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Research Article

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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: $(SQR)_z = 0.65 > (SQR)_y = 0.45 > (SQR)_x = 0.40$ for the FePd/Si(100)-pillar film. From the in-plane rotation angle (φ) and the out-of-plane tilting angle (θ) 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 properties [3].The $L1_0$ 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 (ICPCVD) 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 2×10^{-6} Torr; the deposition temperature (T_S) 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 Δt= 30 minutes, and then quenched to room temperature in 25 minutes. If Δt = 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 Δt 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 Δt = 30 minutes RTA condition again on the $Fe_{55}Pd_{45}$/Si (100)-pillars sample. In Figure1, the ellipsoid shape $Fe_{55}Pd_{45}$ nano-dot sits on top each Si (100)-pillar, with a length L ≅ 108nm. 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 by Park System XE-100atomic force microscopy (AFM).The diameters of the nano-dots are from 83 nm to 119 nm; the corresponding image is shown in Figure 2. Figure 3 shows the plane-view pattern of the MDs of FePd/Si (100)-pillar by Magnetic force microscopy (MFM). The overall magnetic domain size (D) ranges from 285 nm to 452 nm, much bigger than d.

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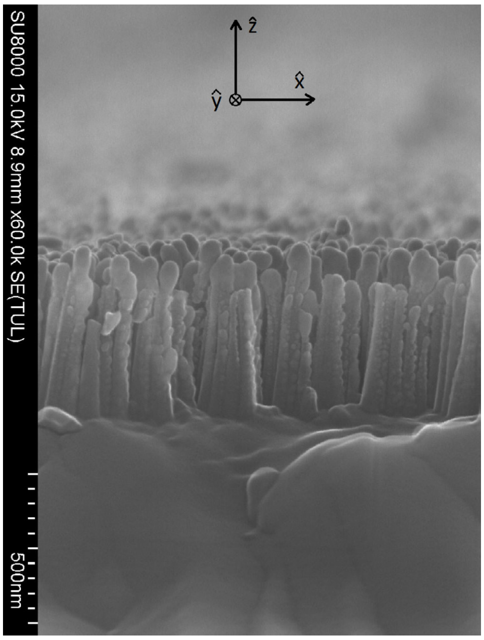

Figure 1: The Scanning Electron Microscope image shows Si(100) pillars with about 500 nm high, and the ellipsoid shape $Fe_{55}Pd_{45}$ wraping around each Si(100)-pillar top with a length L ≅ 108nm. The short-axis (or planar) diameter of the ellipsoid (d) is 67-83 nm.

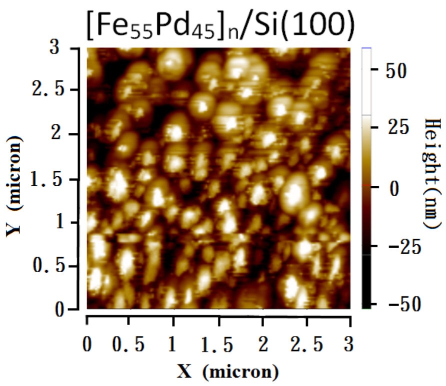

Figure 2: Atomic force microscopy image shows the diameters of the top nano-dots are from 83 nm to 119 nm.

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 $(SQR)_z = 0.65 > (SQR)_y = 0.45 > (SQR)_x = 0.40$ for the FePd/Si(100)-pillar film. As a result, we think $\vec{M}_s$ 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

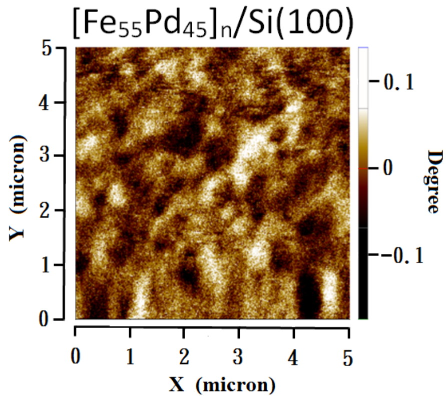

Figure 3: Magnetic force microscopy plane-view pattern shows the magnetic domains of FePd/Si(100)-pillar. The overall magnetic domain size (D) ranges from 285 nm to 452 nm.

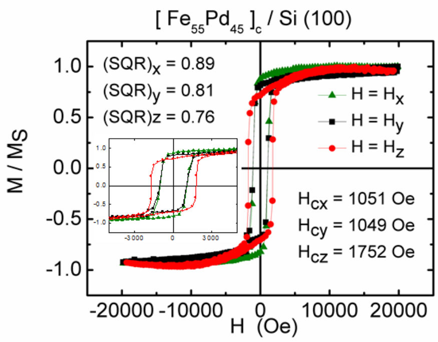

Figure 4a: Shows the in-plane (x-, y-axis) and out-of-plane (z-axis) hysteresis loops of the $Fe_{55}Pd_{45}$/Si(100)-plane film(after RTA). Subscript "c" means continuous film.

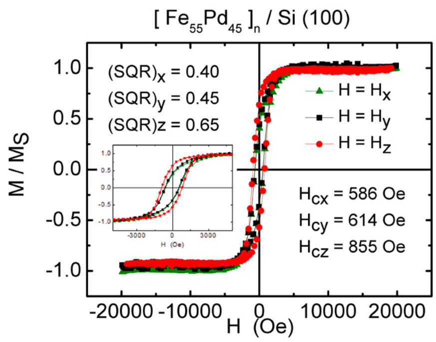

Figure 4b: Shows the $Fe_{55}Pd_{45}$/Si(100)-pillar film (after RTA). Subscript "n" means nano-dot film.

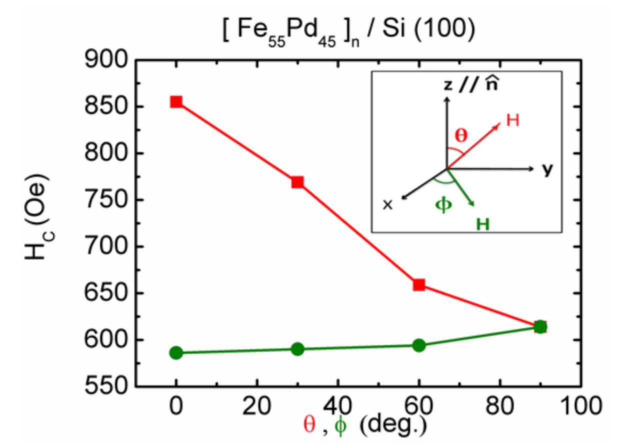

Figure 5: Shows the coercive force (H_c) of the FePd/Si(100)-pillar film is plotted as a function of the inclination angle (θ) and the azimuthal angle (Φ) of the external field (H), respectively.

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 $\theta_o \cong 83^o$, 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_u/E_M ratio of the single fully developed FePd ellipsoid m0-ust be larger than 0.12. Thus, for this FePd ellipsoid (or nano-dot) its θ_o could be much less than 83°. This conclusion is qualitatively in consistent with that from MFM observations. From a simple calculation, we could find that the exchange length, $l_{ex} \equiv \sqrt{\frac{(8\pi A)}{(M_s)^2}} \cong 7.5nm$ where A is the exchange stiffness for $Fe_{55}Pd_{45}$. Then, roughly speaking, the relation between the d of FePd ellipsoid and l_{ex} is d = (8.9 ~ 11)×l_{ex}, and that between the length (L) of FePd ellipsoid and l_{ex} is L = 14×l_{ex}. Moreover, according to Morrish [8], the critical short-axis size ($2b_c$) is given by the transcendental equation,

$$\frac{b_c^2}{\log\left(\frac{2b_c}{a_l}\right)-1} = \frac{6J_eS^2}{a_lD_aM_S^2} \quad (1)$$

Where J_e is the exchange integral, a_l is the lattice spacing, D_a is the demagnetization factor along the long-axis, M_s is the magnetization and the $2b_c$ of an acicular (or a prolate ellipsoidal) magnetic particle (L/d =a/b ≅1.5) is at least 45 to 55 nm. Notice that M_s of $Fe_{55}Pd_{45}$ is only 60% of M_s of Fe used in [8]. In addition, the dipole (or exchange) interaction between neighboring nano-dots could decrease the magneto-static energy per unit volume of the substance. Thus, the estimated $2b_c$ for our FePd ellipsoid can be even larger. Finally, since L >d≥ $2b_c$, 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 (θ) and the azimuthal angle (φ) 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 θ increases from 0 to 90°. In Figure 5 the H_c versus θ (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 φ increase from 0 to 90°. In Figure 5 the H_c versus φ curve has the same trend as the curling mode curve.

Conclusion

In this study, we have made two kinds of ferromagnetic sample: $Fe_{55}Pd_{45}$/Si (100)-plane and $Fe_{55}Pd_{45}$/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 65nm in diameter. On top of each Si (100) pillar there sat a prolate ellipsoid shape $Fe_{55}Pd_{45}$ particle: length L ≅ 108nm and short-axis diameter d ≅ 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 (θ), follows the coherent S-W mode, and which varies, as a function of azimuthal angle (φ), follows the curling mode. We made single-domain or vortex-domain state sample. By depositing $Fe_{55}Pd_{45}$ 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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