May 2005

Magnetic properties and $L1_0$ phase formation of FePt films prepared by high current-density ion-beam irradiation and rapid thermal annealing methods

T. Yokota
University of Nebraska - Lincoln

M.L. Yan
University of Nebraska - Lincoln

Yinfan Xu
University of Nebraska - Lincoln, yxu2@unl.edu

L. Gao
University of Nebraska - Lincoln

R. Zhang
University of Nebraska - Lincoln, ruizhang@bigred.unl.edu

See next page for additional authors

Yokota, T.; Yan, M.L.; Xu, Yinfan; Gao, L.; Zhang, R.; Nicholl, LeighAnn; Yuan, Lu; Skomski, Ralph; Sellmyer, David J.; Liou, Sy_Hwang; Lai, Chih-Huang; Yang, Cheng-Han; and Huang, Sheng-Huang, "Magnetic properties and $L1_0$ phase formation of FePt films prepared by high current-density ion-beam irradiation and rapid thermal annealing methods" (2005). *Si-Hwang Liou Publications*. 81.
https://digitalcommons.unl.edu/physicsliou/81

Authors

T. Yokota, M.L. Yan, Yinfan Xu, L. Gao, R. Zhang, LeighAnn Nicholl, Lu Yuan, Ralph Skomski, David J. Sellmyer, Sy_Hwang Liou, Chih-Huang Lai, Cheng-Han Yang, and Sheng-Huang Huang

JOURNAL OF APPLIED PHYSICS **97**, 10H306 (2005)

Magnetic properties and $L1_0$ phase formation of FePt films prepared by high current-density ion-beam irradiation and rapid thermal annealing methods

T. Yokota, M. L. Yan, Yingfan Xu, L. Gao, R. Zhang, L. Nicholl, L. Yuan, R. Skomski, D. J. Sellmyer, and S. H. Liou[a]
Department of Physics and Astronomy and Center for Materials Research and Analysis, University of Nebraska, Lincoln, Nebraska 68588-0111

Chih-Huang Lai, Cheng-Han Yang, and Sheng-Huang Huang
Department of Materials Science and Engineering, National Tsing Hua University, 300, Hsin-Chu, Taiwan

(Presented on 9 November 2004; published online 11 May 2005)

We investigated magnetic properties and $L1_0$ phase formation of FePt films by rapid thermal annealing (RTA) and high current-density ion-beam irradiation. The sample prepared by RTA at 550 °C has (001) texture and strong magnetic perpendicular anisotropy with H_c equal to 6 kOe. The sample irradiated at 5.04 $\mu\text{A/cm}^2$ has H_c equal to 10 kOe but has isotropic magnetic properties due to the (111) texture. The magnetic correlation length of the ion-irradiated sample was about twice as large as that of the RTA sample. This may be due to the inhomogeneity of the $L1_0$ phase formation in the ion-irradiated film. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853018]

I. INTRODUCTION

Binary alloys such as CoPt and FePt with a $L1_0$ phase exhibiting high magnetocrystalline anisotropy are potential candidates for high-density recording media.[1–4] For such high-density recording media, it is necessary to have a high coercivity and a grain size[5] less than 5 nm. In order to achieve these requirements, several studies were reported.[6–13] For example, a small grain and a high perpendicular magnetic anisotropy $L1_0$ phase has been observed on FePt films using multilayer deposition techniques and a rapid thermal annealing (RTA) method. In general, an annealing temperature of about 350–550 °C is required.[10–14]

Ion-irradiation has been applied widely to modify the magnetic properties in magnetic thin films or superlattices. He-ion irradiation was used to control the degree of chemical ordering of FePd, Co/Pt, and FePt films.[14–19] The long-range ordering factor S, which is defined as the probability of correct site occupation in the $L1_0$ lattice, of sputtered FePt (001) films can be improved by using irradiation. High current-density He-ion irradiation is also effective for low-temperature $L1_0$ phase formation.[20]

Both RTA and ion-irradiation methods have been shown to achieve the $L1_0$ phase in FePt films for high-density recording media. In order to investigate any physical differences between RTA and ion-irradiation methods, we studied the magnetic properties and $L1_0$ phase formation of multilayered $[\text{Fe}(4.8\ \text{Å})/\text{Pt}(5\ \text{Å})]_{10}/\text{C}(100\ \text{Å})$ films using both ion-irradiation and RTA methods.

II. EXPERIMENT

[Fe/Pt]/C films were prepared by conventional dc magnetron sputtering. The thickness of each layer of Fe and Pt was 4.8 and 5 Å, respectively. The total thickness was about 100 Å. C (100 Å) was used as an underlayer on a Si (100) substrate. The base pressure before introducing the Ar gas was 3.0×10^{-7} Torr and the gas pressure during deposition was 4 mTorr. Some as-deposited films were annealed in a rapid thermal annealing (RTA) chamber. The ramp rate was 100 °C/s. The annealing temperatures were varied from 400 to 600 °C and the annealing times were varied from 5 to 600 s. He-ion irradiation was also performed on other as-deposited films at ambient temperature with an energy of 2 MeV by using a Van de Graaff accelerator. The beam current was set between 1.25 and 6 $\mu\text{A/cm}^2$. The temperature on the sample surface during irradiation was measured by an attached thermocouple. The magnetic properties of the sample were measured at room temperature using a superconducting quantum interference device magnetometer. The structural analysis of the films was performed with an x-ray diffractometer (XRD) using Cu K_α radiation. Magnetic domain images were measured by magnetic force microscopy (MFM).

III. RESULTS AND DISCUSSION

Figure 1(a) shows magnetization versus applied magnetic field (M-H) curves, in plane and out of plane, of a RTA sample. Strong perpendicular anisotropy was obtained in this film. The saturation magnetization and the coercive field (H_c) estimated by the perpendicular magnetization curve are about 900 emu/cm^3 and 6 kOe, respectively. Figure 1(b) shows the XRD pattern of the sample annealed at 550 °C for 300 s by RTA method. The (001) peak, which is related to the fct phase, was clearly observed. Since this diffraction intensity was higher than (111) diffraction, which is the most thermodynamically stable plane in the fct structure, this film

---

[a] Author to whom correspondence should be addressed; electronic mail: sliou@unl.edu

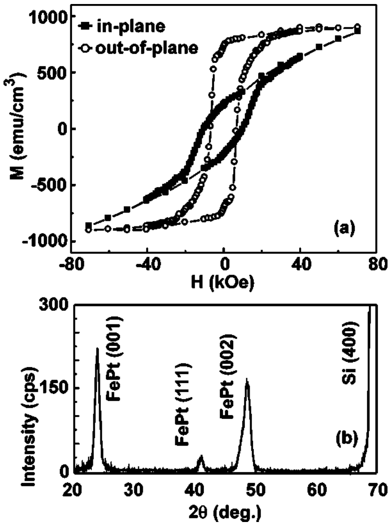

FIG. 1. (a) Typical magnetization curves for in plane (open circle) and out of plane (open square) of the sample annealed at 550 °C for 300 s by RTA method. (b) XRD patterns of the same sample.

is preferentially (001) oriented. The ordering factor S is about 0.81, which was estimated from the integrated diffraction intensity ratio $I_{(001)}/I_{(002)}$.[21–25]

In a second experiment, we performed He-ion irradiation on the same as-deposited films and investigated the dependence of coercivity on current density. From our earlier study on cosputtered FePt films, drastic changes[14] in coercivity have been observed above an ion dose of 10^{16} ions/cm^2. Therefore, in this study the dose number was fixed at 2.4×10^{16} ions/cm^2 and we adjusted only the ion-irradiation current density from 1.2 to 5.04 μA/cm^2. Figure 2 shows the ion-irradiation current density dependence of M-H curves. Increasing the ion-irradiation current density increases the coercivity. For an ion-irradiation current density of 5.04 μA/cm^2, the sample surface temperature was estimated to be about 550 °C, which was measured by an attached thermocouple on the surface. The radiation time was about 6 min. As shown in Fig. 2(d), a coercivity as large as 10 kOe is observed and there is no significant difference in the coercivity as evidenced from the in-plane and out-of-plane M-H curves. This means that the magnetic easy axis is random. Such a large coercivity observed in the FePt film under this irradiation condition should be consistent with the fct structure. Figure 3 shows the XRD patterns of these samples. All samples show only a strong (111) diffraction peak indicating the texture of the crystallites in these films. Since the magnetic easy axis of the ordered $L1_0$ FePt phase is along the ⟨001⟩ direction, the (111) texture is consistent with a randomly distributed magnetocrystalline anisotropy in these films. Although a (001) diffraction peak was not observed, the (111) diffraction peak is shifted toward the higher angle side, which indicates the existence of $L1_0$ phase in these films. Figure 4 shows the change in the d spacing (d_{111}) of these films versus ion current density. The d spacing of the samples is rapidly decreased by an ion-irradiation current density around 3.36 μA/cm^2. Since the d spacing of the sample irradiated at 5.04 μA/cm^2 is about 2.197 Å (which is still higher than the theoretical d_{111} spacing of stoichiometric FePt which is 2.195 Å) it indicates that the disordered fcc FePt phase is not completely transformed into the ordered fct FePt phase in this film. The ordered fct FePt phase in this ion-irradiated film may not be homogeneous.

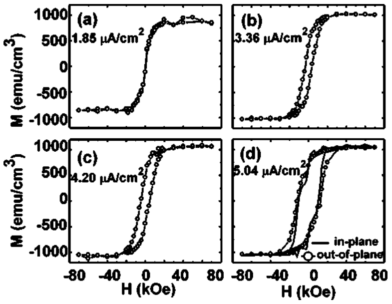

FIG. 2. The beam current-density dependence of out-of-plane M-H curves. He-ion irradiation was performed with an energy of 2 MeV by using a KN accelerator. The dose of He ions was fixed at 2.4×10^{16} ion/cm^2.

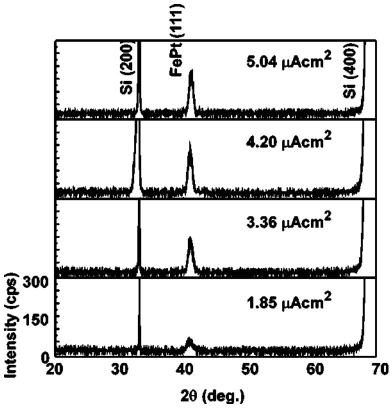

FIG. 3. Beam current-density dependence of XRD patterns for the sample shown in Fig. 2.

Figure 5 shows magnetic domain images measured by MFM. The samples were in a thermally demagnetized state. The images were obtained using a high coercivity CoPt MFM tip which was magnetized along the z direction (perpendicular to the sample surface). The MFM images were measured using a 10-nm lift height. They have been used to deduce correlation lengths (the average interaction-domain sizes). The correlation length shows the magnetic exchange coupling across the grains. The magnetic correlation length of the sample annealed by RTA is about 130 nm and that of the sample irradiated with a current density of 5.04 μA/cm^2

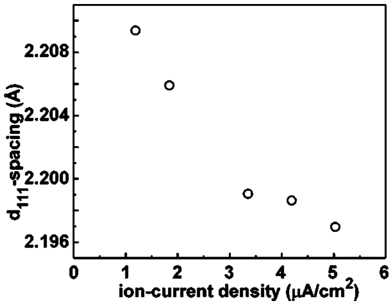

FIG. 4. Change in the d spacing (d_{111}) of the ion-irradiated sample versus beam current density.

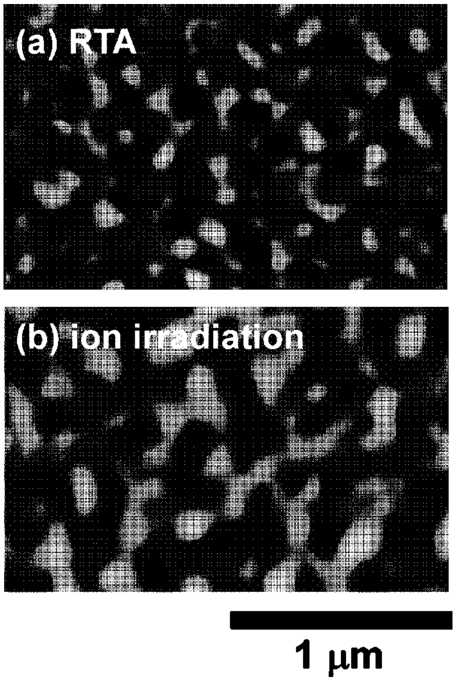

FIG. 5. MFM images of both (a) the sample annealed by RTA method and (b) the sample irradiated at a beam current density of 5.04 μA/cm^2.

is about 260 nm. The MFM observation of the correlation length indicates that more grains are coupled in the irradiated sample than in the RTA sample. This is consistent with the incomplete formation of $L1_0$ phase in the irradiated sample which causes stronger coupling between the grains with hard fct phase and those with soft fcc phase.

IV. SUMMARY

We have investigated the magnetic properties and the $L1_0$ phase formation of FePt multilayered films with ion-irradiation and RTA methods. Judging from the results mentioned above, in FePt:C films both RTA and high current-density ion-irradiation methods can produce the $L1_0$ phase formation. There are physical differences between these methods. The sample annealed at 550 °C by RTA has perpendicular anisotropy with a coercivity of 6 kOe. It also showed (001) texture. The ion-irradiated sample with a current-density of 4.2 μA/cm^2, which corresponds to a surface temperature of 450 °C, has the same coercivity as that of the sample annealed by RTA. All ion-irradiated samples have (111) texture and isotropic magnetic properties. The magnetic correlation length is about two times larger than that of the RTA sample. The high current-density seems to make a high temperature at the surface of the sample. It will produce enhancement of the diffusivity so that a higher volume fraction of the ordered fct phase is formed. However, the phase formation of the sample by ion irradiation is not as uniform as that of the sample annealed by RTA so that the magnetic domain structure of the ion-irradiated sample was larger than that of the sample annealed by RTA. This is likely caused by the inhomogenous distribution of the $L1_0$ phase on the ion-irradiated films.

ACKNOWLEDGMENT

Research was supported by NSF MRSEC Grant No. DMR-0213808, and Army Research Office Grant No. DAAD 19-03-1-0298, DOE, INSIC, and the W. M. Keck Foundation.

[1] E. S. Murdock, IEEE Trans. Magn. **28**, 3078 (1992).
[2] K. R. Coffey, M. A. Parker, and J. K. Howard, IEEE Trans. Magn. **31**, 2737 (1995).
[3] S. Sun, C. B. Murray, D. Weller, L. Folks, and A. Moser, Science **287**, 1989 (2000).
[4] A. S. Darling, Platinum Met. Rev. **7**, 96 (1963).
[5] D. J. Sellmyer, M. Yu, and R. Kirby, Nanostruct. Mater. **12**, 1021 (1999).
[6] T. Suzuki, H. Muraoka, Y. Nakamura, and K. Ouchi, IEEE Trans. Magn. **39**, 691 (2002).
[7] N. Honda, K. Ouchi, and S. Iwasaki, IEEE Trans. Magn. **38**, 1615 (2002).
[8] R. Woods, IEEE Trans. Magn. **36**, 36 (2000).
[9] T. Suzuki, N. Honda, and K. Ouchi, J. Magn. Soc. Jpn. **21**, 177 (1997).
[10] T. Maeda, T. Kai, A. Kikitsu, T. Nagase, and J. Akiyama, Appl. Phys. Lett. **80**, 2147 (2002).
[11] S. R. Lee, S. Yangt, Y. K. Kim, and J. G. Na, Appl. Phys. Lett. **78**, 4001 (2001).
[12] H. Kodama, S. Momose, N. Ihara, T. Uzumaki, and A. Tanaka, Appl. Phys. Lett. **83**, 5253 (2003).
[13] J. A. Christodoulides, M. J. Bonder, Y. Huang, Y. Zhang, S. Stoyanov, G. C. Hadjipanayis, A. Simopoulos, and D. Weller, Phys. Rev. B **68**, 054428 (2003).
[14] M. L. Yan, X. Z. Li, L. Gao, S. H. Liou, D. J. Sellmyer, R. J. M. van de Veerdonk, and K. W. Wierman, Appl. Phys. Lett. **83**, 3332 (2003).
[15] T. Yokota, L. Gao, S. H. Liou, M. L. Yan, and D. J. Sellmyer, J. Appl. Phys. **95**, 7270 (2004).
[16] D. Ravelosona, C. Chappwet, H. Bernas, D. Halley, Y. Samson, and A. Marty, J. Appl. Phys. **91**, 8082 (2002).
[17] T. Develder, Phys. Rev. B **62**, 5794 (2000).
[18] D. Ravelosona, C. Chappwet, V. Mathet, and H. Bernas, Appl. Phys. Lett. **76**, 236 (2000).
[19] B. D. Terris, L. Folks, D. Weller, J. E. Baglin, A. J. Kellock, H. Rothuizen, and P. Vettiger, Appl. Phys. Lett. **75**, 403 (2002).
[20] C. H. Lai, C. H. Yang, and C. C. Chiang, Appl. Phys. Lett. **83**, 4550 (2002).
[21] S. Okamoto, O. Kitakami, and Y. Shimada, J. Magn. Magn. Mater. **208**, 102 (2000).
[22] J.-U. Thiele, L. Folks, M. F. Toney, and D. K. Weller, J. Appl. Phys. **84**, 5686 (1998).
[23] B. E. Warren, *X-ray Diffraction* (Dover, New York, 1990), pp. 208–211.
[24] O. Kitakami, H. Sato, Y. Shimada, F. Sato, and M. Tanaka, Phys. Rev. B **56**, 13849 (1997).
[25] C. Chen, O. Kitakami, S. Sato, and Y. Shimada, Appl. Phys. Lett. **76**, 3218 (2000).