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Effect of Pt underlayer on the coercivity of FePt sputtered film

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Abstract

Magnetic properties of the FePt/Pt bilayers with Pt underlayer were investigated. By introducing the Pt underlayer, coercivity H_c and ordering parameter K of the film were enhanced by about of 50%. After a low-temperature annealing process at only 400 °C, H_c was increased from 6.26 to 9.78 kOe and K was increased from 0.586 to 0.844. Theoretical calculations indicated that there existed a compressive stress in the FePt film. The stress was found to release with the increase in thickness of the Pt underlayer. The increase in lattice parameter a_{FePt} and the decrease in lattice parameter c_{FePt} were closely related to the relaxed compressive stress in the FePt film as the thickness of Pt underlayer was increased. The relaxed compressive stress can account for the enhancement in the ordering parameter and the coercivity of the FePt/Pt bilayer materials.

Keywords: FePt; Thin film; Pt underlayer; Thermal expansion coefficient; Residual stress

1. Introduction

FePt related thin films have been considered to be promising candidates for ultrahigh density magnetic recording media due to their large magnetic magnetocrystalline anisotropy ($\sim 7.7 \times 10^7$ erg/cm^3), excellent magnetization and Curie temperature [1]. The selection of appropriate underlayer is very important for the development of excellent magnetic and recording properties [2–11]. Many papers have reported the development of *c*-axis preferred orientation and low ordering temperature process for the FePt magnetic films. However, only a few papers investigated how the residual stress affects the structure and magnetic properties of the FePt film, such as the effect of in-plane tensile stress induced by CrRu and Ag underlayers [12,13]. Further investigations on the silicide underlayers prove that the ordering transformation of the FePt phase is induced by dynamic tensile stress due to the expanded lattice volume of the underlayer as the copper silicide is formed [14,15]. After the fcc disordered FePt is transformed to fct ordered phase, the *a*-axis of the lattice is expanded while *c*-axis is shrunk. The unit cell volume turns out to increase, compared with the disordered fcc phase. An in-plane tensile stress should stretch the horizontal lattice parameter *a* and enlarge the unit cell volume for the FePt lattice, thus is helpful for the ordering transformation. On the contrary, an in-plane compressive stress suppresses the ordering process.

In our previous studies, we investigated the ordering enhancement of CoPt thin films by using Cu underlayer [16]. However, the enhancement mechanism is not yet clear. Rasmussen et al. reported that residual stress is usually induced by the different thermal-expansion coefficients of the substrate, underlayer and magnetic film [17]. We conjecture that the residual stress resulting from different coefficients of thermal expansion (CTE) can be one of the key reasons for the ordering enhancement in our investigated CoPt/Cu system. In single-layer FePt, tensile residual stress is reported to occur as the coefficient of thermal-expansion for the substrate is larger than that for the magnetic film [17]. It is manifest that a post-annealing process should result in a residual stress due to the different CTEs for two materials in contact; for example, substrate and underlayer, or underlayer and magnetic film.

Besides the aforementioned underlayers Cu, Ag and CrRu, different metallic underlayers with various CTEs were reported, such as Ti [18], Ag [19] and Ag top layer [20], etc. Among the above, the performance for three of them [18–20] is similar to our previous data [16]. In this study, we select Pt as the underlayer material for the FePt hard magnetic film. This is because the

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interdiffusion between Pt and FePt films is negligible at the low annealing temperature of 400 °C in this study. Since the residual stress in the FePt film is found to strongly depend on the thickness of the Pt underlayer, we would like to explore how to modulate the ordering transformation of the FePt film. The relationship between crystallographic data (such as lattice parameters and unit cell volume) and magnetic properties (such as ordering parameter K and coercivity H_c, etc.) will also be presented.

2. Experimental

FePt/Pt bilayers were deposited on quartz substrates by rf sputtering at room temperature, followed by a post-annealing at 400 °C for 1 h. Background vacuum was less than 7×10^{-7} Torr. Working pressure of Ar was fixed at constant value of 10 mTorr. The thickness of FePt magnetic film is fixed at 60 nm while the thickness of Pt underlayer is varied from 0 to 120 nm. The FePt target was made by pasting Pt foils onto a Fe target with 2 in. diameter.

Crystal structure was studied with an X-ray diffractometer using Cu Kα radiation. The ordering parameter is measured from the obtained lattice parameter data by *c*/*a* ratio method [21]. Magnetic properties were measured with a vibrating sample magnetometer (VSM) under a maximum field 12 kOe along the in-plane direction. To obtain saturated magnetic properties, the samples were magnetized using a pulse field 4 T before VSM measurements. Chemical compositions of the films were analyzed by inductively coupled plasma (ICP) spectroscopy.

3. Results and discussion

Magnetic properties of the FePt/Pt bilayer samples are varied with the thickness of Pt underlayer, as indicated in Table 1. The data of the FePt thin film without Pt underlayer is also listed for comparison. Coercivity is increased from 6.26 kOe for a single-layer FePt to 9.53 kOe for the bilayer sample as the thickness of the Pt underlayer (t_{Pt}) is 120 nm. Compared with the single-layer FePt, the maximum enhancements in coercivity H_c and in energy product $(BH)_{max}$ for the bilayer samples are both about 50%. Both the coercivity H_c and the ordering parameter K appear to have the same dependence of underlayer thickness; both are increased with t_{Pt}. However, the remanent magnetization B_r is decreased with t_{Pt}. The decreased B_r is again attributed to the increased ordered phase which has less magnetization values.

X-ray diffraction patterns of the FePt/Pt bilayer samples with different t_{Pt} values are shown in Fig. 1. Both the disordered FePt phase (fcc structure) and the ordered FePt phase (fct structure) coexist in the diffraction patterns. The closest packing face of the face centered cubic structure is (1 1 1), so the highest intensity of FePt and Pt is (1 1 1) peak. Further increase in t_{Pt} makes the face centered cubic FePt (2 0 0) peak split into fct (2 0 0) and fct (0 0 2) peaks; and the fcc (2 2 0) peak splits into fct (2 2 0) and fct (2 0 2) peaks. The peak separation is an indication of the $L1_0$ ordering transformation.

Table 1
The coercivity H_c, ordering parameter K, energy product $(BH)_{max}$, remanent magnetization B_r and squareness S of single-layer FePt and bilayer FePt/Pt samples

t_{Pt} (nm)	H_c (kOe)	K	$(BH)_{max}$ (MGOe)	B_r (T)	S
0	6.26	0.586	12.1	1.05	0.84
10	7.71	0.727	18.2	1.06	0.83
20	8.67	0.811	16.5	1.01	0.85
30	9.37	0.810	14.5	0.90	0.86
60	9.78	0.820	13.6	0.86	0.84
120	9.53	0.844	15.1	0.89	0.86

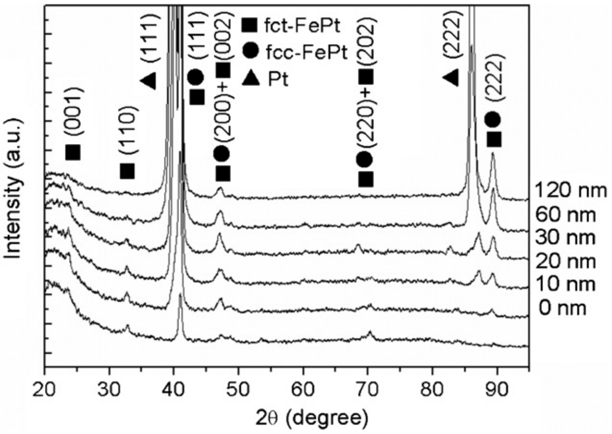

Fig. 1. X-ray diffraction patterns of the FePt/Pt bilayer with various thicknesses of Pt underlayers.

Lattice parameters of the ordered (fct) FePt and the fcc phase Pt, together with the theoretical value of Pt bulk (dash line) are plotted versus the thickness of the Pt underlayer t_{Pt}, as indicated in Fig. 2. The increased t_{Pt} values appear to promote the formation of FePt ordered phase. Compared with the disordered structure, the $L1_0$ ordered phase has an increased a_{FePt} and a decreased c_{FePt} lattice parameters. The lattice parameter of the $t_{Pt} = 10$ nm sample is 0.3853 nm, which is 2% smaller than the theoretical value of Pt bulk (0.3924 nm). The shrink lattice parameter should result from a compressive stress inside the Pt underlayer along the in-plane direction during annealing process. The compressive stress is harmful for ordering transformation. As the thickness of the underlayer is increased, the lattice parameter a_{Pt} is increased, approaching to the theoretical value of Pt lattice parameter. The compressive stress in the Pt underlayer is relaxed as t_{Pt} is increased. The released compres-

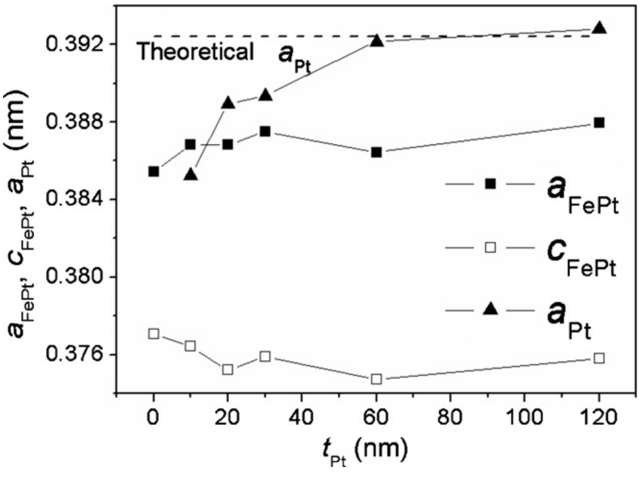

Fig. 2. Lattice parameters of the magnetic FePt film and the Pt underlayer (a_{FePt}, c_{FePt} and a_{Pt}) as a function of the underlayer thickness t_{Pt}. Theoretical value of the lattice parameter for bulk Pt is indicated by dash line for comparison.

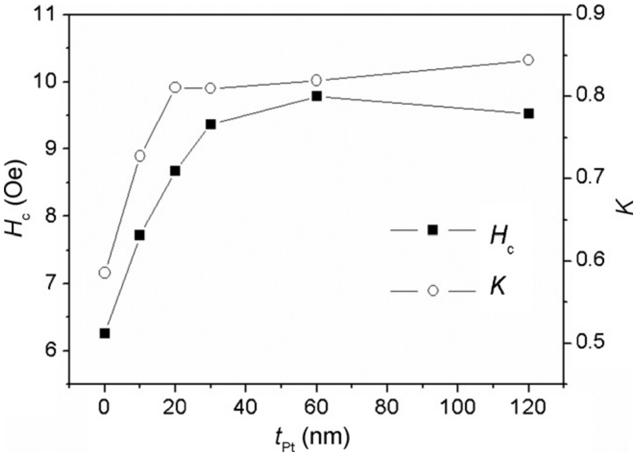

Fig. 3. The variation of coercivity H_c and the ordering parameter K with the underlayer thickness t_{Pt}.

sive stress is advantageous for the formation of face centered tetragonal FePt lattice with elongated *a*-axis and shrinks *c*-axis, thus facilitates the ordering transformation.

Fig. 3 shows the variation of the coercivity H_c and the ordering parameter K with the underlayer thickness. The K value is increased with the increasing t_{Pt} from $K = 0.586$ for a single-layer FePt sample to $K = 0.844$ for the bilayer sample with $t_{Pt} = 120$ nm. Similar trend of H_c versus t_{Pt} is also indicated in Fig. 3, from $H_c = 6.26$ kOe for a single-layer sample to $H_c = 9.53$ kOe for the bilayer sample with $t_{Pt} = 120$ nm. It appears that the coercivity of our FePt/Pt bilayer sample has a strong connection to its ordering parameter.

The effect of in-plane stress on the ordering parameter and coercivity has been reported by Rasmussen et al. [17] and Lai et al. [14,15]. Tensile stress tends to enhance the ordering parameter and the coercivity while compressive stress tends to decrease K and H_c. According to Rasmussen's report [17], coefficients of thermal expansion (CTE) of the substrate are different from that of an underlayer. Also the CTEs of the Pt underlayer and the FePt magnetic film are different. By increasing the temperature, residual stress is induced due to the different CTEs and can be calculated by the equation:

$$\sigma = \Delta\alpha\,\Delta T\left(\frac{E}{1-\upsilon}\right) \tag{1}$$

where $\Delta\alpha$ is the difference between the CTEs of the substrate and the underlayer or between the undelayer and the FePt magnetic film; ΔT the change in temperature between room temperature and annealing temperature; E the elastic modulus of the film and υ is the Poisson's ration. The material constants we used in the calculations are listed below:

Coefficient of thermal expansion: $\alpha_{\text{quartz}} = 0.5 \times 10^{-6}\,\text{K}^{-1}$, $\alpha_{\text{Pt}} = 8 \times 10^{-6}\,\text{K}^{-1}$ and $\alpha_{\text{FePt}} = 10.5 \times 10^{-6}\,\text{K}^{-1}$.
Elastic modulus: $E_{\text{Pt}} = 168$ GPa and $E_{\text{FePt}} = 180$ GPa.
Poisson's ration: $\upsilon_{\text{Pt}} = 0.38$ and $\upsilon_{\text{FePt}} = 0.33$.

A negative value of σ means that the film is in compression while a positive value means a tensile stress. In this study, both the thermal expansion conditions for single-layer FePt ($\alpha_{\text{FePt}} > \alpha_{\text{quartz}}$) and bilayer FePt/Pt ($\alpha_{\text{FePt}} > \alpha_{\text{Pt}}$) would generate a compressive stress in the FePt magnetic film. By using Eq. (1), the compressive stress between quartz substrate and FePt film is calculated to be 1007 MPa for a single-layer sample. In a bilayer sample, the compressive stress between Pt underlayer and the FePt magnetic film is 252 MPa. By the insertion of Pt underlayer, the residual compressive stress in the FePt magnetic film is reduced by 755 MPa as calculated from the above stress data. The insertion of Pt underlayer can reduce the energy barrier of the ordering transformation which compared to the single-layer FePt sample, therefore enhances the ordering parameter and the coercivity. However, the effect of thickness is not considered in the above calculations. Assuming that our low-temperature annealed samples have similar grain size, the total area of grain boundaries is increased with the thickness of the film. It is well known that grain boundaries play an important role in releasing the internal stress of a film. Therefore, the stress releasing effect is more significant as the film is thicker due to its larger area of grain boundaries.

The released stress can be measured from the lattice parameter data in Fig. 2. Compressive stress should decrease the volume of lattice and a tensile stress vice versa. For a single-layer sample, the unit cell volume of the FePt magnetic film (V_{FePt}) is measured to be 56.01 Å^3. After the insertion of a Pt underlayer with 30 nm in thickness, the V_{FePt} value is increased rapidly to 56.44 Å^3 which is very close to the theoretical data of an ordered FePt unit cell (56.47 Å^3). As the thickness of underlayer is further increased from 30 to 120 nm, the V_{FePt} value is only slightly increased to 56.56 Å^3. As estimated from the unit cell volume of the FePt film, the relaxation of the compressive residual stress is most significant as t_{Pt} is 30 nm or less. Further increase in the thickness of Pt underlayer up to 120 nm only slightly enhances the relaxation effect.

4. Conclusions

Thickness effect of Pt underlayer in the FePt/Pt bilayer system has been studied. With the increased thickness of Pt underlayer, about 50% increase in ordering parameter K and in coercivity H_c can be achieved. The enhancement in H_c by increasing the underlayer thickness can be attributed to the increased ordering parameter. By increasing the thickness of Pt underlayer, the compressive stress induced by the different CTEs in the FePt/Pt bilayer system is released. The stress effect further reflects in the lattice parameters and unit cell volumes of the Pt underlayer and FePt magnetic film. The released compressive stress has a significant effect to increase the coercivity and ordering parameter of the FePt film. The stress releasing effect is especially obvious when the thickness of Pt underlayer is 30 nm or less.

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