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Sensitive detection of irreversible switching in a single FePt nanosized dot

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Magnetization of an isolated single dot as small as 60 nm in diameter fabricated from a single crystal $L1_0$-FePt(001) film has been measured by detection of the anomalous Hall effect in the temperature range from 10 to 300 K. Over the whole temperature range, the dots with diameter ranging from 60 nm to 12 μm exhibit perfect rectangular magnetization loops with coercivity almost constant regardless of the very large difference in diameter. The activation energy has been evaluated to be about 4×10^{-19} J, equivalent to the domain-wall energy times the square of the domain-wall thickness, suggesting that the magnetization reversals are initiated by nucleation of reversed embryo with the dimension of the exchange length. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1580994]

Studies of magnetic nanoparticles are being intensified recently because a number of interesting findings have been reported from both physical and technological standpoints.[1–8] It is attractive to investigate magnetic behaviors of an isolated single particle since dispersion of magnetic parameters in assemblies of nanoparticles has often been a serious obstacle to clarify basic physics associated with size reduction. Recently the micro-superconducting quantum interference device (SQUID)[5,6] and Hall magnetometry[7,8] using a semiconductor heterostructure measured magnetization process of nanosized magnets. However, there remain some issues to be overcome, for example, the working temperature of the micro-SQUID is limited by the superconducting temperature of the SQUID element, and Hall magnetometry has sample restriction because of its complex fabrication process. In the present letter, we demonstrate anomalous Hall effect (AHE) measurements as another single particle measurement technique realizing a wide working temperature range with high sensitivity, and discuss the magnetic properties of single crystal FePt dots measured with this method.

In the experiment, disk-shaped samples with 60 nm–12 μm diameters patterned from well-characterized single crystal $L1_0$-FePt film.[9] The films of FePt with thickness of 10 nm were directly grown on MgO (100) substrate at the temperature of 973 K by dc magnetron sputtering. The film composition was confirmed to be equiatomic by energy-dispersive x-ray spectroscopy. The crystal structure was identified by reflection high-energy electron diffraction and x-ray diffraction. The FePt films are single crystals with perfect 001 orientation without any variants, and their chemical-order parameter S was evaluated to be 0.7. Since the magnetic easy axis of $L1_0$-FePt is parallel to the c axis, the 001 orientation gives a strong perpendicular magnetic anisotropy normal to the film plane. The first- and second-order magnetic anisotropy constants K_1 and K_2 of the films were determined to be $K_1=3.0\times10^6$ J/m^3, and $K_2=0.55\times10^6$ J/m^3 at 300 K by analyzing the normalized Hall voltage curves by the generalized Sucksmith–Thompson method.[10,11] The saturation magnetization M_s is 1100 kA/m at 300 K.

Resist mask layers on FePt with various disk sizes were formed by using electron-beam lithography. After etching FePt with Ar ions, the residual resist was removed. We checked magnetic and structural changes during the etching process with a 40 nm thick film and no notable changes were found even when the film was etched to thickness of 5 nm. Next, a 5 nm thick Pt layer was deposited after the fabrication of disks. Finally, the Pt layer was patterned into a cross-electrode shape by the aforementioned manner. Figure 1 shows the scanning electron microscopy (SEM) images of a 60 nm FePt disk covered with a cross-shaped electrode. The bright spot near the center indicates the disk.

Hall effect measurements were carried out in an external

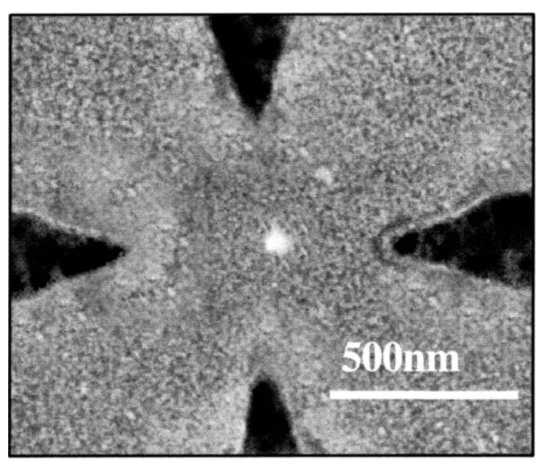

FIG. 1. SEM image of a 60 nm diameter FePt dot covered with a 5 nm thick Pt cross-shaped electrode for Hall effect measurements. The bright spot at the center of the photo corresponds to the FePt dot.

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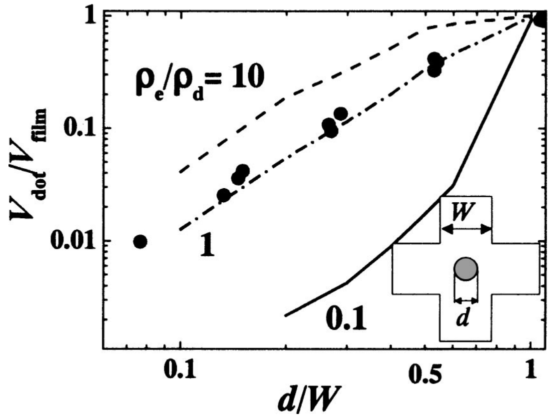

FIG. 2. Experimental (solid circles) and calculated (lines) anomalous Hall voltages as functions of dot diameter over electrode width. The inset is the scheme of the sample geometry.

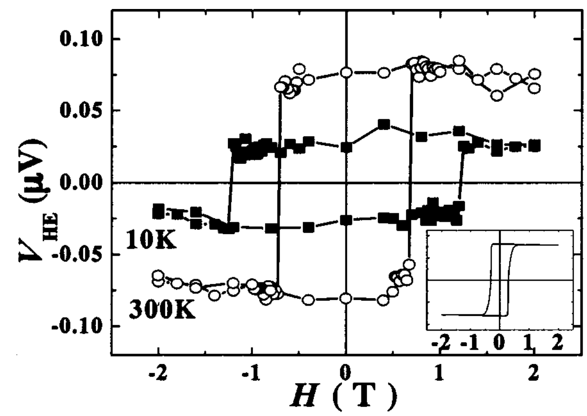

FIG. 3. Anomalous Hall voltage curves of a 60 nm diameter FePt dot measured at 10 and 300 K. The external field was applied along the direction normal to the film plane. Shown in the inset is the curve for the unpatterned FePt film at 300 K.

field with maximum of 9 T in the temperature range from 10 to 300 K. The current for Hall effect measurements was fixed at 10 μA. The measured Hall voltage V_{HE} in the sample geometry as shown Fig. 1 is given by

$$V_{HE} = V_{AHE}(\text{FePt}) + V_{NHE}(\text{FePt}) + V_{NHE}(\text{electrode}) + \Delta V_{BG}, \quad (1)$$

where V_{AHE}(FePt) is the anomalous Hall voltage from the FePt disk, V_{NHE}(FePt) and V_{NHE}(electrode), respectively, are the normal Hall voltages from the FePt disk and the electrode, and ΔV_{BG} is the dc background offset due to misalignment between the electrode and the disk. Since V_{NHE} is a linear function of the external field, it is easy to separate V_{AHE} that corresponds to vertical magnetization component of the FePt dot. We calculated V_{AHE} by using the finite-element method for various resistivity ratios of electrode (ρ_e) and dot material (ρ_d). In Fig. 2, the calculated anomalous Hall voltage V_{dot} for FePt dots normalized by the value V_{film} for the unpatterned film is plotted against the ratio d/w, where d is the dot diameter and w is the electrode width. With decreasing d/w and ρ_e/ρ_d, the detected Hall voltage steeply decreases. An electrode with higher resistivity seems to be suitable, but it enhances not only V_{AHE} but also ΔV_{BG}, and degrades the sensitivity. In the present work, we chose Pt as an electrode material because it has resistivity nearly equal to that of FePt. As seen in Fig. 2, V_{AHE} for $\rho_e/\rho_d = 1$ sustains enough signal level even when $d/w = 0.1$. Moreover, note that V_{AHE} is almost proportional to $(d/w)^2$ in very good agreement with experimental data.

Figure 3 shows the Hall voltage curves of the 60 nm $L1_0$-FePt(001) disk with vertical external field. In Fig. 3, V_{NHE} and ΔV_{BG} were already subtracted from the measured Hall voltage curve. The important point to note is that the $M-H$ curves of the dot with diameter much smaller than the electrode width are available with high accuracy. The shape of magnetization curves is always rectangular and the coercivity (H_c) is larger than that of the unpatterned FePt film shown in inset of Fig. 3, although it is still much smaller than the anisotropy field $H_k = 2K_1^{eff}/M_s = (2K_1 - 4\pi M_s^2)/M_s \sim 4.6$ T. Temperature dependences of H_c for various diameter dots are presented in Fig. 4. The magnetic anisotropies K_1 and K_2 measured for the unpatterned film are also plotted in Fig. 4. The value of H_c in all of the dots decreases very gradually with the increase of temperature although both K_1 and K_2 remain almost constant over the whole temperature range. Such a gradual decrease of H_c with temperature should be attributed to thermal agitation as will be discussed later. Figure 5 shows an irreversible switching field H_{sw} of the 60 nm diameter disk as a function of field direction θ_H with respect to the film normal. What is important is that H_{sw} follows $1/\cos\theta_H$ given by the dotted line in Fig. 5 rather than coherent rotation model[12] given by the dashed line, suggesting that the magnetization reversal proceeds in an incoherent manner.[13]

We analyzed the temperature dependence of H_c in Fig. 4 by assuming an energy barrier function $E(T) = E_0(T)[1 - H/H_c^0(T)]^2$, where E_0 is the energy barrier in the absence of external field H and H_c^0 is coercivity without thermal agitation. Since H_c^0 is proportional to H_k which remains almost constant over the whole temperature range (Fig. 4), H_c^0 is assumed to be independent of T. By best fitting the experimental data using with the Néel–Arrhenius law and assuming time of coercivity measurements to be 10^3 s, we obtain

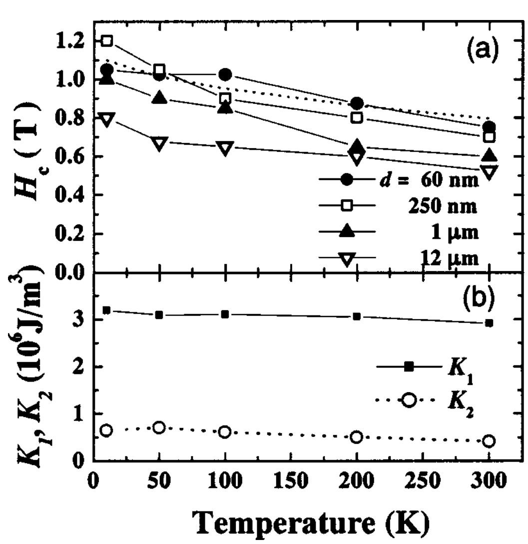

FIG. 4. Temperature dependences of (a) coercive field H_c for FePt dots with various diameters, and that of (b) magnetic anisotropy constants K_1 and K_2. The dotted line in (a) stands for the best-fitting curve based on the Néel–Arrhenius law.

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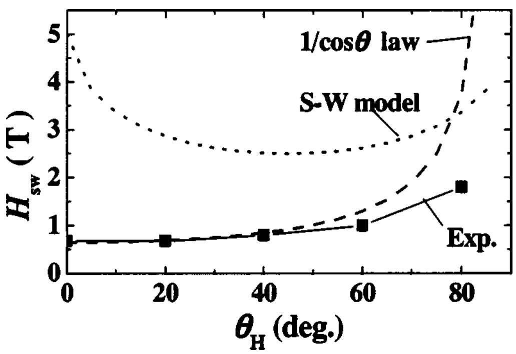

FIG. 5. Irreversible switching field H_{sw} (solid squares) of a 60 nm diameter FePt dot at 300 K as a function of field direction θ_H. The dotted line indicates H_{sw} predicted by the coherent rotation model, and the dashed line gives a function of 1/cos θ_H.

$E_0 \sim 4\times10^{-19}$ J and $H_c^0 \sim 1.2$ T for the FePt dot, as indicated by the dotted line in Fig. 4(a). It should be noted that E_0 is two orders of magnitude smaller than $K_1 v_{dot}$ (v_{dot}: dot volume)$=8\times10^{-17}$ J even for the 60 nm dot. This small E_0 is almost equal to the energy barrier $\gamma\delta^2$ to be overcome for formation of a small reversed nucleus where δ is the domain-wall thickness $\delta\approx\pi\sqrt{A/K_1}$ and the domain-wall energy density $\gamma\approx4\sqrt{AK_1}$. Substitution of $A=1\times10^{-11}$ J/m and $K_1=3\times10^6$ J/m^3 gives $\gamma\delta^2\approx7\times10^{-19}$ J, comparable to the experimentally obtained E_0. The idea that the magnetization reversal process is initiated by a small reversed nucleus with the dimension of the exchange length δ was originally proposed by Givord *et al.*[14] and they semiquantitatively explained various experimental results on permanent magnets. In the present study, the model is explicitly supported and it turned out that it works for a very wide range of dimensions when a magnet has a high anisotropy field.

In summary, we fabricated single crystal L1$_0$-FePt(001) disks with 60 nm–12 μm in diameter and 10 nm in height by patterning a well-characterized epitaxial film. We demonstrated that the AHE detection with a cross electrode much larger than the disks is a powerful means to measure magnetic properties of an isolated single disks, such as coercivity, its temperature dependence, and angular dependence of irreversible switching in the temperature range from 10 to 300 K. All of the dots with a diameter down to 60 nm diameter dot showed smaller coercivity than anisotropy field, a smaller energy barrier than $K_1 v_{dot}$, and an asymmetric angular dependence of irreversible switching fields. From the analysis of temperature dependence of coercivity, the energy barrier was estimated to be 4×10^{-19} J, equivalent to the energy barrier for formation of a reversed nucleus with the dimension of the exchange length.

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