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Highly (001)-oriented Ni-doped $L1_0$ FePt films and their magnetic properties

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We report on Ni-doped nonepitaxial $L1_0$ FePt thin films with strong (001) texture. The influences of Ni doping on $L1_0$ ordering, orientation, and the magnetic properties of the FePt films have been investigated. In-plane and out-of-plane x-ray diffractions (XRD) were used to analyze the texture of FeNiPt films. For $[Fe(0.38 \, nm)/Ni(0.04 \, nm)/Pt(0.4)]_{13}$ sample, the out-of-plane XRD data showed only $(00l)$ peaks and in-plane data showed $(hk0)$ peaks after annealing, indicating high (001) texture of the FeNiPt films. In comparison with FePt, the $(00l)$ peak positions shifted to higher angle, indicating partial Ni substitution in the $L1_0$ lattice. The coercivity, measured at room temperature, decreased as a function of Ni doping. For the film with a Ni layer thickness of 0.06 nm, the coercivity is about 6 kOe after annealing, which is suitable for the writing performance of high-anisotropy perpendicular recording media. © *2005 American Institute of Physics.*
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INTRODUCTION

Areal densities in magnetic recording have been increasing at such a rapid rate that 1Tbit/in.^{2} densities are now targeted. In order for these recording densities to be obtained, the media must have small isolated grains and adequate thermal stability. The thermal stability factor $\xi = K_u V/k_B T$ must be larger than about 50, where K_u is the anisotropy and V is the grain volume. $L1_0$ structure FePt exhibits a high magnetocrystalline anisotropy ($K_u \sim 5-7 \times 10^7 \, erg/cm^3$) and has the potential for thermally stable 1 Tbit/in.^{2} perpendicular recording media. Recently, FePt and/or FePt-based films with c axis perpendicular to the film plane [(001) texture] have been obtained by two methods. In the epitaxial-growth method, heated single-crystal, textured substrates or seed layers, such as MgO, etc., have been used for the epitaxial growth of the FePt to obtain c axis perpendicular to the film plane.[1,2] Another method is that of nonepitaxial growth. In this method, FePt and/or FePt-based films were first deposited onto Si wafer or glass substrates with an initial multilayered structure, and then the as-deposited films were annealed at a temperature necessary to obtain $L1_0$ phased films with (001) texture. The multilayering of Fe/Pt and dimensions of the Fe and Pt individual layers, annealing temperature and time, total film thickness, alloy composition, etc., appear to play an important role in obtaining the films with c axis perpendicular to the film plane.[3,4] Recent modeling results suggested that the media for future 1 Tbit/in.^{2} should have small grain size ($d \sim 4 \, nm$) and narrow distribution ($\sigma/d \sim 0.07$), moderate anisotropy ($H_k \sim 25 \, kOe$), coercivity ($H_c \sim 5-8 \, kOe$), and saturation magnetization ($M_s \sim 750 \, emu/cc$). In this study, we report on Ni-doped nonepitaxial $L1_0$ FePt thin films with strong (001) texture. The Ni doping is used to control and adjust magnetic properties of the FePt films for use as an extremely high-density perpendicular recording media.

EXPERIMENTAL METHODS

All FeNiPt thin films in this study were sputtered directly onto the thermally oxidized Si(100) wafer with a $(Fe/Ni/Pt)_n$ multilayer structure at room temperature. No buffer layer or seed layer was used. Figure 1 shows the initial structure schematically for the preparation of FeNiPt thin films. The thicknesses of individual Fe and Pt layers were 0.38 and 0.4 nm, respectively. The thicknesses of the Ni layer were changed from 0 to 0.1 nm to adjust the Ni-doping level. The sputtering pressure was 4 mTorr for all layers in
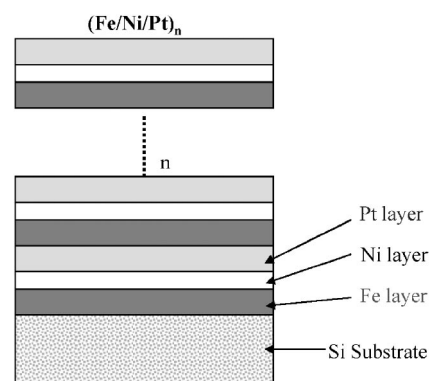

FIG. 1. Preparation schematic sketch of the nonepitaxially grown FeNiPt thin films.
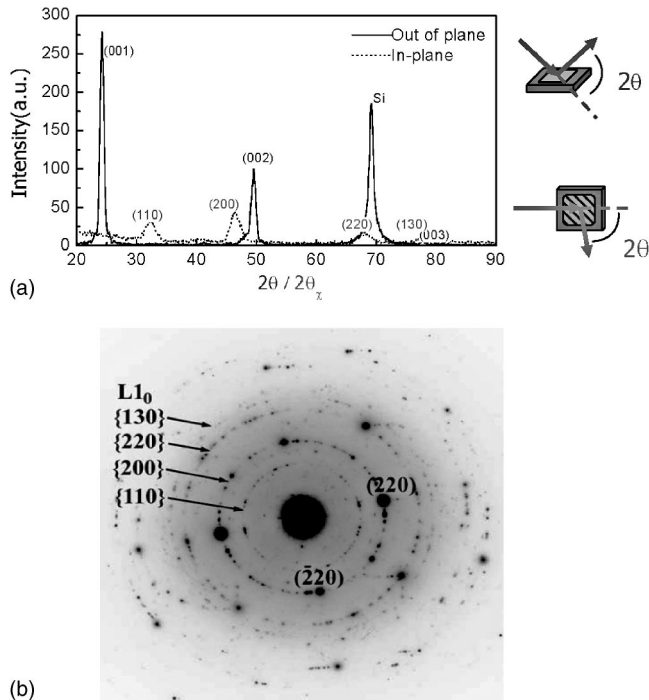
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(a)

(b)

FIG. 2. (a) Out-of-plane and in-plane XRDs and (b) SAED patterns of [Fe(0.38 nm)/Ni(0.04 nm)/Pt(0.4 nm)]$_{13}$ film. Film was annealed at 600 °C for 10 min.

FIG. 3. XRD patterns of [Fe(0.38 nm)/Ni(x)/Pt(0.4 nm)]$_{13}$ films with x =0, 0.02, 0.04, 0.06, 0.08, and 0.1 nm. Films were annealed at 600 °C for 5 min.

the film structure. The deposition rates for all layers were around 0.5 Å/s. The as-deposited films were annealed by rapid thermal annealing (RTA) at 600 °C for 5–10 min. Magnetic properties were measured using a superconducting quantum interference device (SQUID) in fields up to 7 T. A microstructural evolution of the nonepitaxial growth was investigated by Rigaku x-ray diffraction (XRD) and JEOL 2010 transmission electron microscope (TEM).

RESULTS AND DISCUSSION

Out-of-plane and in-plane XRDs and selective-area electron diffraction (SAED) were used to characterize the phase transformation and orientation. Figure 2 shows (a) the out-of-plane and in-plane XRDs and (b) SAED patterns for annealed FeNiPt sample. The sample was deposited with multilayer structure of [Fe(0.38 nm)/Ni(0.04 nm)/Pt(0.4 nm)]$_{13}$ and postannealed at 600 °C for 10 min. As shown in Fig. 2(a), (200) and (002) peaks were clearly separated, which implies that the film is a single $L1_0$ fct phase, without a significant amount of fcc phase after annealing. The interesting result is that the out-of-plane XRD data show only (001), (002), and (003) peaks except for the Si diffraction peak and the in-plane data show only (110), (200), (220), and (130) peaks. This result indicates that the film is highly (001) textured. The SAED pattern [Fig. 2(b)] shows diffraction rings corresponding to the indices of {110}, {200}, {220}, and {130} of the $L1_0$ phase, together with the diffraction spots of the Si[001] zone axis (two basic diffraction spots are indexed). Both XRD and SAED patterns confirm the perpendicular orientation [high (001) texture] of the film.

Figure 3 compares the out-of-plane XRD data for [Fe(0.38 nm)/Ni(x)/Pt(0.4 nm)]$_{13}$ films with x=0, 0.02,

0.04, 0.06, 0.08, and 0.1 nm. All samples were annealed at 600 °C for 5 min. For the sample with x=0, i.e., the Fe$_{55}$Pt$_{45}$ film, the XRD pattern shows a clear (001) chemically ordered FePt peak and the fct (002) peak, indicating that the film was strongly (001) textured. With an increase of the Ni layer thickness, i.e., Ni content, the (00l) peak positions of FeNiPt films shifted to higher angle in comparison with FePt, which suggested partial Ni substitution in the $L1_0$ lattice. The same result has been obtained by Thiele *et al.*[5] They observed the change in the lattice parameters as a function of Ni content x in Fe$_{55-x}$Ni$_x$Pt$_{45}$ films. Figure 3 also shows that the trends in (001) and (002) peak intensities of FeNiPt films decrease with the increase of Ni layer thickness, and the (111) peaks are visible when Ni layer thickness is larger than 0.06 nm. The measured I_{001}/I_{002} intensity ratio in the XRD patterns can be used to estimate the approximate order parameter in the $L1_0$ structure. If we assume that Ni and Fe atoms were randomly distributed and partial Ni substitution for Fe in the lattice site of the $L1_0$ structure, the trend of the ordering could be estimated by using I_{001}/I_{002} ratio. The decrease of I_{001} and I_{002} as well as I_{001}/I_{002} ratio reflects the changes in either order parameter or texture with the increase of the Ni content. These results show that it becomes more difficult to obtain the phase transform from fcc to fct in the same annealing temperature in FeNiPt films, and the (001) texture also becomes weaker with an increase of the Ni content.

Figure 4 shows the perpendicular hysteresis loops of [Fe(0.38 nm)/Ni(x)/Pt(0.4 nm)]$_{13}$ films with x=0, 0.02, 0.04, and 0.06 nm measured at room temperature by SQUID with applied field up to 7 T. The annealing condition for these samples is the same as mentioned above. As shown in Fig. 4, hysteresis loop shape, coercivity, and remanence ratio of the FeNiPt films are changed with Ni doping. The FePt film has high remanence ratio and coercivity around 11 kOe, while the film with a Ni layer thickness of 0.06 nm has its coercivity reduced to 6 kOe and loop shows a lower remanence ratio. The dependence of coercivity on Ni content is shown in Fig. 5. These results indicate that magnetic properties can be tailored with different Ni content, and FeNiPt films may be prepared suitably for reading and writing in practical recording media. The origin of the decrease of co-
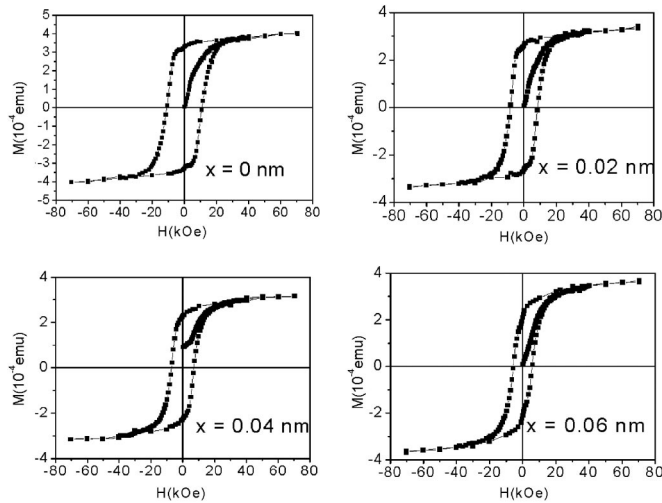
FIG. 4. Perpendicular hysteresis loops of [Fe(0.38 nm)/Ni(x)/Pt(0.4 nm)]$_{13}$ films with $x=0$, 0.02, 0.04, and 0.06 nm. Films were annealed at 600 °C for 5 min.

ercivity on adding Ni to FePt is likely to be a decrease in the anisotropy of the alloy. This follows because magnetization of FeNiPt is smaller than that of FePt and the anisotropy is proportional to $M^n(T)$, where $n=2$.[5]

Based on NiPt phase diagram, the variation of Curie temperature with composition in Ni-rich solid solution follows an approximately linear relationship and drops very quickly with the increase of the Ni content. So it is interesting in understanding and comparing the temperature dependence of magnetization between NiPt and FeNiPt films because Ni-doping level may affect the behavior of temperature dependence of FeNiPt. Figure 6 shows the temperature dependence of normalized magnetization $m=M(T)/M(4$ K$)$ and coercivity H_c for the [Fe(0.38 nm)/Ni(0.04 nm)/Pt(0.4 nm)]$_{13}$ film annealed at 600 °C for 5 min. Magnetization M was measured at 7 kOe. As shown in Fig. 6, magne-

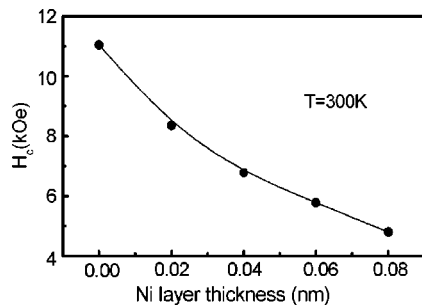FIG. 5. Coercivity H_c variation with Ni layer thickness for [Fe(0.38 nm)/Ni(x)/Pt(0.4 nm)]$_{13}$ films. Film was annealed at 600 °C for 10 min.
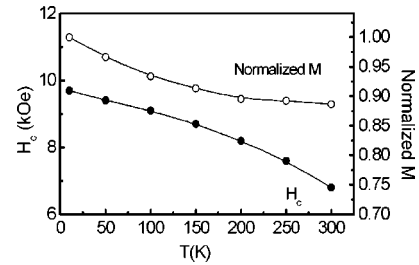
FIG. 6. Temperature dependences of coercivity H_c and normalized magnetization m of [Fe(0.38 nm)/Ni(0.04 nm)/Pt(0.4 nm)]$_{13}$. $m=M(T)/M(4$ K$)$ and measured at 70 kOe. Film was annealed at 600 °C for 5 min.

tization M drops only around 10% and coercivity H_c drops steadily from 9.8 to 6.9 kOe when temperature changes from 4 K to room temperature. A similar behavior has been observed by Thiele *et al.*[5] They measured Curie temperature of FeNiPt films with different Ni content and found that Curie temperature drops from 770 to 490 K when Ni content increases from 0 to 30 at. % in FeNiPt films. In comparison with NiPt, in which the Curie temperature drops to 373 K when Ni content increases to 25 at. %,[6] this result shows that dependence of magnetization on temperature in FeNiPt films is relatively weaker than that of NiPt.

CONCLUSIONS

In this paper we have studied the magnetic property, structure, and orientation of nonepitaxially grown $L1_0$ FePt films with Ni doping. XRD and SAED patterns show that FeNiPt films were highly (001) textured. Ni doping of FePt was effective in reducing the coercivity of the films. Temperature dependence of coercivity and magnetization shows that FeNiPt films have suitable magnetic properties for perpendicular magnetic recording at room temperature.

ACKNOWLEDGMENTS

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