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Crystallographic texture and angular dependence of coercivity of ordered CoPt thin film

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Effect of crystallographic texture on the angular dependence of coercivity of ordered CoPt thin film was studied by successfully controlling the texture of the ordered CoPt thin film. We have developed, based on the Stoner–Wohlfarth interacting particles model, a micromagnetic simulation technique which can simulate the effect of distribution of magnetocrystalline easy axis on the magnetization behavior of thin film. The good agreement between the experiments and simulation suggested that the magnetization reversal in ordered CoPt thin film occurs not by the domain wall motion but by the Stoner–Wohlfarth interacting particles model. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1849031]

I. INTRODUCTION

When magnetic hysteresis loop is measured by changing the applied field angle with respect to a longitudinal direction on the film plane, its coercivity is in general found to vary with the applied field angle. This is called angular dependence of coercivity (ADC). The ADC behavior is well known to provide useful information on the magnetization reversal mechanism because of its sensitive dependence on its mechanism. For this reason, there have been numerous investigations of ADC behaviors of various magnetic films.[1–7] The studies on thin film media CoCrX alloys[2,7] in particular showed that the coercivity significantly increases before declining at large angle reaching a maximum at an intermediate angle; this result was frequently interpreted as evidence of domain wall motion for magnetization reversal mechanism.

In our recent measumenents, we found no such coercivity peak behavior in the ADC curves of ordered CoPt thin film, which is a potential candidate for ultrahigh density recording media. Furthermore, we found that its ADC behavior greatly depends on the crystallographic film texture. In order to analyze this unusual ADC behavior, we have investigated the ADC behavior of magnetic thin film using micromagnetics simulation based on the Stoner–Wohlfarth interacting particles model.[8]

II. EXPERIMENTS AND SIMULATION

Equiatomic CoPt thin film of about 20 nm was rf sputter deposited on the thermally oxidized Si substrate under 5 mTorr Ar pressure in a vacuum chamber with a base pressure 1×10^{-6} Torr. The substrate temperature was either room temperature or high temperature of 650 °C. The film deposited at room temperature was annealed for ordering at 650 °C for 30 min in a high vacuum chamber; the average grain size of ordered film was measured as about 40 nm. The magnetization and ADC curves were measured using a vibrating sample magnetometer.

Micromagnetic simulation[8] was performed using cubic unit cell of $30\times30\times1$ with a periodic boundary condition to predict the texture effect on the angular dependence of coercivity (ADC) of magnetic thin film. Each cubic array stands for crystalline grain. A coherent spin rotation was assumed in each grain and the easy-axis direction was specified for each grain.

To investigate the effect of magnetocrystalline easy-axis distribution on the magnetization behavior of thin film, the easy axis was randomly assigned in three dimensions (3D) for the case of 3D random model, whereas the easy axis was randomly assigned in plane for the case of a two-dimensional (2D) random model. For the (111) texture model, the magnetocrystalline easy axis points 36° out of film plane and forms a surface of cone making 36° with the film plane. In the case of (110) texture model, the easy axis lies on the film plane as in the 2D random model. The only difference is the assumption that the (110) texture is imperfect and that it assumes the Gaussian distribution with a standard deviation of 10°. The same Gaussian distribution was also assumed for the (111) texture to simulate the real texture as close as possible.

III. RESULTS AND DISCUSSION

The as-deposited CoPt thin film showed only a weak disordered (111) peak. Postannealing the film at 650 °C for 30 min in a high vacuum chamber led to a pronounced ordered (111) texture [Fig. 1(a)]. In order to alter the film texture, we have rf sputter deposited the film at the high substrate temperature of 650 °C by doping a small amount of Ag and were able to produce the ordered (110) texture [Fig. 1(b)]; the measurement of magnetization curve further confirmed the occurrence of *in situ* ordering.

Figure 2 shows the results of measurement of the ADC behavior of two ordered CoPt films showing distinctively different textures. The film with the (111) texture exhibits a

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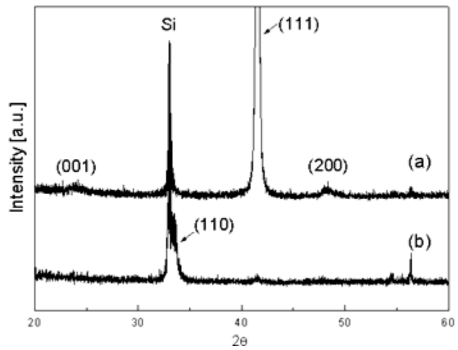

FIG. 1. X-ray diffraction patterns of (a) ordered CoPt film deposited at room temperature and vacuum annealed at 650 °C for 30 min and (b) ordered CoPt(Ag) film deposited at the high substrate temperature of 650 °C.

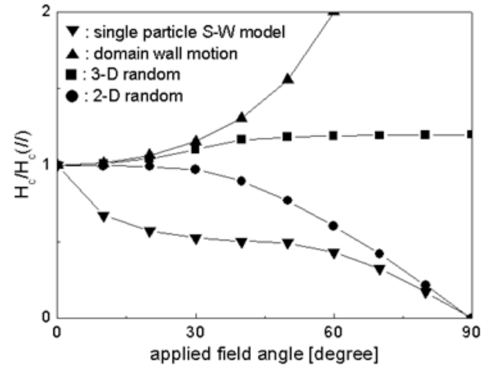

FIG. 3. Variation of the calculated coercivity, normalized with respect to the in-plane coercivity, as a function of applied field angle using micromagnetic simulation at the absence of magnetic interactions, i.e., at $h_m = h_e = 0$.

nearly constant coercivity regardless of the applied field angle. On the other hand, the coercivity of the film with the (110) texture is nearly constant up to 45° and then begins to decrease with applied field angle; this is believed to be due to a pure texture effect rather than due to other possible causes from Ag addition. These ADC behaviors are quite different from the previously reported ADC behavior of CoCrX films,[2,7] where the coercivity first increases with field angle before a later decline showing a maximum at an intermediate angle.

In order to investigate the possible mechanisms for these unusual ADC behaviors, we have calculated the ADC behavior using micromagnetic simulation based on the Stoner–Wohlfarth (SW) interacting particles model.[8] Figure 3 illustrates the calculated results for the 3D and 2D random models at the absence of magnetic interactions among magnetic grains; this compares the ADC curves predicted by domain wall motion and by Stoner-Wohlfarth (SW) single particle model.[9] The normalized coercivity of the 3D random model slowly increases with applied field angle before reaching a saturation value at large angles, whereas the normalized coercivity of 2D random model continuously decreases up to zero value at 90° after an initial period of constant coercivity. It is evident that these ADC curves are characteristically different from the ADC curve expected either from the domain wall motion or from the SW single particle model.

Figure 4 illustrates the variation of the z component (normal to the film plane) and x component (parallel to the film plane) of remanence as a function of applied field angle. The z component of remanence in the 3D random model initially rapidly increases and gradually approaches its maximum value at large field angle near 90°. One can notice that the M_{rz} at 90° is larger than M_{rx} at 0°; this explains why the coercivity slightly increases with field angle before saturating to a slightly larger value at 90°. On the other hand, the z component of remanence in the 2D random model stays nil regardless of the field angle because the magnetocrystalline easy axis is confined to the film plane. Thus at 90°, the magnetization should linearly increase with the applied field strength, which results in a zero coercivity. This explains why the coercivity initially slowly and rapidly declines afterwards with field angle before reaching zero coercivity at 90°.

Figure 5 illustrates how the ADC curve varies with the variation of strength of exchange interaction h_e and of magnetostatic interaction h_m for 2D random model. As the strength of exchange interaction increases, the normalized coercivity decreases more rapidly with applied field angle and the ADC curve eventually approaches that of the SW single particle model. If one increases the strength of magnetostatic interaction, one can observe that the normalized

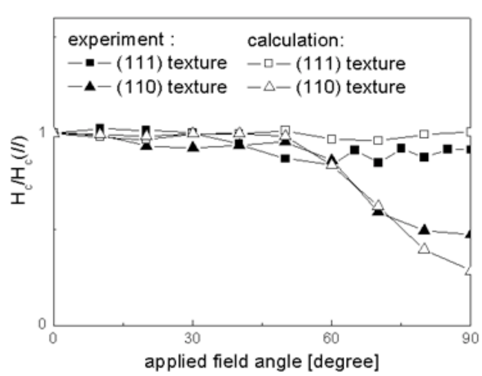

FIG. 2. Variation of the experimentally measured coercivity, normalized with respect to the in-plane coercivity, of the (111) ordered CoPt and (110) ordered CoPt (Ag) thin films as a function of applied field angle. The results are compared with the calculated ADC curves for the (111) ordered CoPt thin film ($M_s = 500$ emu/cm^3; $K_{\mathrm{eff}} = 4 \times 10^6$ erg/cm^3) and for the (110) ordered CoPt (Ag) thin film ($M_s = 350$ emu/cm^3; $K_{\mathrm{eff}} = 2 \times 10^6$ erg/cm^3).

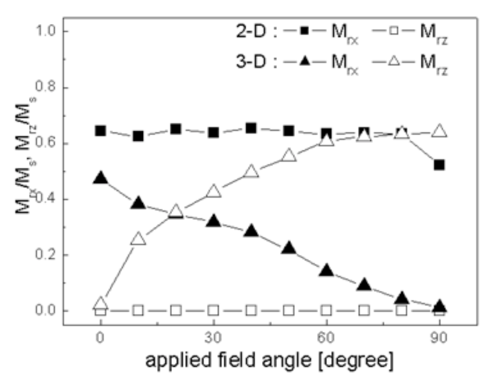

FIG. 4. Variation of the z and x components of calculated remanence, normalized with respect to the saturation magnetization, as a function of applied field angle using micromagnetic simulation in the absence of magnetic interactions, i.e., at $h_m = h_e = 0$.

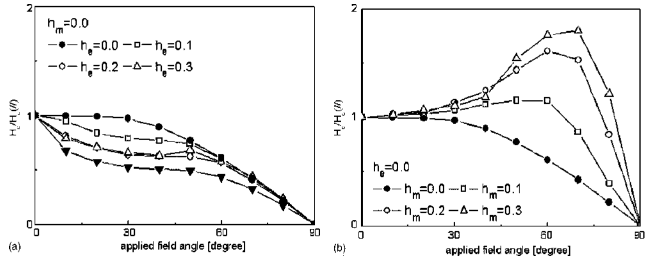

FIG. 5. Variation of the angular dependence of the normalized coercivity calculated at various strengths of (a) exchange interaction $h_e(=A^*/KD^2 : A^* = 0.4\times10^{-6}$ erg/cm; D=40 nm) and of (b) magnetostatic interaction $h_m(=M_s/H_k)$ for the case of 2D random model.

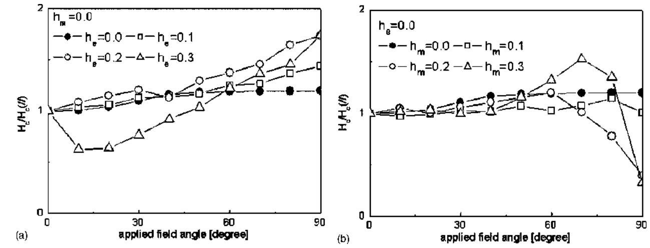

FIG. 6. Variation of the angular dependence of the normalized coercivity calculated at various strengths of (a) exchange interaction and of (b) magnetostatic interaction for the case of 3D random model.

coercivity first increases with field angle before declining to zero coercivity showing a peak in the ADC curve; this curve is thus similar to the case where the transition of magnetization reversal mechanism occurs from domain wall motion to SW single particle model. The coercivity increase at intermediate field angles is primarily because the demagnetization field along the z axis increases with the field angle due to its shape anisotropy.

Figure 6 shows the variation of normalized coercivity of 3D random model with applied field angle at various strengths of the exchange and magnetostatic interactions. The normalized coercivity tends to continuously increase with applied field angle and its increasing rate increases with the exchange interaction strength except at low angles for a large exchange interaction. This is probably because the exchange energy can vary depending on the applied field angle even though the exchange interaction strength is constant since the exchange energy depends on the distribution of mutual angles between two magnetization directions. On the other hand, for the case of magnetostatic interactions, the coercivity tends to first increase with applied field angle before a continuous decline in a later stage showing a maximum coercivity. However, this peak behavior in the ADC curve is observed, unlike the 2D random model, only when the magnetostatic interaction strength is sufficiently large, that is when h_m is larger than about 0.1.

The simulated ADC curves for (111) and (110) textures for ordered CoPt thin films are compared in Fig. 2 with the experimentally measured ADC curves. The strengths of exchange and magnetostatic interactions were calculated using the experimentally measured M_s and K_{eff} in each ordered CoPt thin film by assuming K_{eff} as K_u:K_{eff} was experimentally estimated from the initial magnetization curve.[10] The simulation for the film with (111) texture showed a fairly constant coercivity regardless of the applied angle and this is in good agreement with the experimentally measured ADC curve. The simulation for the film with (110) texture, on the other hand, showed gradually declining coercivity at large applied field angle after initial constant coercivity. Apart from a slightly smaller coercivity at 90°, the simulated ADC curve is in good agreement with the experimentally measured curve.

This result indicates that the magnetization reversal in ordered CoPt thin film predominantly occurs not by the domain wall motion but by the Stoner–Wohlfarth interacting particles model and that the angular dependency of coercivity is governed by the film texture. The effect of film texture cannot be differentiated in the case when the magnetostatic interaction is strong; it can be distinguishable only when the magnetostatic interaction is weak, that is, h_m is less than about 0.1. The estimation showed that h_m in the present ordered CoPt film amounts to 0.008–0.031, which is indeed smaller than 0.1. Therefore no maximum coercivity is expected to be observed in the ADC curve of ordered CoPt film and the angular dependency of coercivity of (111) texture is expected to be characteristically different from that of (110) texture.

IV. CONCLUSIONS

The measurement of angular dependence of coercivity (ADC) of ordered CoPt thin film at two distinctively different textures (111) and (110) showed characteristically different ADC curves. We have developed, based on the Stoner–Wohlfarth interacting particles model, a micromagnetic simulation technique which can calculate the effect of the distribution of magentocrystalline easy axis on the magnetization behavior of magnetic thin films. The simulation of ADC curve for the (111) and (110) texture was in good agreement with the experimentally measured ADC curve for each texture. We believe that the magnetization reversal in ordered CoPt thin film occurs not by the domain wall motion but by the Stoner–Wohlfarth interacting particles model and that the angular dependence of coercivity of ordered CoPt thin film differs depending on the film texture primarily because of its relatively weak magnetostatic interaction.

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