Superparamagnetic Behavior of Pt/CoFe/Pt Nanowires With Decreasing Wire Width

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We present experimental demonstration that the thermal unstability grows with reducing the width of Pt/CoFe/Pt nanowires on the way to the superparamagnetic transition. The magnetic hysteresis loops measured at room temperature using a magneto-optical Kerr effect system reveal that the coercive field decreases drastically when the nanowire width is reduced smaller than 160 nm. To understand the origin of the coercive field reduction, the coercive field is measured with varying the sweep rate of the external magnetic field and then, analyzed with a thermally-activated magnetization reversal model. It is revealed that the reduction of the coercive field is mainly ascribed to the decrement of the thermal stability parameter, which in turn induces the abrupt reduction of the retention time down to a few seconds.

***Index Terms*—Nanowire, superparamagnetism, thermal activation.**

I. Introduction

FOR future advance in high-density magnetic recording and nonvolatile memory, it is essential to confirm superparamagnetic limit of the ferromagnetic nano-structures [1]–[3]. The magnetic storage systems can be modeled by two potential wells separated by an energy barrier. The process of writing a data bit corresponds to forcing the system to be one of the two possible states. To accomplish the data storage technology, it is required that the thermally activated reversal between the potential wells is improbable over very long time. Such reversal is called thermally activated magnetic relaxation (or magnetic aftereffect). For the case of the extremely small energy barrier, the superparamagnetic phase appears. Superparamagnetic particles tend to randomly orient their magnetic moments due to thermal fluctuation. Néel [4] and Brown [5] explained that the thermal stability of magnetization in fine magnetic particles is given by the thermal stability parameter, i.e., the ratio of the anisotropy energy KV with the thermal energy K_BT, where K is the anisotropy constant, V is the volume of magnetic segments, K_B is the Boltzmann constant, and T is the temperature. For small thermal stability parameter, the particles become thermally unstable and superparamagnetism appears. The superparamagnetism has frequently appeared in ferromagnetic nanoparticles with decreasing the particle size.

Recently, the ferromagnetic nanowire structures have extensively studied due to the possible applications such as the racetrack memory and magnetic logic devices [6], [7]. To increase the storage density, the width of the nanowires is reduced down to 100–500 nm. The reduction of the nanowire width provides the reduction of the volumetric magnetic energy, which consequently evokes the superparamagnetic behavior. The present study is motivated to examine the superparamagnetic limit of the nanowires, based on Pt/CoFe/Pt nanowires with decreasing the nanowire width from 3 μm to 70 nm.

II. Experiments

The magnetic thin films with perpendicular magnetic anisotropy have three contrasting domain evolution phases: the nucleation, the stripe-growth and the wall-motion phases [8], [9]. Among these evolution phases, the wall-motion phase might be suitable for the racetrack memory, since the racetrack memory is operated by manipulating the domain wall motion. The sandwiched Pt/0.3-nm CoFe/Pt film structure is, therefore, chosen, since it is well-known typical structure showing wall-motion phase. Nanowires with various widths ranging from 3 μm to 70 nm were patterned by electron-beam lithography onto a 5.0-nm Ta/2.5-nm Pt/0.3-nm $Co_{90}Fe_{10}$/1.0-nm Pt films. The magnetic hysteresis of the nanowires was then measured by means of the magneto-optical Kerr effect. The laser spot of 440 nm in diameter with 50 μW was focused on the nanowires to monitor the magneto-optical Kerr effect signal with sweeping the magnetic field along the out-of-plane direction. The 658-nm laser with an objective lens having N.A. $= 0.9$ was used In the measurement system,. The spatial resolution with this setup is about 440 nm based on Abbe criterion, and we confirmed it experimentally [10]. To analyze the super-paramagnetic behavior, the measurement was done with varying the sweeping rate from 1 to 1300 Oe/s. The coercive field H_C was obtained as a function of the sweep rate, which is then analyzed by a thermal-activated reversal model to determine the width dependence of the thermal stability parameter.

III. Results and Discussion

The widths of nanowires are first examined using a secondary electron microscope. The top-view images for the series of nanowires are shown in Fig. 1. The large square pattern is reference for measuring the properties of the film. The inset (a) shows that the wall-motion phase is maintained even after patterning process. The inset (b) is the high-magnification image of the 100-nm-wide nanowire to visualize the edge

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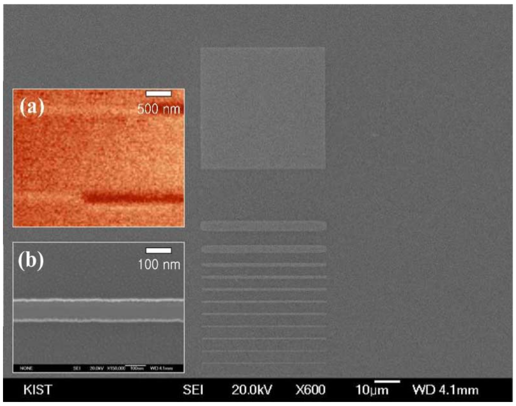

Fig. 1. SEM image for the series of nanowires with the width from 70 nm to 3 μm. The inset (a) is a MFM image for the nanowires. The inset (b) is a enlarged SEM image of 100 nm width wire.

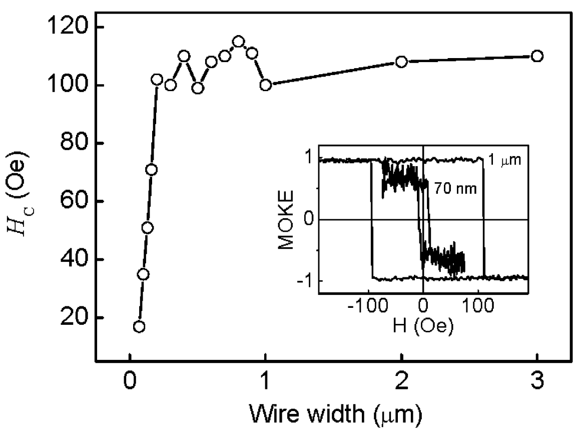

Fig. 2. Coercivities for Pt/CoFe/Pt nanowires with various widths measured at room temperature by MOKE in magnetic fields applied perpendicular to the wire axis. Superparamagnetic influences become apparent in the narrowest wires below 160 nm. The inset is representative magnetic hysteresis loops for 70 nm and 1 μm.

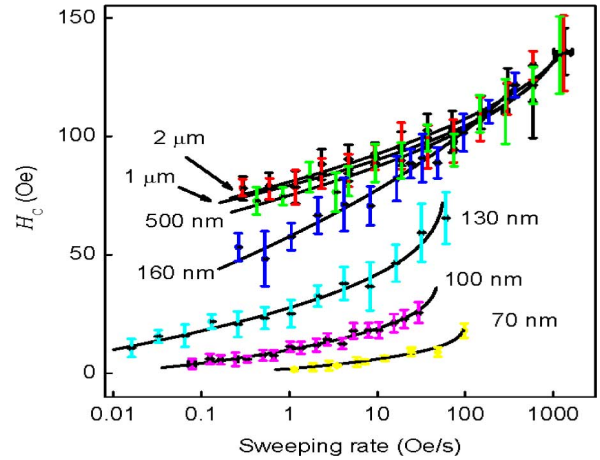

Fig. 3. Variation of H_C as a function of dH/dt for the nanowires width various widths. Continuous line is a fit using (4). The trend curves deviate below 160 nm abruptly.

roughness profile. The edge roughness is improved by about 50% by two step ion-milling process with 15 and 75 degrees of the incident ion beam. The edge roughness is found to be the one of the crucial factors in determining the coercive field in nanostructures [11]. All nanowires are patterned from a single film at the same time to avoid any other effects.

In general, superparamagnetism is indicated by vanishing of the coercive field in the hysteresis loop measurement. We, therefore, measure magnetic hysteresis loops of nanowires at the ambient temperature. It is clearly seen from Fig. 2 that the coercive field is drastically decreased with decreasing the width of the nanowires down to 160 nm. It decreases from ~100 Oe to 17 Oe, with decreasing the width from 160 to 70 nm. These results indicate how the thermal unstability grows with reducing the wire width on the way to the superparamagnetic transition. The inset shows the typical magneto-optical Kerr effect hysteresis loops for 70-nm- and 1-μm-wide nanowires for the sweep rate 100 Oe/s, respectively.

The effect of the demagnetization field is first considered with decreasing the wire width. However, the demagnetizing field decreases with decreasing the wire width, and, thus, the coercive field should be increased with reducing the demagnetizing field. Note that $H_c = 2$ K/Ms-H_d. Therefore, the change in demagnetization field is inconsistent with the observed coercive field change.

To understand the origin of the drastic reduction of the coercive field, we examine the magnetic aftereffect [2], [12]. For this purpose, the sweep-rate-dependent coercive field measurement is carried out. Fig. 3 shows the coercive field with respect to the sweeping rate for several nanowires with different widths as denoted in the figure. It is clearly seen from the figure that the coercive field exhibits almost the same dependence on the sweeping rate for wide nanowires, but the dependence varies significantly for wires narrower than 160 nm. Several models based on the conventional Néel-Brown formula are examined to explain these abnormal behaviors; the droplet model [12], the linear model [13], and the forward-backward hopping model [10]. However, all these models are inconsistent with our experimental data. Finally, we find that they are well fitted by an equation of the energy barrier, obtained by Taylor expansion around $H = 0$ up to the second order terms. The energy barrier equation can be converted to the equation proposed in [1]. However, since it is not possible to experimentally resolve all the magnetic parameters introduced in [1], we simply describe the energy barrier equation in the concept of the Taylor expansion without loss of generality as

$$\Delta E = a + bH + cH^2 \tag{1}$$

where a, b, and c are the Taylor coefficients. Note that a equals *KV*. It is well-known that the thermal relaxation of magnetic nanoparticles is expressed in terms of the Arrhenius formula

$$\tau = \tau_0 \exp\left[\frac{\Delta E}{k_B T}\right] \tag{2}$$

where τ is the reversal time and τ_0 is a characteristic time constant (or inverse of the attempt frequency). The characteristic time τ_0 has been first introduced by Néel and Brown in the case of ferromagnetic systems [4], [5], and known to have the magnitude in the range 1 ps–1 ns. In our analysis, τ_0 is chosen to be a constant, 1 ns.

Sweeping the external magnetic field from positive to negative, the magnetization is reversed at a critical field, i.e., the coercive field. However, due to the time required for the magnetization reversal, the apparent coercive field varies with respect to the sweeping rate of the external magnetic field. The change of the magnetization in comparison with the change of the external magnetic field is then given by an integral equation as [12]

$$\int_{M_{\mathrm{S}}}^{M} \frac{dM}{M+M_{\mathrm{S}}} = \int_{0}^{H} -\frac{dH}{\tau \frac{dH}{dt}} \tag{3}$$

where dH/dt is the sweeping rate of the external field. In (3), the magnetization is initially saturated to $+M_{\mathrm{S}}$ and then, the external field is applied in the opposite direction. By replacing τ by (1) and (2), the integration is readily carried out to obtain

$$\frac{M(H)}{M_S} = 2\exp\left\{-\frac{\sqrt{\pi k_{\mathrm{B}}T}}{2\sqrt{c}\tau_0 \frac{dH}{dt}} \exp\left(\frac{b^2-4ac}{4ck_{\mathrm{B}}T}\right) \times \left[\mathrm{erf}\left(\frac{b+2cH}{2\sqrt{ck_{\mathrm{B}}T}}\right) - \mathrm{erf}\left(\frac{b}{2\sqrt{ck_{\mathrm{B}}T}}\right)\right]\right\} - 1 \tag{4}$$

where $\mathrm{erf}()$ is the error function. From the definition of the coercive field, i.e., $M(H_C)=0$, one can obtain the relation between the sweeping rate and the coercive field as

$$\frac{dH}{dt} = \frac{\sqrt{\pi k_{\mathrm{B}}T/c}}{2\log 2\tau_0} \exp\left(\frac{b^2-4ac}{4ck_{\mathrm{B}}T}\right) \times \left[\mathrm{erf}\left(\frac{b+2cH_C}{2\sqrt{ck_{\mathrm{B}}T}}\right) - \mathrm{erf}\left(\frac{b}{2\sqrt{ck_{\mathrm{B}}T}}\right)\right]. \tag{5}$$

The solid lines in Fig. 3 show the best fit with using (5). The excellent conformity verifies the validity of (5). From the least square fit, the thermal stability constant $KV/k_{\mathrm{B}}T$ is determined. The results are summarized in Fig. 4. The thermal stability constant is turned out to be sharply decreased from 55 to 22 with decreasing the nanowire width. The retention time, therefore, drastically changes from ten years to a few seconds with decreasing the nanowire width. Based on (2), $\Delta E \geq 50K_BT$ corresponds to the stability criterion for an acceptably long data retention time, taken nominally as ten years. On the other hand, it is often considered that the threshold between superparamagnetism and ferromagnetism is to be about $\Delta E \sim 25K_BT$, at zero external fields. We thus conclude that the nanowires narrower than 100 nm are in the vicinity of the superparamagnetic phase, and the origin of the drastic decrement of the coercive field is the transitional behavior from the ferromagnetic and superparamagnetic phases with decreasing the nanowire width.

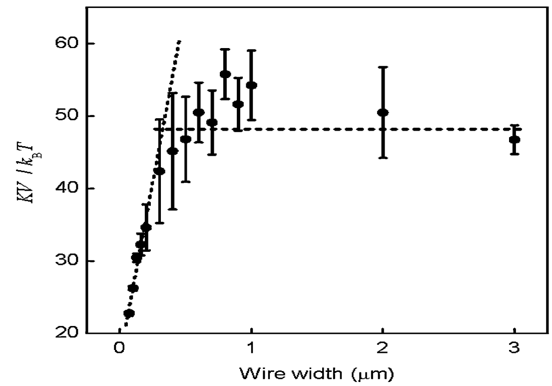

Fig. 4. Thermal stability parameter with respect to the wire width from the best fit. The thermal stability constant is sharply decreased from 55 to 22 below 160 nm.

IV. CONCLUSION

We have observed a superparamagnetic behavior in nanowires patterned on Pt/CoFe/Pt film with perpendicular magnetic anisotropy. With decreasing the nanowire width narrower than 160 nm, a superparamagnetic behavior begins to appear at room temperature. The thermal activation model reveals that the reduction of the thermal stability is the origin of the coercive field decrement.

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