Reduction of grain size and intergrain interaction in FePt/Pt/Cr trilayer thin films for perpendicular magnetic recording

An-Cheng Sun, Jen-Hwa Hsu,[a] and H. L. Huang
Department of Physics and Center for Nanostorage Research, National Taiwan University, Taipei 106, Taiwan

P. C. Kuo
Institute of Materials Science and Engineering and Center for Nanostorage Research, National Taiwan University, Taipei 106, Taiwan

(Presented on 2 November 2005; published online 21 April 2006)

A FePt single layer, a FePt/Cr bilayer, and a FePt/Pt/Cr trilayer were fabricated. Transmission electron microscope images revealed that the grain size of a FePt single layer was around 50 nm, and decreased to 20 nm with a Cr underlayer. When a Pt layer was inserted between the FePt magnetic layer and the Cr underlayer, $L1_0$ FePt(001) thin films with perpendicular magnetic properties can be obtained with a grain size of around 20 nm determined primarily by the Cr underlayer. The intergranular interactions determined from the Kelly-Henkel plot were the exchange coupling between magnetic grains in the FePt single layer. In contrast, negative values of the δM curve were obtained for the FePt/Cr bilayer and the FePt/Pt/Cr trilayer, implying the presence of dipole interactions in both films. Smaller grains and the negative δM of FePt/Cr were derived from the diffusion of Cr into the FePt layer.
[DOI: 10.1063/1.2171941]

INTRODUCTION

The perpendicular magnetic recording method has been proposed for ultrahigh-density magnetic recording applications, because it can overcome thermal instability at room temperature, even when the magnetic grains are very small.[1,2] The magnetic $L1_0$ FePt(001) thin film with perpendicular magnetic anisotropy is regarded as a candidate for ultrahigh-density recording medium because it has a large uniaxial magnetocrystalline anisotropic energy and enhanced thermal stability. Theoretical calculations indicate that the magnetic grain size of the $L1_0$ FePt phase may be as small as 2.8 nm, while maintaining magnetic thermal stability. At present, large grains in magnetic media with poor signal-to-noise ratio (SNR) are problematic.[3–5] Doping with a third element,[3,6–8] the granulation of ceramic matrices[9–11] and the diffusion of a top layer[12] have been developed to solve this problem. However, these studies are all limited to longitudinal magnetic recording applications, and do not address perpendicular magnetic recording. In this work, an ordered $L1_0$ FePt(001) film with perpendicular magnetic anisotropy was fabricated in the presence of both a Cr underlayer and a Pt intermediate layer on an amorphous glass substrate. The grains can be as small as 20 nm, with weak dipolar interactions among the magnetic grains in the $L1_0$-ordered FePt(001) film. The origin of small grains and weak intergrain interactions is discussed herein.

EXPERIMENT

A FePt single layer, a FePt/Cr bilayer, and a FePt/Pt/Cr trilayer were fabricated on preheated 7059 Corning glass substrates by conventional dc magnetron sputtering in an ultrahigh-vacuum sputtering chamber. Before sputtering, the base pressure of the sputtering chamber was under 5×10^{-9} Torr. A Cr underlayer and a Pt buffer layer were deposited after the substrate was preheated to 350 °C. The deposition temperature of FePt magnetic layer was 450 °C, because a soft magnetic fcc FePt phase was transformed into an ordered $L1_0$ FePt phase at 450 °C.[13] The thicknesses of the Cr underlayer, the Pt buffer layer, and the FePt magnetic layer were 90, 2, and 20 nm, respectively. These were measured using an atomic force microscope (AFM). The crystal structure of the films was investigated by x-ray diffraction (XRD) with Cu $K\alpha$ radiation and the sizes of the grains in the magnetic films were obtained by transmission electron microscopy (TEM). The chemical composition of the magnetic FePt alloy layer was $Fe_{48}Pt_{52}$, which is determined by energy dispersive x-ray diffractometry (EDS). The element depth profiles of the films were investigated by Auger electron spectroscopy (AES). Magnetic properties were measured using a vibrating-sample magnetometer (VSM) at room temperature with a maximum applied field of 1.2 T. Magnetic interactions were studied by Kelly-Henkel plot.

RESULTS AND DISCUSSION

As described in a previous article,[14] FePt films with perpendicular magnetic anisotropy could be prepared on Pt/Cr bilayers with glass substrates. The thicknesses of the Cr undrlayer and the Pt intermediate layer were 90 and 2 nm, respectively. The out-of-plane squareness $S_\perp$ of Fe/Pt/Cr was about unity. The $L1_0$-ordered FePt(001) phase was formed because of semicoherent epitaxial growth initiated from Cr(001), through Pt(001), and continuing into the FePt layer. Figure 1 schematically depicts the orientations of

[a]Electronic mail: jhhsu@phys.ntu.edu.tw

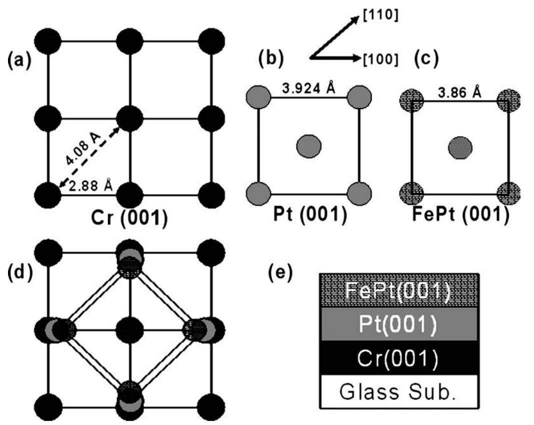

FIG. 1. Lattice parameter of (a) Cr(001) plane, (b) Pt(001) plane, and (c) FePt(001) plane, (d) top view of the atomic positions of each layer, and (e) layers stacking drawing of (d).

FePt(001)∥Pt(001)∥Cr(001), indicating the epitaxial growth of the FePt/Pt/Cr trilayer. Figures 1(a)–1(c) display the crystal planes of Cr(001), Pt(001), and FePt(001). In Fig. 1(a), the lattice constant of Cr is 2.88 Å and the diagonal distance in the [110] direction is 4.08 Å, which is close to the lattice constant of Pt, 3.92 Å [Fig. 1(b)]. In Fig. 1(c), the lattice constant of FePt is 3.86 Å, which is slightly smaller than that of Pt. Figure 1(d) displays a top view of the stacked layers and Fig. 1(e) depicts the layer stacking in FePt/Pt/Cr/glass. The Pt(001)[100] grows epitaxially along Cr(001) [110]. Therefore, when the FePt layer is deposited on this Pt(001) buffer layer, it may grow epitaxially with the FePt(001) preferred orientation, because lattice matching is favorable between the *a* axis of the FePt and the Pt(001).

Figure 2 plots the *M-H* loops of the FePt film, the FePt/Cr bilayer film, and the FePt/Pt/Cr trilayer film. The applied field was perpendicular to the film plane. Figure 2 shows that the maximum magnetization of FePt single layer was approximately 600 emu/cm^3, and is not saturated at 1.2 T. The saturation magnetization (M_s) of the FePt/Cr bilayer film is only about 400 emu/cm^3, which is less than that of the FePt/Pt/Cr trilayer film around 700 emu/cm^3, because the Cr atoms of the Cr underlayer diffused into the magnetic FePt layer, reducing the M_s value. The AES element depth profile analysis revealed that when a Pt intermediate layer was inserted between the FePt layer and Cr underlayer, the diffusion of Cr atoms into the magnetic FePt layer was suppressed. The out-of-plane squareness ($S_\perp$) of the FePt film, the FePt/Cr bilayer, and the FePt/Pt/Cr trilayer are around 0.66, 0.55 and 1, respectively, as shown in Fig. 2, suggesting that only the FePt/Pt/Cr trilayer exhibited perpendicular magnetic anisotropy.

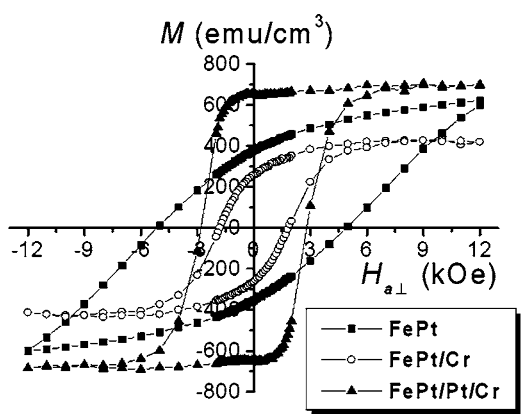

FIG. 2. Magnetic hysteresis loops of FePt single layer, FePt/Cr bilayer, and FePt/Pt/Cr trilayer films.

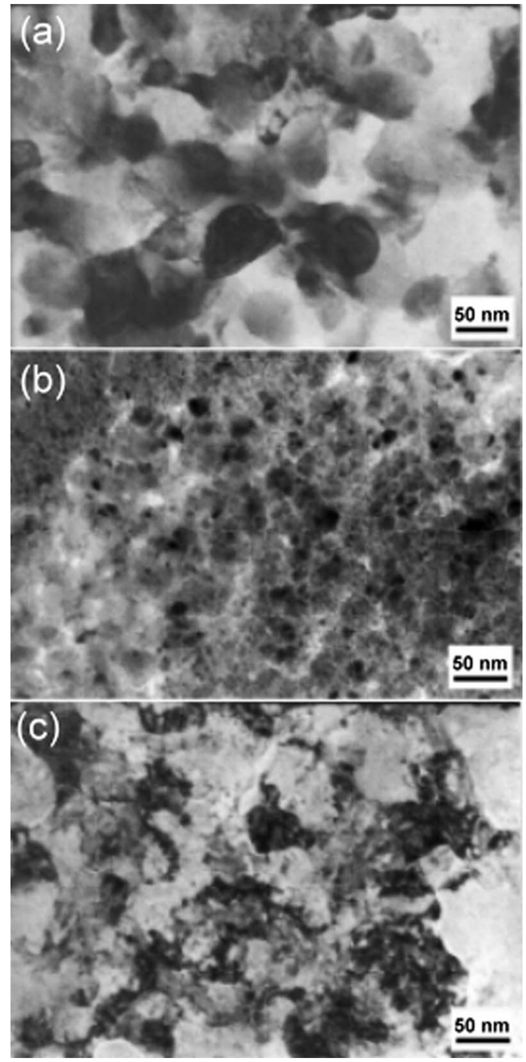

FIG. 3. Plane view TEM images of (a) FePt single layer, FePt/Cr bilayer, and FePt/Pt/Cr trilayer films.

Figure 3 presents the TEM bright field images of the FePt film, the FePt/Cr bilayer film, and the FePt/Pt/Cr trilayer film. The mean grain size of the FePt single film was about 50 nm and the grains were connected with each other, so the structure looks like that of a continuous film. When a Cr underlayer was employed, the mean grain size of FePt was reduced to around 20 nm. The grains did not connect to each other and the film looked granular. The distance between the grains exceeded that of the FePt single layer. In our previous study,[15] Cr atoms were found to diffuse into the FePt magnetic film and be present mostly in the surface between the grain boundaries. Therefore, the TEM bright field images and magnetic studies revealed that the Cr underlayer not only reduced the magnetic hardening of the film but also limited the grain growth of the magnetic FePt phase during

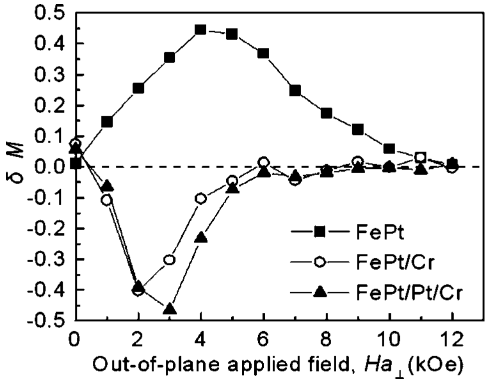

FIG. 4. δM curves of FePt single layer, FePt/Cr bilayer, and FePt/Pt/Cr trilayer.

deposition. When a Pt intermediate layer was inserted between the FePt magnetic layer and the Cr underlayer, the average grain size did not increase and was maintained at about 20 nm. Small magnetic FePt grains were essentially related to the smallness of the grains in the Cr underlayer. As discussed in Ref. 14, FePt(001) was epitaxially grown from the Cr(001) orientation. In an FePt/Pt/Cr trilayer, the average grain size of the underlayer was also about 20 nm. Therefore, the smallness of the FePt grains was considered to be originated from the Cr underlayer.

A Kelly-Henkel plot (also called δM plot) was obtained to elucidate the intergrain magnetic interactions in FePt/Pt/Cr trilayer films.[16] The δM can be determined from the following equation:

$$\delta M = M_d(H) - [1 - 2M_r(H)], \tag{1}$$

where $M_d(H)$ is the normalized dc-demagnetization (DCD) remanence as a function of the reversal field, and $M_r(H)$ is the normalized isothermal remanence (IRM) curve. According to the Kelly-Henkel plot, a positive δM indicates that intergrain interactions are ferromagnetic exchange interactions. A negative δM value suggests that intergrain interactions are dipolar interactions. Figure 4 plots the δM curves of an FePt single layer, Fe/Cr bilayer, and the FePt/Pt/Cr trilayer films. δM value was positive for the FePt single layer and negative for the FePt/Pt bilayer film and the FePt/Pt/Cr trilayer film. The results reveal that intergranualr interactions in FePt/Pt/Cr trilayer films are dipolar interactions. Thus, inserting a Pt layer or a Pt/Cr bilayer between the FePt layer and the substrate tends to reduce the intergrain interactions, reducing the medium noise and facilitating magnetic applications.

CONCLUSION

Microstructures and intergrain interaction in the $L1_0$ FePt thin film were examined. Perpendicular magnetic anisotropy appears only in the presence of both a Cr underlayer and a Pt buffer layer, because epitaxial growth was initiated from the Cr(001) underlayer, continued through the Pt buffer layer, and extended into the $L1_0$ FePt(001) magnetic layer. The diffusion of Cr atoms into the FePt magnetic layer increases the distance between the grains and limits the grain growth of the FePt magnetic grains. Epitaxial growth from the Cr(001) underlayer to the FePt(001) magnetic layer also limited the growth of the FePt grain. Ferromagnetic exchange coupling was found to be present in an FePt single layer. Using a Cr underlayer or a Pt/Cr bilayer changes the ferromagnetic interaction to a dipolar interaction.

ACKNOWLEDGMENT

The authors would like to thank the Ministry of Economic Affairs of the Republic of China, Taiwan, Contract No. MOEA 93-EC-17-A-08-S1-0006 for financially supporting this research.

[1] S. Iwasaki, Y. Nakamura, and K. Ouchi, IEEE Trans. Magn. **15**, 1456 (1979).
[2] T. Suzuki, IEEE Trans. Magn. **20**, 675 (1984).
[3] C. L. Platt, K. W. Wierman, E. B. Svedberg, R. van de Veerdonk, J. K. Howard, A. G. Roy, and D. E. Laughlin, J. Appl. Phys. **92**, 6104 (2002).
[4] T. Suzuki, N. Honda, and K. Ouchi, J. Appl. Phys. **85**, 4301 (1999).
[5] S. Jeong, Y.-N. Hsu, D. E. Laughlin, and M. E. McHenry, IEEE Trans. Magn. **36**, 2336 (2000).
[6] P. C. Kuo, Y. D. Yao, C. M. Kuo, and H. C. Wu, J. Appl. Phys. **87**, 6146 (2004).
[7] C.-M. Kuo, P. C. Kuo, W.-C. Hsu, C.-T. Li, and A.-C. Sun, J. Magn. Magn. Mater. **209**, 317 (2003).
[8] S.-R. Lee, S. Yang, Y. K. Kim, and J. G. Na, Appl. Phys. Lett. **78**, 4001 (2001).
[9] M. Yu, Y. Liu, A. Moser, D. Weller, and D. J. Sellmyer, Appl. Phys. Lett. **75**, 3992 (1999).
[10] J. A. Christodoulides, Y. Huang, Y. Zhang, G. C. Hadjipanayis, I. Panagiotopoulos, and D. Niarchos, J. Appl. Phys. **87**, 6938 (2000).
[11] C. M. Kuo and P. C. Kuo, J. Appl. Phys. **87**, 419 (2000).
[12] S. K. Chen, F. T. Yuan, and S. N. Shiao, IEEE Trans. Magn. **41**, 921 (2005).
[13] A. C. Sun, P. C. Kuo, S. C. Chen, C. Y. Chou, H. L. Huang, and J. H. Hsu, J. Appl. Phys. **95**, 7624 (2004).
[14] A.-C. Sun, P. C. Kuo, J.-H. Hsu, H. L. Huang, and J.-M. Sun, J. Appl. Phys. **98**, 1 (2005).
[15] S. C. Chen, P. C. Kuo, A. C. Sun, C. T. Lie, and C. C. Chiang, IEEE Trans. Magn. **39**, 584 (2003).
[16] P. E. Kelly, K. O'Grady, P. I. Mayo, and R. W. Chantrell, IEEE Trans. Magn. **25**, 3881 (1989).