Magnetic Properties of Fe$_{55}$Pd$_{45}$ Films Deposited on Si (100) Nano-meter Wide Pillars

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Abstract

Magnetic nano-dot arrays with (tilted) perpendicular anisotropy are useful for the high-density magnetic recording. In this study, we deposited two kinds of ferromagnetic sample: Fe$_{55}$Pd$_{45}$/Si (100)-plane and Fe$_{55}$Pd$_{45}$/Si (100)-pillar. Each sample underwent a rapid thermal annealing (RTA) treatment: with a heating rate of 40°C/sec up to 500°C, being annealed there for 30 minutes, and then quenched to room temperature. After fabrication, X-ray diffraction (XRD) indicated that after RTA the FePd alloy transformed from the fcc to the fct phase with lattice constants: $a = 0.380$ nm and $c = 0.378$ nm. The Si(100) pillars are 500 nm in length, 65nm in diameter, and with a density of about $10^{12}$ cm$^{-2}$. On top of each Si(100) pillar there sat a prolate ellipsoid shape Fe$_{55}$Pd$_{45}$ particle: length $L = 108$ nm and short-axis diameter $d = 67$ to 83 nm. Magnetic domain (MD) pattern of the FePd nano-dot array was studied by magnetic force microscopy (MFM). The overall magnetic domain size (D) is from 285 to 452 nm. The squareness ratio (SQR) of the magnetic hysteresis loop reaches as: (SQR)$_x = 0.65 >$ (SQR)$_y = 0.45 >$ (SQR)$_z = 0.40$ for the FePd/Si(100)-pillar film. From the in-plane rotation angle ($\phi$) and the out-of-plane tilting angle ($\theta$) dependencies of the coercivity ($H_C$), we find that the former exhibits the characteristics of the curling-mode-like switch, while the latter exhibits the Stoner-Wohlfarth-like switch.

Introduction

The magnetic recording technology was developed very early in 1898; sound was first recorded on magnetic materials. Today, we still record digital information on magnetic materials. Convenient, reliable, and inexpensive are the most advantages in magnetic recording. There are technical limits in classical magnetic recording in terms of longitudinal or perpendicular recording. The super para-magnetic phenomenon will set an upper limit on the storage density in the ferromagnetic recording layer [1,2]. Usually, magnetic nano-dot media with perpendicular anisotropy are used for the high-density magnetic recording.

The key properties for the magnetic recording media with high-density and low noise are associated with the high squareness in the perpendicular hysteresis loops and reduced magnetic domain sizes [3]. The L$_1$ phase of FePd alloys exhibits the perpendicular magnetic anisotropy. Besides, the production cost of FePd is lower than that of FePt. Moreover, FePt has very large coercive force (Hc), about 2 T, which means large power to write in recording. FePd needs less power in magnetic recording [4]. In this article, we studied magnetic properties, including various types of the magnetic hysteresis loops and the magnetic domain (MD) structures of FePd nano-dots deposited on top of nano-meter wide Si (100) pillars.

The Si (100) nano-pillars substrates were prepared by J. Shieh in National Nano Device Laboratory. He used the inductively coupled plasma chemical vapor deposition (ICPVD) system to grow Si (100) nano-pillars [5,6]. From the Scanning Electron Microscope (SEM) image, the Si-nanowires are about 500 nm in length, aligned vertically with an average diameter of about 65 nm, and a density of about $10^{12}$ cm$^{-2}$. The average diameter of the nano wire tip is about 15 nm.

Experimental

Fe$_{55}$Pd$_{45}$ alloy films were deposited on the previously mentioned Si(100)-pillar and Si(100)-plane wafers, respectively, by the thermal evaporation method. The various fabrication conditions are summarized below: the base pressure ($p$) was $2 \times 10^{-6}$ Torr; the deposition temperature ($T_d$) was room temperature (RT), and the film thickness ($t_f$) was fixed at 80 nm.

After film fabrication, we tried to induce an additional thermal stress in the Fe$_{55}$Pd$_{45}$ alloy film and/or nano-dot by using a post Rapid Thermal Annealing (RTA) treatment. The sample temperature was heated up to 500°C, with a heating rate of 40°C/sec, and kept at 500°C for $\Delta t = 30$ minutes, and then quenched to room temperature in 25 minutes. If $\Delta t = 30$ minutes with RTA, we found that the structure of the FePd/Si(100)-plane film contained two phases, fcc and fct, in the Philips PW3040/60 X-ray diffraction (XRD) scan. If $\Delta t$ was less than 10 minutes or more than 60 minutes with RTA, we found only pure fcc phase in the XRD scan. From XRD data of the sample with two phases, fcc and fct, we calculated the lattice constants: $a = 0.380$ nm and $c = 0.378$ nm. Next, we applied the $\Delta t = 30$ minutes RTA condition again on the Fe$_{55}$Pd$_{45}$/Si (100)-pillars sample. In Figure 1, the ellipsoid shape Fe$_{55}$Pd$_{45}$ nano-dot sits on top each Si (100)-pillar, with a length $L = 108$ nm. The short-axis (or planar) diameter of the ellipsoid ($d$) is 67-83 nm. We checked the rms surface roughness; it was about 14 nm. The magnetic properties, including various types of the magnetic hysteresis loops and the magnetic domain (MD) structures of FePd nano-dots deposited on top of nano-meter wide Si (100) pillars.

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The magnetic hysteresis loops were obtained from Lake Shore 7400 Series vibration sample magnetometer (VSM) measurements. The in-plane (x-, y-axis) and out-of-plane (z-axis) hysteresis loops of the Fe$_{55}$Pd$_{45}$/Si(100)-plane film (after RTA) is shown in Figure 4A, and the Fe$_{55}$Pd$_{45}$/Si(100)-pillar film (after RTA) is shown in Figure 4B.

**Results and Discussion**

From Figure 4a, the relationship among the x-, y-, and z-axis squareness ratios (SQRs) is that $(SQR)_x = 0.89 > (SQR)_y = 0.81 > (SQR)_z = 0.76$. Hence, we believe that the easy-axis (EA) of the FePd/Si(100)-plane films tends to be in the film plane. Even though we have succeed in acquiring the fct phase by RTA, without a proper seed layer, it is still difficult to obtain large enough magneto-crystalline or magneto-elastic perpendicular anisotropy to overcome the demagnetizing effect. Figure 4B shows $(SQR)_x = 0.65 > (SQR)_y = 0.45 > (SQR)_z = 0.40$ for the FePd/Si(100)-pillar film. As a result, we think $M_s$ tends to be aligned along the z-axis direction or the long-axis ($l = L/2$) of the FePd ellipsoid. This phenomenon may be due to the shape anisotropy (e.g., $l > d$) of the ellipsoid [1,7]. Yet, $(SOR)_z$ is still not close to 1, which indicates that the EA of the Fe$_{55}$Pd$_{45}$ dot is somewhat tilted from the z (or perpendicular) direction. The ratio $(K_u/E_m = 0.12)$ between magnetic anisotropy energy $(K_u \cong K_{ux} - K_{uz})$ and magneto static (or demagnetizing) energy $(E_m \cong 2\pi M_s^2)$ for the Fe$_{55}$Pd$_{45}$/Si(100)-pillar sample implies that it should...
exhibit a very weak perpendicular magnetic anisotropy. Thus, simple calculations show that the overall (or average) EA is tilted relative to the long Si pillars axis by an angle \( \theta \approx 83^\circ \), when the film is in the demagnetized state. Notice that because, as shown in Figures 1, 2 and 3, some pillars were shorter, and could not get enough FePd deposition, the specific \( K_{c}/E_{\text{u}} \) ratio of the single fully developed FePd ellipsoid \( \text{m0-ust} \) be larger than 0.12. Thus, for this FePd ellipsoid (or nanodot) its \( \theta_n \) could be much less than \( 83^\circ \). This conclusion is qualitatively in consistent with that from MFM observations. From a simple calculation, we could find that the exchange length, \( L_{ex} = \sqrt{K_{c}/A} \), \( D_{a} \) is the lattice spacing, \( D_{a} \) is the lattice spacing, and that between the length (L) of FePd ellipsoid and \( L_{ex} = L = 14 \times 1_{ex} \), where \( A \) is the exchange stiffness for Fe 55Pd 45. Then, roughly speaking, the critical short-axis size (2b) is given by the transcendental equation,

\[
\frac{b^2}{a^2} \log \left( \frac{2b}{a} \right) = \frac{6J_{s}^{2}}{a_{D}M_{s}^{2}}
\]

Where \( J_{s} \) is the exchange integral, \( a_{D} \) is the lattice spacing, \( D_{a} \) is the magnetization factor along the long-axis, \( M_{s} \) is the magnetization per unit volume of the substance. Thus, the estimated \( 2b \) for our FePd ellipsoid can be even larger. Finally, since \( L_{ex} > 2b \), we conclude that the magnetic state of the FePd ellipsoid is likely to be either in a single-domain or vortex-domain state.

In Figure 5, the \( H_{c} \) of the FePd/Si(100)-pillar film is plotted as a function of the inclination angle (\( \theta \)) and the azimuthal angle (\( \phi \)) of the external field (H), respectively. Based on Figure 9.6 of [9], we found two modes to explain Figure 5. First, Figure 9.6 of [9] exhibits the Stoner-Wohlfarth (S-W) mode curve, which shows a decrease of coercive field, as \( \theta \) increases from 0 to 90°. In Figure 5 the \( H_{c} \) versus \( \theta \) (in-plane) curve has the same trend as the S-W mode curve. Second, Figure 9.6 of [9] exhibits the curling mode curve, which shows \( H_{c} \) increases, as \( \phi \) increase from 0 to 90°. In Figure 5 the \( H_{c} \) versus \( \phi \) curve has the same trend as the curling mode curve.

Conclusion

In this study, we have made two kinds of ferromagnetic sample: Fe55Pd45/Si(100)-plane and Fe55Pd45/Si(100)-pillar. Both of them have been treated by the RTA method at 500°C. The Si (100) pillars are 500 nm in length and 65 nm in diameter. On top of each Si (100) pillar there sat a prolate ellipsoid shape Fe55Pd45 particle: length \( L \approx 108 \)nm and short-axis diameter \( d \approx 67 \) to 83 nm. The overall magnetic domain size (D), as revealed from MFM, ranges from 285 to 452 nm.

A theoretical estimation shows that the magnetic state of the FePd ellipsoid should be in a single-domain or vortex-domain state. The switch-filed, which varies a function of inclination angle (\( \theta \)), follows the coherent S-W mode, and which varies, as a function of azimuthal angle (\( \phi \)), follows the curling mode. We made single-domain or vortex-domain state sample. By depositing Fe55Pd45 on Si (100) nano-meter wide pillars we decreased the domain sizes of each nano-dot FePd particle. That is a good and economic way for the magnetic recording media with high-density and low noise in the perpendicular magnetic recording.

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