]. We believe that our finding gives a new strategy to control the magnetization switching for future ultrahigh density magnetic recording.

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