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The anisotropy field of FePt $L1_0$ nanoparticles controlled by very thin Pt layer

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Abstract

We have prepared epitaxial FePt $L1_0$ (001) nanoparticles covered with Pt [d_{Pt} nm]/Ag[(4 − d_{Pt}) nm] overlayers. The particles are oblate spheroids approximately 10 nm in diameter and 2 nm in height. The anisotropy field H_k at 0 K, which is evaluated from the temperature dependences of coercivity H_c, decreases from 90 to 60 kOe on increasing the Pt thickness from $d_{Pt} = 0$ to 1.5 nm, while the energy barrier at zero field remains unchanged. The significant reduction of H_k due to the presence of the adjacent Pt layer can be attributed to an enhanced magnetic moment caused by the ferromagnetic polarization of Pt atoms at the interface. This finding suggests an effective method of controlling the switching field of FePt $L1_0$ nanoparticles.

Magnetic recording technology has been increasing the recording density at a phenomenal rate, and the magnetic particles that constitute recording media are becoming smaller in order to retain a high signal to noise ratio. However, a further increase in recording density would give rise to thermal instability of recorded bits because of the very small particle size. Various high magnetic anisotropy materials have been investigated to suppress such thermal instability. The equiatomic FePt $L1_0$ ordered alloy is one of the most promising candidates because its magnetic anisotropy constant K_u of 5–8 × 10^7 erg cm^{-3} [1, 2] is an order of magnitude higher than that of the currently used Co–Cr based alloys [3]. Numerous studies on granular films or isolated particle arrays of FePt $L1_0$ have been reported so far [4–7]. However, its high anisotropy field H_k (∼100 kOe) makes it difficult to realize saturation recording. Heat-assisted magnetic recording may be an effective method to avoid this problem [8], although there remain a lot of technological obstacles for practical application [9].

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In our previous work [10] we have reported that the magnetization reversals and thermal stability of FePt $L1_0$ (001) epitaxial nanoparticles are perfectly described by the classical Stoner–Wohlfarth (SW) model [11] when the particle diameter D is smaller than 20 nm. It was also found that the effective anisotropy field H_k can be reduced by the presence of adjacent Pt atoms without any reduction of K_u, probably due to an enhanced magnetic moment caused by the polarization of Pt.

In this paper, we show that the switching field of FePt $L1_0$ (001) nanoparticles can be controlled only by varying the Pt overlayer thickness while keeping the zero field energy barrier unchanged.

Two dimensional assemblies of FePt $L1_0$ (001) nanoparticles were grown on MgO(100) single crystal substrates at 973 K by dc magnetron sputtering. The detailed fabrication procedure and sample characterization are described elsewhere [10]. The nominal deposition thickness of FePt was fixed at 1 nm, and the particle shape is found to be an oblate spheroid with 10 nm in average diameter and 2 nm in height. The FePt particles are well isolated from each other and fully ordered with no crystal domain variants. Deposition of Pt and Ag was carried out after cooling the sample down to the room temperature in order to avoid interdiffusion at the interface and to obtain a uniform continuous overlayer. The Pt and Ag overlayers were sequentially deposited onto the FePt particles. Fixing the total thickness at 4 nm, the Pt thickness d_{Pt} was varied from 0 to 2 nm. These very thin but good conducting overlayers also work as electrodes for anomalous Hall effect (AHE) measurements. Highly sensitive AHE measurements enable us to accurately detect the vertical magnetization component of FePt nanoparticles [10, 12]. The measurements were carried out with a bias current of 10 μA in the temperature range of 10–300 K.

Figures 1(a) and (b) show the vertical magnetization curves of FePt $L1_0$ (001) nanoparticles ($d_{Pt} = 0$ and 2 nm) at $T = 10$ and 300 K, respectively. The appreciable decrease in coercivity H_c with T is mainly due to thermal fluctuation of magnetic moments. Note that H_c for $d_{Pt} = 2$ nm is much smaller than that for $d_{Pt} = 0$ nm even at 10 K, indicating that the presence of the adjacent Pt layer considerably decreases the switching field.

Figure 2 shows the temperature dependences of H_c for various Pt layer thickness d_{Pt}. As the thickness d_{Pt} increases, H_c decreases, and its temperature dependence becomes more gradual. In order to clarify the effect of Pt on the magnetization reversals of FePt nanoparticles, we evaluated the anisotropy field H_k and the activation energy E_b of FePt nanoparticles by analysing the temperature dependences of H_c shown in figure 2. For aligned non-interacting Stoner–Wohlfarth (SW) magnets, El-Hilo *et al* [13] formulated the sweep rate dependence of H_c. By taking the easy axis dispersion into account, the formula is modified as [10]

$$H_c(T) = \eta H_k(T) \left\{ 1 - \sqrt{\frac{k_B T}{E_b(T)} \ln(t^{\mathrm{eff}} f_0)} \right\}, \tag{1}$$

where k_B is the Boltzmann constant, f_0 is the attempt frequency, and $E_b(T)$ is the activation energy for the magnetization reversal at zero field, respectively. η is the coefficient determined by dispersion of the easy axis. Based on the SW model [11], $\eta = 0.82$ for the present FePt particles with c-axis dispersion of $\Delta\theta_{50} = 6^\circ$ [10]. $t^{\mathrm{eff}} = t_m + t_R$ is the effective time factor, where t_m is the data acquisition time at fixed field and $t_R = (H_k k_B T / E_b R)$ arises from the field sweeping effect with sweep rate R. In our experiments, t_m and R were fixed at 3 s and 61 Oe s^{-1}, respectively. The activation energy E_b at zero field can be expressed as

$$E_b(T) = K_u^{\mathrm{eff}}(T) V_m, \tag{2}$$

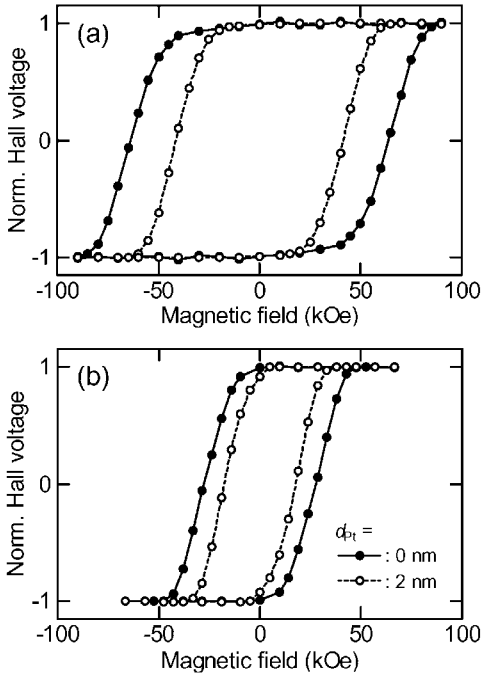

Figure 1. Normalized Hall voltage curves at (a) $T = 10$ K and (b) 300 K for the FePt nanoparticles covered with Pt [d_{Pt} nm]/Ag [$(4 - d_{Pt})$ nm] overlayers.

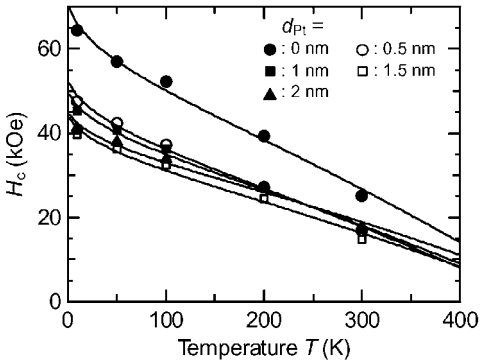

Figure 2. The coercivity H_c of the FePt nanoparticles covered with Pt [d_{Pt} nm]/Ag[$(4 - d_{Pt})$ nm] overlayers as a function of temperature. Solid curves indicate the best fittings based on the thermal fluctuation analysis.

where V_m is the mean particle volume of FePt and $K_u^{eff}(T)$ is the effective uniaxial anisotropy energy including the demagnetization energy expressed as

$$K_u^{eff}(T) = K_u(T) - 2\pi N_d M_s(T)^2, \tag{3}$$

where N_d is the demagnetization factor of each particle. The attempt frequency f_0 in equation (1) can be expressed as [10, 14]

$$f_0(T) = \sqrt{\frac{E_b(T)}{\pi k_B T}}\gamma_0 H_k(T), \tag{4}$$

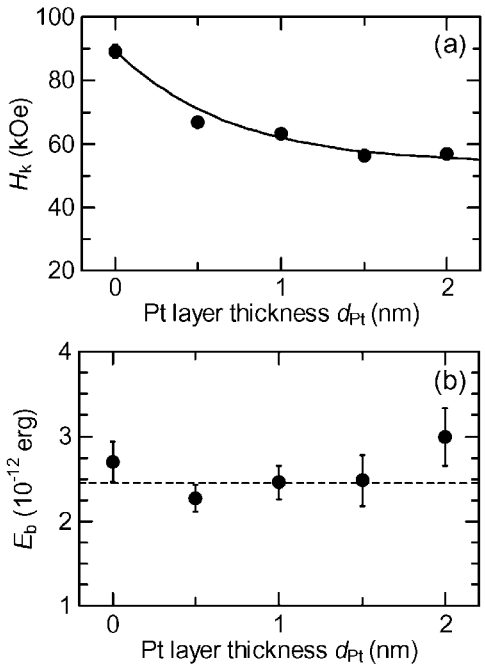

Figure 3. (a) The anisotropy field H_k and (b) energy barrier E_b of the FePt nanoparticles covered with Pt [d_{Pt} nm]/Ag [$(4 - d_{Pt})$ nm] overlayers as functions of Pt interlayer thickness d_{Pt}. The solid curve in (a) is the best fitting by equation (7), and the broken line in (b) is a guide to the eye.

where γ_0 is the gyromagnetic constant. Since the temperature dependences of K_u and M_s of FePt $L1_0$ have been determined experimentally [2], we can numerically fit the experimental $H_c(T)$ by equations (1)–(4) using only two adjustable parameters: $H_k(0\ \mathrm{K})$ and the energy barrier $E_b(0\ \mathrm{K})$. The best fittings are shown in figure 2 as indicated by the solid curves. All the data in figure 2 can be reproduced very well by the present analysis. $H_k(0\ \mathrm{K})$ and $E_b(0\ \mathrm{K})$ are plotted in figures 3(a) and (b) as functions of d_{Pt}. Note that $H_k(0\ \mathrm{K})$ reaches 90 kOe for $d_{Pt} = 0$ nm, which is almost equal to that of fully ordered FePt $L1_0$ [1, 2], and it rapidly and then gradually decreases with increasing d_{Pt}. In spite of the notable change in $H_k(0\ \mathrm{K})$, $E_b(0\ \mathrm{K})$ is almost independent of d_{Pt} within experimental error, indicating that K_u^{eff} remains unchanged with d_{Pt}. Using the demagnetization factor for an oblate spheroid with 10 nm in diameter and 2 nm in height, the intrinsic K_u in equation (3) is estimated to be 6×10^7 erg cm^{-3} at $T = 0$ K, which is also equivalent to that of the fully ordered FePt $L1_0$ [1, 2]. From figures 3(a) and (b), it is evident that the H_k of FePt nanoparticles can be controlled by varying the adjacent Pt layer thickness without any degradation of E_b. Here, we point out three possible origins for the reduction of H_k. First, the reduction comes from compositional deviation from equiatomic FePt due to interfacial diffusion between FePt and Pt. Second, the magnetic anisotropy includes the interface anisotropy at Pt/FePt. Third, enhanced magnetization due to ferromagnetic Pt polarization decreases H_k. The first two possibilities are easily eliminated, because the reduction of H_k caused by interfacial diffusion and/or interface anisotropy must bring about appreciable reduction of K_u. This is contrary to the fact that the energy barrier $E_b(=K_u^{eff} V_m)$ is invariant of d_{Pt}, as can be seen in figure 3(b). The third possibility is the most likely in this case. It is well known that Pt atoms adjacent to a ferromagnet are ferromagnetically polarized due to the proximity effect [15]. Thus, this gives

a picture of a FePt particle surrounded by a ferromagnetically polarized Pt layer, where Pt atoms near the interface have certain induced magnetic moments, resulting in enhancement of the effective magnetization. Let us estimate the induced Pt moments under the assumption of a uniform Pt layer over the FePt particles. Assuming an exponential decay of Pt polarization from the interface, the magnetization m^{Pt} of the polarized Pt can be expressed as

$$m^{\mathrm{Pt}} = \int_0^{d_{\mathrm{Pt}}} S(x) M_0 \exp(-x/\lambda)\,\mathrm{d}x, \tag{5}$$

where $S(x)$ is the surface area of a half oblate spheroid $10 + 2x$ nm in diameter and $2 + x$ nm in height, x is the distance from the Pt/FePt interface, M_0 is the induced Pt magnetization at $x = 0$, and λ is the characteristic decay length of Pt polarization. The anisotropy field H_{k} for a FePt nanoparticle covered with a polarized Pt shell can be obtained from the following relation:

$$-(M_{\mathrm{s}} V_{\mathrm{m}} + m^{\mathrm{Pt}}) H_{\mathrm{k}} \sin\theta = -\left.\frac{\partial E_{\mathrm{a}}}{\partial\theta}\right|_{\theta\approx 0}, \tag{6}$$

where $M_{\mathrm{s}} = 1250$ emu cm^{-3} is the magnetization of FePt at 0 K [2], and θ is the angle of magnetization from the easy axis. When we ignore the anisotropy energy of polarized Pt, the total anisotropy energy E_{a} is equal to $K_{\mathrm{u}}^{\mathrm{eff}} V_{\mathrm{m}} \sin^2\theta$. Thus, H_{k} can be expressed as

$$H_{\mathrm{k}} = \frac{2K_{\mathrm{u}}^{\mathrm{eff}}}{M_{\mathrm{s}} + (m^{\mathrm{Pt}}/V_{\mathrm{m}})}. \tag{7}$$

By adjusting M_0 and λ in equation (5), the variation of H_{k} with d_{Pt} can be reproduced very well, as is indicated by the solid curve in figure 3(a). The values of M_0 and λ thus obtained are 500 emu cm^{-3} and 0.44 nm, respectively. Using these two values, the induced Pt moment of the first Pt layer on the FePt surface is estimated to be 0.65 μ_{B}/atom, and the moment decays to zero around at 10 monolayers ($\sim$2 nm) from the interface. A recent x-ray magnetic circular dichroism (XMCD) study on the Pt layer on Co has confirmed almost the same values: the magnetic moment of the first Pt layer is 0.7 μ_{B}/atom and the decay length is 0.41 nm [16]. In spite of this good agreement with the XMCD result, it should be mentioned here that the above induced Pt moment might be somewhat overestimated, because the magnetic moments of the Fe atoms in FePt may also be enhanced at the interface due to the change of hybridization of Pt 5d and Fe 3d bands. In addition, the weak effect of interparticle exchange interaction between the neighbouring FePt particles through the ferromagnetically polarized Pt atoms observed in [10] is also ignored. A quantitative correlation with these two small effects is very difficult, and it is beyond the scope of this study. Therefore, we conclude here that the significant reduction of H_{k} should be mainly attributed to the enhancement of the effective magnetization due to the ferromagnetic polarization of Pt atoms at the Pt/FePt interface.

In summary, we have investigated the influence of a Pt layer on the magnetic behaviour of FePt nanoparticles and found that the coercivity significantly decreased due to presence of a very thin ($\sim$0.5 nm) Pt layer. A thermal fluctuation analysis has revealed that the anisotropy field decays exponentially from 90 to 60 kOe on increasing the Pt layer thickness, while the zero field energy barrier remains unchanged. The reduction of the anisotropy field due to Pt is attributed to the larger effective magnetization enhanced by the ferromagnetic polarization of Pt atoms at the Pt/FePt interface. The present results suggest that we can control the effective anisotropy field of FePt $L1_0$ nanoparticles simply by adjusting the Pt layer thickness without a decrease in the zero field energy barrier.

Acknowledgments

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