

Interfacial disorder in the $L1_0$ FePt particles capped with amorphous Al_2O_3

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$L1_0$ -FePt particles disorder at the interface when an amorphous Al_2O_3 layer is capped on an ordered FePt particulate film at room temperature. The coercivity decreases drastically as a result. Interfacial disordering does not progress when the capped layer is deposited at elevated temperature, indicating that the disordering is driven by the strain at the interface. The FePt particulate film becomes magnetized more easily by the Al_2O_3 capping. © 2004 American Institute of Physics.
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Because of the small superparamagnetic limit due to the large magnetocrystalline anisotropy,¹ the $L1_0$ -FePt phase has been receiving much research interest for a possible application to the next-generation ultrahigh-density magnetic recording media. For this application, it is necessary to disperse ferromagnetic particles of less than 10 nm in a nonmagnetic matrix. Thus, many investigations have been carried out on the fabrications of FePt/oxide granular films and their magnetic properties.²⁻⁶

The microstructure of FePt nanogranular films is influenced by the interfacial energy between the FePt and nonmagnetic matrix, because the ratio of interface to volume increases drastically when the particle size becomes smaller than a few ten nanometers. Recently, we reported that FePt particles that are smaller than a critical size do not order to the $L1_0$ structure by annealing.⁶ This size effect of ordering is due to the depression of the thermodynamic ordering temperature as a result of the increased interfacial energy with respect to the volume free energy. Although there have been many investigations on the microstructure-property relationships in the FePt nanogranular film,²⁻⁶ there are no reports on the possible presence of disordered phase at the interface between the FePt nanoparticles and the matrix. Metal/nonmetal nanogranular film structure is also important in tunneling magnetoresistance devices,⁷ in which the interfacial structure should also provide much influence on the electron transport properties. For any magnetic recording application, thin nonmagnetic layers will be capped on particulate magnetic layers in view of better tribology and corrosion resistance. Thus, the investigation of interfacial structure of the FePt particles in contact with oxide matrix is of great importance in view of applications. In this work, we have investigated the interfaces between the $L1_0$ -FePt particles capped with an amorphous Al_2O_3 layer.

FePt films were prepared by cosputtering high-purity (99.99%) Fe and Pt targets on heated MgO(001) single-crystal substrates using a multiple dc-sputtering system. The substrates were heated at 700 °C on a rotating table during film deposition. The base pressure of the system was $\sim 6.0 \times 10^{-7}$ Pa and high-purity argon of 0.1 Pa was flown during sputtering. Under this condition, films grow with a Volmer-Wever (VW) growth mode, forming island-like fully ordered

$L1_0$ -FePt particles.⁸ The growth rate of FePt was controlled to 0.10 nm/s, and the nominal thickness of all the films was fixed to 10 nm based on the deposition time. Five-nm-thick amorphous Al_2O_3 layer was subsequently deposited at room temperature and at 700 °C.

Figure 1(a) shows x-ray diffraction (XRD) patterns of 10-nm-thick FePt film deposited on a MgO substrate at 700 °C. (001) and (003) superlattice reflections are observed at around $2\theta = 24^\circ$ and 77° , respectively. In addition to these superlattice reflections, (002) and (004) fundamental reflections are observed at around $2\theta = 49^\circ$ and 112° , respectively. The unlabeled sharp peaks are due to the MgO substrate. No peaks from the other planes of the $L1_0$ -FePt phase are seen because of the strong (001) texture. Figure 1(b) is the XRD pattern of the FePt film capped with 5 nm amorphous Al_2O_3 layer at RT. A shoulder can be observed at around $2\theta = 47^\circ$, as indicated by the arrow. The shoulder disappeared after annealing the capped film at 700 °C for 1 h, as shown in Fig. 1(c). Thus, we conclude that the shoulder observed in Fig. 1(b) was due to the appearance of a disordered phase. This interfacial disordering occurred only when the capped layer is deposited at RT. When the capped layer was deposited at the same temperature for the film deposition

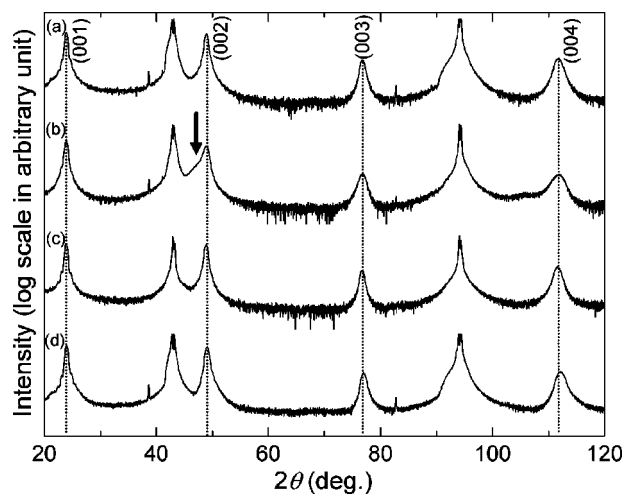


FIG. 1. XRD patterns of FePt 10-nm-thick film (a) deposited on a heated MgO substrate at 700 °C, (b) capped with amorphous Al_2O_3 at RT, (c) capped and subsequently annealed at 700 °C for 1 h, and (d) capped with amorphous Al_2O_3 at 700 °C.

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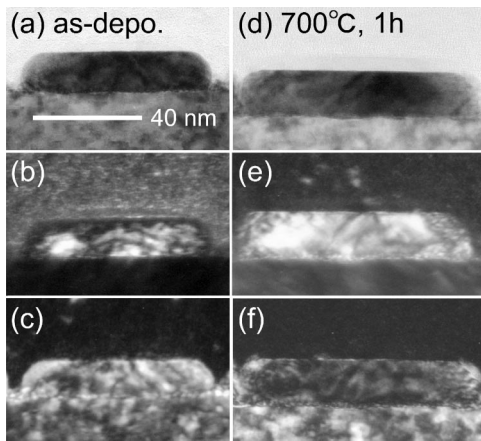


FIG. 2. TEM bright-field images (a) and (d), dark-field images taken with the (001) superlattice spot (b) and (e) and those taken with the (002) fundamental spot (c) and (f) of the 10-nm-thick FePt film capped with Al_2O_3 at RT and that annealed at 700°C for 1 h.

(700°C), the shoulder does not appear as shown in Fig. 1(d).

Figure 2 shows cross-sectional bright-field and dark-field transmission electron microscopy (TEM) images of the FePt film capped with an Al_2O_3 layer and the one subsequently annealed for 1 h at 700°C . The bright-field images show that the morphology of the FePt film is particulate with a uniform thickness of about 15 nm, which is 50% thicker than the nominal thickness because the films were grown with the VW mode. The dark-field image taken with the (001) superlattice spot of the capped film [Fig. 2(b)] shows a dark area surrounding the brightly imaging $L1_0$ ordered area. The dark-field image taken with the (002) fundamental spot [Fig. 2(c)] shows uniform brightness. From these two images, we conclude that the $L1_0$ -FePt particles are surrounded by a disordered FePt layer. The thickness of the disordered region is about 2.5 nm. After annealing at 700°C for 1 h, the entire volume of the FePt particles are brightly imaged in the dark-field image taken with the (001) superlattice spot [Fig. 2(e)]. This means that the disordered layer was ordered by the annealing. We confirmed that FePt particles were fully ordered before the Al_2O_3 capping layer was deposited. A possible reason for the formation of the disordered phase is an interfacial strain. The XRD pattern [Fig. 1(b)] clearly shows the broadening of the diffraction peak after being capped with the Al_2O_3 layer at RT. After annealing for 1 h at 700°C , the strain is released, as indicated from the sharpened diffraction peaks. The XRD pattern of the FePt film capped with Al_2O_3 at 700°C [Fig. 1(d)] also shows that there is no strain in the film, hence no disordered layer is observed.

Figure 3 shows magnetization curves of FePt film (a) deposited at 700°C , (b) capped with the Al_2O_3 layer at RT, (c) capped with the Al_2O_3 layer at RT and subsequently annealed at 700°C , and (d) capped with Al_2O_3 at 700°C . The filled and open marks show the magnetization curves in the perpendicular and in-plane direction to the film, respectively. The magnetic easy axis is perpendicular to the film plane for all the samples, since the [001] axis of the $L1_0$ structure is perpendicular to the film plane, as shown in Fig. 1. Magnetization does not saturate in the as-grown FePt film even at 50 kOe [Fig. 3(a)]. Perpendicular coercivity (H_c) of this film

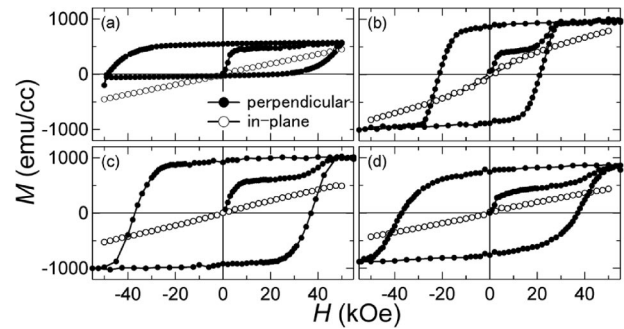


FIG. 3. Hysteresis loops of FePt film (a) deposited at 700°C , (b) Al_2O_3 -capped at RT, (c) Al_2O_3 -capped at RT, then annealed at 700°C for 1 h, (d) and Al_2O_3 -capped at 700°C . The magnetic field was applied in the perpendicular direction to the film (filled marks) and in the in-plane direction (open marks).

is larger than 50 kOe. When this film is capped with Al_2O_3 at RT, H_c decreases drastically to about 24 kOe [Fig. 3(b)]. After annealing this film at 700°C , H_c increases to about 35 kOe. Unlike the RT capping, the FePt film capped with Al_2O_3 at 700°C shows a high H_c of about 37 kOe. Because the magnetization at 55 kOe is smaller than that of a bulk sample (1100 emu/cc), it is probably not saturated. The uniaxial anisotropies (K_u) estimated from the perpendicular and parallel magnetization curves of Fig. 3(b) and 3(c) are about 3.2×10^7 and 4.8×10^7 erg/cm³, respectively. K_u of the FePt film capped with Al_2O_3 at RT is almost the same as the expected value from the volume fraction of ordered and disordered phase. The reason for the drastic decrease of H_c by capping is the formation of the interfacial disordered phase. H_c increases when the disordered phase disappears after annealing at 700°C . However, H_c of the annealed, Al_2O_3 -capped FePt film is much lower than that of the original FePt film. This is probably due to the residual strain at the FePt/ Al_2O_3 interface. Initial magnetization curves are also shown in the same figure. The magnetization increases rapidly at low magnetic field. The magnetization does not increase above 5 kOe until it reaches a higher field, then increases again gradually.

To understand this two-stage magnetization behavior, the initial magnetization curves and the hysteresis loops of FePt particulate films with various thicknesses were measured, as shown in Fig. 4. TEM bright-field images are also shown in the same figure. The particle size of the 5-nm-thick film is very small (~ 26 nm). Since all the particles in Fig. 4(a) are expected to be single-domain particles, the magnetization process will occur only by the rotation mechanism. Therefore, a very high magnetic field is required to magnetize the particles, and hence the film does not saturate even at 50 kOe. The magnetization curve shows the inflection point. This is because there are some particles that are smaller than the superparamagnetic limit or critical size of ordering.⁶ The magnetization mechanism changes from rotation to a nucleation-type with the increase of the film thickness or the particle size. The magnetization of the 10 nm film increases initially at a low magnetic field, regardless of the high coercivity. This is because the magnetization of that portion progresses by the nucleation mechanism. However, since there are a number of smaller particles, the overall magnetization processes in the 10 and 20 nm films will be a combi-

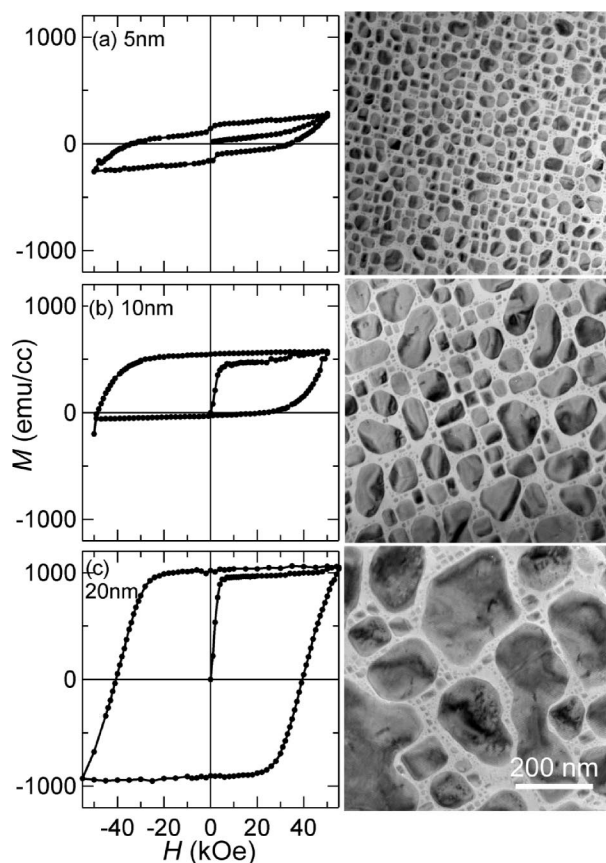


FIG. 4. Hysteresis loops and TEM bright-field images for FePt thin films with different film thicknesses: (a) 5 nm, (b) 10 nm, and (c) 20 nm.

nation of domain wall displacement in larger FePt particles and rotation magnetization of smaller FePt particles. As the film thickness grows, the fraction of the larger particles increases, so that most of the particles are magnetized at a low magnetic field [Fig. 4], and the remaining small particles are magnetized by the rotation mechanism, which requires a large magnetic field.

Based on this observation, the two-step initial magnetization process in Fig. 3 can be explained as follows. The initial magnetization at a low magnetic field in Fig. 3(b) is due to the nucleation-type magnetization of larger particles. The second increase of magnetization near 20 kOe is due to the magnetization of smaller particles capped with Al_2O_3 . Since the fraction of the disordered phase is larger in smaller particles, the rotation of these fine particles would occur more easily than in the case of uncapped films; hence, a large degree of magnetization progresses at this field. After anneal-

ing at 700 °C, the disordered phase disappears. Thus, the H_c increases, as shown in Fig. 3(c). Because of the disappearance of the disordered phase, the rotation magnetization of the smaller particles occurs at a higher magnetic field (~ 35 kOe). However, compared to the uncapped 10 nm FePt film, annealed, capped film saturates more easily. This would probably be due to the presence of a FePt/ Al_2O_3 interface. When the FePt film is capped at 700 °C, the film is more difficult to saturate. This is probably because of the presence of the strained interface. These observations have shown that the deposition of nonmagnetic capping layer influences the magnetization process of the particulate films significantly. Although uncapped ultrafine FePt particulate film is very difficult to saturate, it can become more easily saturated by capping.

In summary, this work has shown that the disordering of FePt particles occurs at the interface with the Al_2O_3 capping layer. The interfacial strain is thought to be the reason for this disordering of the initially ordered phase. The existence of this disordered phase causes the decrease of H_c , but it can be ordered by annealing. When the capping layer is deposited at an elevated temperature, no disordered phase appear at the interface. By using the interfacial disordering and re-ordering process, it is possible to fabricate a particulate FePt film that can be easily saturated.

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