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Effects of Ag underlayers on the microstructure and magnetic properties of epitaxial FePt thin films

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In this work Ag underlayers, with a slightly larger unit cell than FePt, were found not only to induce epitaxial growth of the FePt films but also to reduce the FePt ordering temperature. Without using the Ag underlayer, the FePt film deposited onto the Si substrate was fcc disordered. By the use of the Ag underlayer, it was observed that the FePt unit cells were expanded in the film plane. This has caused the shrinkage of the FePt unit cells along the film normal direction and resulted in the *in situ* ordering of the FePt thin film at reduced temperatures. The microstructural and magnetic properties of the FePt/Ag films at varied substrate temperature and FePt thickness were studied to investigate the $L1_0$ FePt ordering. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1360683]

INTRODUCTION

Recently, due to the large magnetocrystalline anisotropy of the ordered tetragonal $L1_0$ FePt phase, FePt thin films have drawn considerable attention as a potential high-density magnetic recording material.[1] However, in order to use FePt as recording media, the $L1_0$ FePt ordering temperature has to be reduced and the easy axis should be either perpendicular or parallel to the film plane, according to the recording mode.

Because the (111) plane is the FePt close-packed plane, the FePt thin film deposited directly onto an amorphous substrate tends to have (111) texture. After the fcc FePt thin film is annealed and becomes $L1_0$ ordered, the easy axis is tilted 35° away from the film plane. This was shown by Ristau *et al.* that FePt films deposited onto glass substrates are fcc disordered and (111) textured.[2] The FePt film has to be annealed at a temperature higher than 550 °C in order to obtain the $L1_0$ ordered phase.[2] Taking advantage of the small lattice mismatch (5.2%) between Ag and FePt, Ag (001) underlayers are used in this work to induce the FePt epitaxial films with the *c* axis perpendicular or parallel to the film plane. As reported by Yang *et al.*,[3] single crystal Si (001) substrates can be used to induce epitaxial growth of the Ag (001) film based on the orientational relationship of Ag (001)[110] ∥ Si (001)[110]. In order to understand the FePt $L1_0$ ordering, the microstructural and magnetic properties of the FePt/Ag thin films were investigated.

EXPERIMENT

The FePt/Ag thin films were deposited on single crystal Si (001) substrates by rf diode sputtering in a Leybold–Heraeus Z-400 system. To remove oxide layers, the Si (001) substrates were etched with hydrofluoric acid (HF).[3] The base pressure was 6×10^{-7} Torr. The atomic composition of the FePt film deposited from a composite target was measured to be $Fe_{55}Pt_{45}$ by x-ray fluorescence. The Ag underlayers were deposited with a fixed argon pressure of 10 mTorr and rf power density of 2.3 W/cm^2. The FePt layers were deposited at sputtering power density of 0.5 W/cm^2 and Ar pressure of 2.5 mTorr. The thickness of Ag films was fixed at 175 nm. The FePt thickness was varied from 2.5 to 30 nm. The deposition temperature was varied from 25 to 300 °C. The thin film microstructures were studied by $\theta/2\theta$ Rigaku x-ray diffractometer with Cu $K\alpha$ radiation as well as with a Philips EM 420T transmission electron microscope (TEM). The FePt planar spacings were measured by the peak positions detected by a Phillips X'Pert x-ray diffractometer equipped with a lens. The magnetic properties were measured by a vibrating sample magnetometer (VSM) with fields up to 13 kOe.

RESULTS AND DISCUSSION

For the case of no Ag underlayer being used, the FePt (111) peak is observed and shown in Fig. 1(a). The electron diffraction pattern (EDP) in Fig. 1(b) shows that the 30 nm FePt thin film directly deposited onto the HF-etched Si at 300 °C is nonepitaxial and displays randomly oriented grains. In addition, no superlattice reflections of the $L1_0$ or-

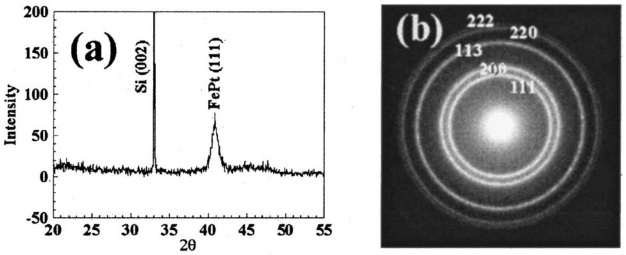

FIG. 1. (a) The $\theta/2\theta$ x-ray diffraction spectrum and (b) the plane-view electron pattern of the FePt (30 nm)/Si thin film deposited at 300 °C.

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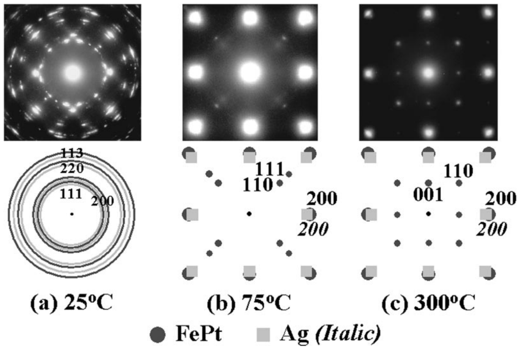

FIG. 2. The EDP and simulated patterns of the FePt (30 nm)/Ag (175 nm)/Si thin films deposited at (a) 25 °C, (b) 75 °C, and (c) 300 °C. [(b) and (c) are enlarged to show the ordered reflections and employ a different camera length from (a).]

dered phase are observed in the EDP in Fig. 1(b). Hence the FePt thin film is fcc disordered in the absence of the Ag underlayer.

The effects of substrate temperature on the FePt ordering and texture are shown in Fig. 2. As shown in Fig. 2(a), the electron diffraction arcs of the FePt/Ag film deposited at 25 °C indicate that the epitaxial growth of the FePt and Ag layers is not very good. No $L1_0$ ordered reflection is observed. This indicates that FePt film is fcc disordered as deposited at 25 °C. In addition, all of the fcc reflections are present in EDP. The fcc FePt (111) and (002) peaks are also observed in the x-ray diffraction spectra. This suggests that FePt/Ag thin films are not of one orientation.

As the substrate temperature is increased to 75 °C, the Ag underlayer is observed to grow epitaxially on the Si (001) substrate and become (002) oriented [Fig. 2(b)]. Furthermore, the Ag (002) oriented underlayer induces epitaxial growth of the $L1_0$ ordered FePt (002) thin film, indicated by the four FePt 110 reflections observed in the EDP of Fig. 2(b). The low intensity of the 110 reflections implies that the $L1_0$ ordering at 75 °C is very weak. In addition, the FePt 111 reflections are also observed in Fig. 2(b). These arise from a few perpendicular oriented (112) grains at this temperature.

At 300 °C, no FePt 111 reflections are observed in the EDP [see Fig. 2(c)]. The epitaxial growth of FePt, as induced by the Ag underlayer, is clearly improved with increasing substrate temperature. While the EDP at 75 °C showed only weak $L1_0$ (001) oriented grain formation, both of the $L1_0$ FePt 110 and 001 reflections are observed in the EDP at 300 °C [Fig. 2(c)]. This indicates that the $L1_0$ FePt thin film deposited at 300 °C has the easy axes distributed equally along the [100], [010], and [001] directions of the single crystal Si substrate. The presence of the $L1_0$ (001), (010), and (100) oriented grains at 300 °C implies that the (010) and (100) oriented grains with easy axes parallel to the film plane are formed at higher substrate temperatures than 75 °C. In addition, the intensity of the $L1_0$ FePt reflections is stronger at 300 °C than at 75 °C. This demonstrates that the FePt thin film is more $L1_0$ ordered when prepared at 300 °C than at 75 °C.

The EDP of a very thin FePt film (5 nm) deposited onto a Ag underlayer of the same thickness (175 nm) at 300 °C is shown in Fig. 3. The $L1_0$ FePt 110 superlattice reflections are observed in the EDP. This implies that the FePt thin film is (001) oriented with the *c* axis (easy axis) perpendicular to the film plane. The epitaxial relationship between the FePt and Ag is shown to be FePt [110](001) ∥ Ag [110](001) by the EDP in Fig. 3. The intensity of the 110 reflections from the 5 nm FePt film deposited at 300 °C is stronger than that of the 30 nm FePt film deposited at 75 °C. As a result, the thin FePt film is more $L1_0$ ordered compared to the thick FePt film deposited at 75 °C [Fig. 2(b)].

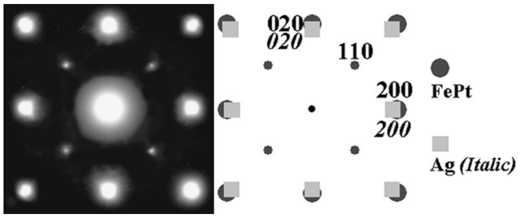

FIG. 3. The TEM diffraction pattern and index of the FePt (5 nm)/Ag (175 nm)/Si thin films deposited at 300 °C.

Compared to the 5 nm FePt thin film, it has been shown earlier that the 30 nm FePt thin film has its c axes distributed along the [100], [010], and [001] directions of the Si single crystal [Fig. 2(c)]. Thus it appears that the $L1_0$ FePt (001) oriented grains are formed before the $L1_0$ FePt (100) and (010) oriented grains. The $L1_0$ FePt (100) and (010) oriented grains begin to form as the FePt thickness increases.

The FePt $L1_0$ ordering is associated with changes of the lattice parameters. In order to understand the FePt $L1_0$ ordering, it is essential to investigate the changes of the FePt lattice parameter with substrate temperature and FePt thickness. The FePt lattice parameters of the [001], [010], and [100] axes can be calculated to be twice the FePt (002), (020), and (200) planar spacings, respectively. The FePt (002) planar spacing can be measured from the FePt (002) peak position of the $\theta/2\theta$ x-ray diffraction scan. The FePt (200) and (020) planar spacings can be obtained by an in-plane x-ray diffraction scan. The FePt (002), (020), and (200) planar spacings are plotted in Fig. 4.

As seen in Fig. 4, the FePt (200) and (020) planar spacings increase and (002) planar spacing decreases with increasing substrate temperature. This indicates that the FePt [100] and [010] lattice parameters are dilated and the [001]

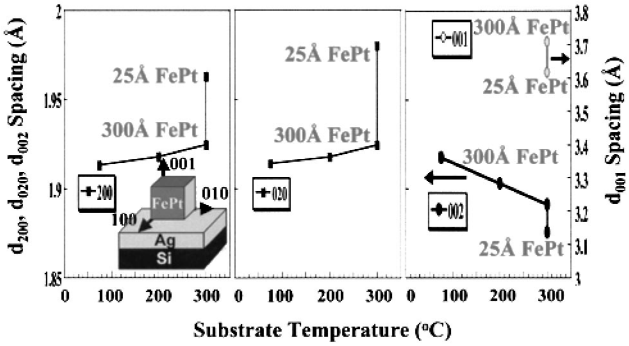

FIG. 4. The FePt (200), (020), (002), and (001) planar spacing at varied substrate temperature and FePt thickness.

lattice parameter is contracted at high substrate temperature. As shown in Fig. 2(b), the FePt thin film has good epitaxial growth induced by the Ag undelayer at 75 °C. The FePt [010] and [100] axes may be expanded by the Ag underlayer whose unit cell is 5.2% larger than FePt during the epitaxial growth. This expansion has caused the shrinkage of the FePt [001] axis. Compared to the fcc FePt disordered phase, the tetragonal $L1_0$ FePt has a smaller c axis than the a and b axes. This distortion of the FePt unit cell may result in aiding the formation of the $L1_0$ FePt grains with easy axis perpendicular to the film plane, which is consistent with the EDP observed in Fig. 2(b).

As the substrate temperature increases from 75 to 300 °C, the FePt (002) planar spacing decreases and the FePt (200) and (020) planar spacings increase. This indicates that the FePt [001] axis is further contracted and the [100] and [010] axes are further expanded with increasing substrate temperatures. This appears to cause even more $L1_0$ FePt ordering and more $L1_0$ FePt (001) oriented grains. As more $L1_0$ FePt (001) oriented grains are present, the $L1_0$ (100) and (010) oriented grains may begin to grow to relax the strain energy resulting from the $L1_0$ FePt (001) oriented grains.[4] As a consequence, the FePt thin film deposited at 300 °C has the c axes distributed equally along the [100], [010], and [001] directions of the single crystal Si substrate as shown earlier in EDP [See Fig. 2(c)].

Compared to the 30 nm FePt, the thin FePt (2.5 nm) deposited at the Ag underlayer of same thickness and substrate temperature has even smaller (001) planar spacing and larger (100) and (010) planar spacing (Fig. 4). This is probably because the thin FePt film (2.5 nm) can be expanded by the Ag underlayer more than the thick FePt film (30 nm). This explains why the strong $L1_0$ FePt 110 reflections are observed in the EDP shown in Fig. 3.

The EDP in Fig. 1 shows that the FePt thin film directly deposited onto the Si substrate at 300 °C is fcc disordered. This may be because the FePt thin film is not contracted along the film normal direction in the absence of the Ag underlayer. Hence the FePt film does not form the $L1_0$ ordered phase at 300 °C without using the Ag underlayer.

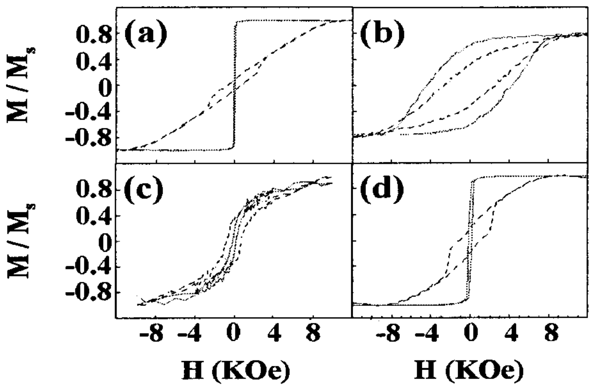

FIG. 5. The hysteresis loops of the (a) FePt (30 nm)/Ag (175 nm)/Si film deposited at 25 °C, (b) FePt (30 nm)/Ag (175 nm)/Si film deposited at 300 °C, (c) FePt (2.5 nm)/Ag (175 nm)/Si film deposited at 300 °C, and (d) FePt (30 nm)/Si film deposited at 300 °C. (Solid line: in-plane loop and dotted line: perpendicular loop).

The in-plane and perpendicular hysteresis loops of the FePt films are shown in Fig. 5. Both the FePt (30 nm)/Ag (175 nm)/Si thin film deposited at room temperature and the FePt (30 nm)/Si thin film deposited at 300 °C show low in-plane coercivity due to the fcc disordered phase in the film. The reversible rotation of the magnetization vector is observed when the magnetic field is applied perpendicular to the film plane. This is indicated by the rounded magnetization curve shoulders of the perpendicular loop. The open region of the perpendicular loop most likely reflects wall motion of the magnetization. The FePt/Ag thin film is deposited at 300 °C [Fig. 5(b)], and the high coercivity is due to high anisotropy energy associated with the $L1_0$ ordered phase. The c axes are distributed equally along the [100], [010], and [001] directions of the single crystal Si substrate. Thus the difference of the in-plane and perpendicular loop is less pronounced. For the very thin FePt film (2.5 nm) [Fig. 5(c)], the in-plane loop is almost closed. The perpendicular coercivity is higher than the in-plane coercivity because only the (001)-oriented grains are present in the thin film.

CONCLUSION

It has been shown that a Ag underlayer can be used to induce epitaxial growth of the FePt thin film. Because Ag has a slightly larger unit cell than FePt, the FePt unit cells were found to stretch in the film plane by the Ag underlayers during epitaxial growth. This has caused the contraction of the FePt unit cells along the plane normal direction, which results in the $L1_0$ FePt ordering at reduced temperature and forms $L1_0$ (001) oriented grains. In addition, it has been shown that the greater the contraction of the FePt unit cell along the plane normal, the greater the tendency for the $L1_0$ FePt phase to form.

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