10-2-2000

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Luo, C.P.; Liou, Sy_Hwang; Gao, L.; Liu, Yi; and Sellmyer, David J., "Nanostructured FePt:B$_2$O$_3$ thin films with perpendicular magnetic anisotropy" (2000). Si-Hwang Liou Publications. 65.
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Nanostructured FePt:B$_2$O$_3$ thin films with perpendicular magnetic anisotropy

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(Received 24 April 2000; accepted for publication 3 August 2000)

FePt/B$_2$O$_3$ multilayers were deposited by magnetron sputtering onto 7059 glass substrates. By annealing the as-deposited films at 550 °C, nanostructured FePt:B$_2$O$_3$ films consisting of FePt grains with $L1_0$ structure, embedded in a glassy B$_2$O$_3$ matrix, were obtained. The $c$ axes of the FePt grains can be made to align with the film normal direction, which results in a perpendicular anisotropy constant of $3.5 \times 10^7$ erg/cc. The films remain layered structures after annealing when the B$_2$O$_3$ layer thickness exceeds 16 Å. The nanostructure of the films was investigated by transmission electron microscopy. The coercivities and the average grain sizes of the films are dependent on the B$_2$O$_3$ concentrations, with coercivities varying from 4 to 12 kOe, while average grain sizes vary from 4 to 17 nm. Strong perpendicular anisotropy, adjustable coercivity, and fine grain size suggest this nanocomposite system might have significant potential as recording media at extremely high areal density. © 2000 American Institute of Physics.

The growth mechanism, magnetic, and structural properties of FePt equiatomic alloy thin films with the $L1_0$ ordered structures are of great interest from both scientific and application viewpoints. They are potential high-density recording media and high-energy permanent magnets because of their exceptional magnetic properties. The essential feature is that they can undergo a phase transition from the disordered face-centered cubic (fcc) structure to the ordered face-centered tetragonal (fct) structure ($L1_0$ phase) after post-deposition annealing, or when deposited at an elevated substrate temperature. The long-range ordering has critical effects on the magnetic properties of the films. It is well known that the ordered FePt alloy has a very high anisotropy constant $K_1$ of $7 \times 10^6$ erg/cc, and recently $K_1$ values greater than $10^8$ erg/cc were found in fully ordered FePt films grown by molecular beam epitaxy (MBE). FePt thin films deposited by magnetron sputtering tend to grow with a (111) texture, placing the $c$ axes of the grains at an angle of 36° above the film plane. By applying the MBE technique, FePt can grow epitaxially on MgO (001) single-crystal substrates with the $c$ axes of the grains in the film normal direction, resulting in perpendicular magnetic anisotropy. However, this requires complex MBE technology and MgO single crystals as substrates. In this research, we successfully deposited the FePt:B$_2$O$_3$ nanocomposite thin films on 7059 glass substrates, which consist of nanometer size, $L1_0$ structured FePt particles embedded in a B$_2$O$_3$ matrix. The $c$ axes of the particles are aligned along the film normal direction. The magnetic and structural properties of these films were investigated.

FePt/B$_2$O$_3$ multilayers were deposited on 7059 glass substrates by dc- and rf-magnetron sputtering. The base pressure of the sputtering chamber was $2 \times 10^{-7}$ Torr and high purity Ar was used for deposition at a pressure of 5 mTorr. A composite FePt target was made by putting some Fe chips (99.99% purity) on the Pt target (99.99% purity). The composition of the FePt target was adjusted by the number of Fe chips. The B$_2$O$_3$ target with a purity of 99.9% was obtained from Target Materials, Inc. The as-deposited films were annealed in vacuum at 550 °C for 30 min. The structure of the films was investigated by transmission electron microscopy (TEM) and x-ray diffraction (XRD) with Cu$K\alpha$ radiation. Magnetic properties were measured by a Quantum Design superconducting quantum interference device. Domain patterns were observed with a magnetic force microscope (MFM).

(FePt 32 Å/B$_2$O$_3$, $x$ Å)$_3$ multilayers with $x$ varying from 4 to 48 Å were deposited with the glass substrates held at ambient temperatures. The as-deposited films contain a disordered fcc FePt phase and are magnetically soft with coercivity less than 100 Oe. After annealing at 550 °C, the Fe–Pt undergoes a phase transition from the disordered fcc to the ordered fct structure, which is characterized by the (001) and (002) superlattice peaks of the XRD scans, as shown in Fig. 1. Compared with the FePt single-layer film, the intensity of the (111) diffraction peaks decreases as the B$_2$O$_3$ layer thickness increases in the FePt/B$_2$O$_3$ multilayers. As the B$_2$O$_3$ layer thickness increases to 12 Å and above, the (111) peak

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$^5$Received 24 April 2000; accepted for publication 3 August 2000

$^6$APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 14 2 OCTOBER 2000

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disappears while the (001) and (002) peaks dominate, which implies that the c axes of the grains are aligned along the film-normal direction. The full width at half-maximum intensity of the (001) peak rocking curve [inset of Fig. 1(c)] is about 2.9°, indicating the c axes are aligned quite well along the film-normal direction. The reason for this c-axis orientation is not clear, but presumably involves the growth mechanism of the ordered FePt crystallites; further investigations are in progress. The broadening of the (001) and (002) peaks indicates shorter coherence length normal to the film as the B$_2$O$_3$ layer thickness increases. The films with B$_2$O$_3$ layer thickness equal to 16 Å or larger retain a layered structure after annealing; an example of the low-angle XRD pattern is shown in the inset of Fig. 1(d).

The nanostructure of the annealed FePt/B$_2$O$_3$ multilayers was investigated by TEM. Figure 2(a) is a bright field image of the 550 °C annealed (FePt 32 Å/B$_2$O$_3$ 12 Å)$_5$ multilayer. The FePt grain size was found in a wide range from 10 to 30 nm. As the B$_2$O$_3$ concentration increases, the grain size decreases. Figure 2(b) is a high resolution TEM image of the annealed (FePt 32 Å/B$_2$O$_3$ 20 Å)$_5$ multilayer. It shows that fine FePt single crystals about 4 nm in size were randomly dispersed in the B$_2$O$_3$ matrix.

Hysteresis loops were measured with applied fields both parallel and perpendicular to the film plane. For the FePt L$_1_0$ phase, the c axis is the magnetic easy axis. Similar hysteresis loops were obtained in both directions for the FePt single-layer film and the (FePt 32 Å/B$_2$O$_3$ 8 Å)$_5$ multilayer, as shown in Figs. 3(a) and 3(b), which implies the random ori-
magnetization. The in-plane hysteresis loops diminish as the B$_2$O$_3$ layer thickness increases. This is consistent with the XRD measurements.

The saturation magnetization $M_s$ of the films decreases as B$_2$O$_3$ thickness increases due to the increase of B$_2$O$_3$ concentration, as shown in Fig. 4(a). After normalization by the volume fraction of FePt, the $M_s$ of the FePt phase in the FePt:B$_2$O$_3$ nanocomposites is about 1000 emu/cc, slightly less than the $M_s$ (~1100 emu/cc) of the FePt single layer film. This might be due to the isolation of FePt grains by the B$_2$O$_3$ matrix, resulting in smaller moments for the atoms at the grain surface. By extrapolating the magnetization curves, the anisotropy field $H_K$ and anisotropy energy $K_u=M_sH_K/2$ were obtained, as shown in Fig. 4(b). The $H_K$ values are around 70–80 kOe, which is close to the $H_K$ value of the Fe$_{45}$Pt$_{55}$ thin film measured by Li and Lairson. With $M_s=1000$ emu/cc, the $K_u$ value is about $3.5 \times 10^7$ erg/cc.

The average grain size $d$ was estimated by the Scherrer formula$^{11}$ from the (001) diffraction peak. The dependence of $d$ and coercivity $H_c$ on the B$_2$O$_3$ layer thickness are shown in Fig. 5. The average grain sizes are well below the critical single domain particle size ($\sim 300$ nm). Since the coercivity is much smaller than the anisotropy field ($H_c/H_K<0.2$), an incoherent reversal mechanism is suggested. As shown in Fig. 5, a small amount (up to 20 vol. %) of B$_2$O$_3$ sharply increases the coercivity from 5.2 to 12 kOe. At the same time, the grain size $d$ only slightly changes. Therefore, the increase in coercivity might be due to the decrease of intergranular exchange coupling and/or the increase of the number of pinning sites when B$_2$O$_3$ is added. However, further increase of B$_2$O$_3$ results in the sharp decrease of $H_c$. This is probably due to the sharp decrease in grain size and thermal activation effect plays an important role in magnetization reversal when grain size is below 10 nm. When the B$_2$O$_3$ layer thickness reaches 28 Å and above, $d$ remains a constant value, close to the FePt layer thickness. This is consistent with the low angle XRD scans which indicate that the film retains a layered structure after annealing.

In summary, FePt:B$_2$O$_3$ nanocomposite thin films with strong perpendicular anisotropy were successfully fabricated on glass substrates. The fabrication of the films requires only conventional sputter-deposition and thermal-annealing processing. Under appropriate conditions these films consist of L1$_0$ FePt particles embedded in the B$_2$O$_3$ matrix with the c axes of the grains aligned along film normal direction. A high anisotropy energy was found, about $3.5 \times 10^7$ erg/cc. The grain sizes and coercivities were found to be dependent on the B$_2$O$_3$ layer thickness. These films have fine grain sizes (<10 nm), adjustable coercivities (4–12 kOe), and perpendicular magnetic anisotropy, which suggest this nanocomposite system may have significant potential as recording media at extremely high areal densities.$^{12}$

This research was supported by the DOE under Grant No. DOE-DE-FG-03-98ER45703. In addition Y.L. and D.J.S. benefited from the support of DARPA/ARO and AFOSR, and S.H.L. and L.G. were supported by ARO under Grant No. DAAG 55-98-1-0014, and from the support of CMRA and NRI at the University of Nebraska.