FePt film on self-assembled SiO₂ particle arrays

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Chemically $L1_0$ ordered (001) textured FePt thin films with perpendicular magnetic anisotropy can be grown on amorphous planar SiO₂ substrate with an underlayer stack of [Pt (3 nm)/Cr (50 nm)] adopting a [002] orientation when deposited at 350 °C. This knowledge of optimum layer stack was transferred to self-assembled SiO₂ particle arrays. While 330 nm SiO₂ particle arrays reveal perpendicular magnetic anisotropy with a remanence of almost one and a coercivity of 370 mT, on 160 nm particles, the FePt caps show a (111) texturing, leading to the random orientation of the easy axis of the magnetization. © 2008 American Institute of Physics. [DOI: 10.1063/1.2841729]

I. INTRODUCTION

Information density of modern magnetic storage devices is rapidly increasing. For a further increase of data density, the concept of patterned media where an information unit (bit) is stored in a single nanostructure is considered to be one of the most promising candidates. To produce patterned magnetic media, numerous lithography techniques and nanoimprint approaches^{1–4} have been applied. In addition, different self-assembly techniques such as anodized alumina,⁵ phase separation in block copolymers,⁶ surface instability induced by ion bombardment,⁷ nanoindentation approach,⁸ and self-assembled magnetic particles^{9–12} have attracted much attention. For the latter, combining nanoparticle self-assembly with defined magnetic properties provided by a magnetic film, deposited onto the particles,^{13,14} enables an elegant possibility to create magnetic nanostructure arrays with high perpendicular magnetic anisotropy required for high thermal stability. An ideal candidate for such a material is the FePt alloy in chemically $L1_0$ ordered phase. However, several issues have to be addressed: (i) chemical ordering of the alloy has to be achieved in order to induce high magnetic anisotropy values and (ii) (001) texturing of the FePt alloy is required to achieve uniaxial anisotropy perpendicular to the surface. While the first issue can be easily solved by thermal annealing during alloy deposition onto SiO₂ particles, the second property is more difficult to achieve, because it requires the growth of the ordered alloy with the [001] tetragonal axis perpendicular to the surface on an amorphous SiO₂ surface.

In this regard, Sun *et al.*¹⁵ have recently reported an approach where partly ordered $L1_0$ FePt(001) films were grown on amorphous glass substrates utilizing Cr seed layer. In the present study, this approach has been transferred to the FePt growth on arrays of amorphous SiO₂ particles. The

magnetic and structural properties of FePt alloy films deposited onto self-assembled SiO₂ particle arrays with sizes of 160 and 330 nm are discussed and the results were compared to the continuous FePt films deposited on planar thermally oxidized Si(001) substrates.

II. SAMPLE PREPARATION AND INVESTIGATION TECHNIQUES

A monolayer of self-assembled SiO₂ particles was prepared by using the conventional routine proposed by Micheletto *et al.*,¹⁶ where a droplet of a particle/water mixture is deposited onto a thermally oxidized silicon wafer. After the preparation of the particle array, the sample was introduced into a molecular beam epitaxy chamber operating at a base pressure of 2×10^{-10} mbar. Metal deposition was carried out utilizing two electron beam sources. The composition of the codeposited FePt alloy was controlled by a mass spectrometer adjusting the ratio between the individual Fe and Pt fluxes. Typical values of the rates R are $R(\text{Fe}) = 0.023 \text{ Å/s}$ and $R(\text{Pt}) = 0.029 \text{ Å/s}$. The rate during Cr deposition was 0.1 Å/s . The complete film stack is as follows: FePt (5 nm)/Pt (3 nm)/Cr (t_{Cr}), where the thickness of the Cr seed layer t_{Cr} was varied. While the deposition temperature T_{dep} of the FePt alloy was kept constant at 450 °C, the deposition temperature for the Cr seed layer and the Pt buffer layer was varied between 350 and 450 °C. For comparison, film stacks were deposited at the same time on the sphere arrays and on planar thermally oxidized Si(001) substrates.

The structural characterization has been carried out by x-ray diffraction (XRD) using a four-circle Huber diffractometer equipped with a Cu $K\alpha$ rotating anode and by high-resolution transmission electron microscopy (HRTEM) employing a Philips CM300 TEM with a field emission gun operating at 300 kV. Magnetic properties of the samples were investigated by a polar magneto-optical Kerr effect (P-MOKE) magnetometer using a focused laser beam with a wavelength of 670 nm and by a superconducting quantum interference device (SQUID) magnetometer in both in-plane

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FIG. 1. (a) SQUID hysteresis loops of a FePt (5 nm)/Pt (3 nm)/Cr (50 nm) film stack grown on a planar SiO₂ substrate. The loops were measured by applying the magnetic field in the film plane and perpendicular to the film plane. (b) Atomic force and corresponding magnetic force microscope image in the demagnetized state. (c) XRD θ - 2θ scans revealing chemical L1₀ ordering with a (001) orientation.

and out-of-plane geometries. Magnetic force microscopy (MFM) was utilized to image the magnetic domain configurations of the samples at room temperature.

III. RESULTS AND DISCUSSION

Continuous films of FePt (5 nm)/Pt (3 nm)/Cr (t_{Cr}) with varying Cr layer thickness were deposited on flat thermally oxidized Si(001) substrates. While the Pt/Cr underlayer system was deposited at 350 °C, the FePt film was grown at a higher temperature of 450 °C, following the approach reported in Ref. 15. An almost square hysteresis loop in perpendicular geometry of the applied magnetic field with an effective uniaxial magnetic anisotropy of 7×10^5 J/m³ was obtained for an optimal Cr layer thickness of 50 nm, as presented in Fig. 1(a). The value of the saturation magnetization of 0.9 T was found to be slightly reduced compare to the value reported in literature for the bulk FePt alloy. Atomic force microscopy (AFM) imaging shows a rather smooth film morphology with a root-mean-square roughness

FIG. 2. (Color online) (a) Cross-sectional bright field TEM image of a FePt (5 nm)/Pt (3 nm)/Cr (50 nm) film stack grown on a planar SiO₂ substrate. (b) HRTEM micrograph of the interfacial region between the Cr and the FePt/Pt layer. (c) Cross-sectional bright field TEM image and (d) HRTEM micrograph showing the FePt/Pt/Cr layer stack on 160 nm particle.

of about 0.2 nm and the corresponding magnetic domain size measured by MFM was estimated to be about 100 nm [Fig. 1(b)].

The growth orientation of the FePt film and its chemical ordering parameter were analyzed by XRD. As shown in Fig. 1(c), a 002 peak was measured coming from both Pt underlayer and FePt layer, while no 111 reflection was detected. In addition, a pronounced 001 superstructure reflection due to chemical L1₀-type ordering in the FePt film was observed. In order to calculate the long-range ordering (LRO) parameter, the contribution of the 002 FePt peak has to be separated from 002 Pt. Assuming that the L1₀ phase is preferably grown with the tetragonal axis along the normal direction, the contribution of 002 FePt is $\sim 53\%$ of the total integrated intensity of the measured 002 peak taking into account the difference in Pt and FePt layer thicknesses and absorption coefficients. From the intensity ratio between the FePt 001 and 002 reflections, a LRO parameter of 0.7 was calculated by a standard routing presented in Ref. 17. The microstructure of the FePt/Pt/Cr film stack was studied by cross-sectional bright field TEM imaging [Fig. 2(a)], revealing columnar grains in the Cr layer with a width of 15–30 nm, while FePt grains are formed with a smaller size of 10–15 nm, in agreement with the lateral coherence length extracted from x-ray data. A HRTEM micrograph of the interfacial region between the Cr and the FePt/Pt layer is presented in Fig. 2(b). While the Cr layer has a clear [001] orientation [(110) planes are tilted by 45° with respect to the surface], the FePt/Pt layer grows along the [001] orientation with (111) planes tilted by 54° with respect to the substrate plane [Fig. 2(b)]. The difference in (111)FePt and (110)Cr plane stacking gives rise to numerous dislocations forming in the FePt layer.¹⁸ It is worth mentioning that attempts to improve the quality of the (001) texturing of the FePt alloy by increasing the deposition temperature for the Pt/Cr underlayer of up to 450 °C, resulted in a preferential [110] orientation of the Cr layer independently on the Cr layer thickness (t_{Cr} =30, 50, and 70 nm), which, in turn, leads to a mixture of (111) and (002) texturing for the FePt alloy.

FIG. 3. P-MOKE loops of a FePt (5 nm)/Pt (3 nm)/Cr (50 nm) film stack grown on an array of 160 (filled circles) and 330 nm (filled triangles) SiO₂ particles. The result on the planar SiO₂ substrate is also presented for comparison (open squares).

The optimized layer stack [FePt (5 nm, $T_{\text{dep}} = 450^\circ\text{C}$)/Pt (3 nm, $T_{\text{dep}} = 350^\circ\text{C}$)/Cr (50 nm, $T_{\text{dep}} = 350^\circ\text{C}$)] was deposited onto amorphous SiO₂ particle arrays. Figure 3 shows P-MOKE hysteresis loops for 160 and 330 nm particle arrays. The hysteresis loops reveal larger coercivity fields of about 370 mT but a rather broad switching field distribution compared to the continuous film, which is typically observed for patterned systems.¹⁹ While a remanent magnetization of almost 1 is obtained for the 330 nm particle array, a reduced value of 0.7 is observed for the 160 nm particles, indicating a drastic loss in perpendicular magnetic anisotropy. In order to visualize locally the magnetic domain configuration of the FePt cap structures, MFM imaging was carried out [Fig. 4]. For both particle sizes, a multidomain configuration, indicated by the presence of the dark/bright contrast on individual caps, is observed after demagnetizing the samples [Figs. 4(a) and 4(c)]. However, after saturation of the samples in a perpendicular field, the magnetic caps on the 330 nm particles remain in a single-domain state [Fig. 4(b)], while the 160 nm particle caps brake up into a multidomain state at remanence [Fig. 4(d)]. In this case, the different magnetic contrast on the 160 nm caps suggests that various domain orientations are present and magnetic exchange coupling might exist between the caps.

In order to shed some light into the change of magnetic

FIG. 4. [(a) and (c)] AFM/MFM images of the particle arrays at remanence after demagnetizing, and [(b) and (d)] after saturation the sample in the perpendicular magnetic field.

properties observed for the FePt film grown on the 160 and 330 nm particle arrays, the microstructure analysis of the film stack on the 160 nm particle was performed by TEM. Figure 2(c) shows a cross section of the magnetic caps on the 160 nm SiO₂ particles. First, a drastic decrease in the grain size down to 7 nm, compared to the planar SiO₂ substrate is apparent [Fig. 2(a)]. The grain structure is columnar, as for the planar film and preferentially directed perpendicular to the particle surface. The interfacial area between the grains is much wider (2–3 nm) most likely due to atomic shadowing effects during material deposition. The HRTEM analysis of an individual cap structure [Fig. 2(d)] reveals a [110] orientation of the bcc Cr layer and (111) texturing of the FePt layer revealed by inclined (002) planes [cf. dotted line in Fig. 2(d)]. However, it can be expected that a mixture of (111) and (002) texturing of the FePt alloy is present in the array, resulting in a random distribution of anisotropy directions.

IV. CONCLUSION

FePt thin films were grown on Pt/Cr underlayer stacks, which were deposited onto SiO₂ spherical particle arrays, and for comparison, on planar thermally oxidized Si(001) substrates. It was found, that the deposition of a 50 nm thick Cr seed layer at 350 °C induces a (002) texturing in the Cr layer. In addition, a 3 nm thick Pt buffer layer was deposited on the Cr layer acting as a diffusion barrier for the following FePt growth. The growth of FePt at 450 °C leads to partially ordered $L1_0$ phase with a (001) orientation, which results in strong perpendicular magnetic anisotropy of $7 \times 10^5 \text{ J/m}^3$. This optimized layer stack was successfully transferred to 330 nm SiO₂ particle arrays, where a remanence value of almost one with an out-of-plane coercivity of 370 mT was obtained. However, structural and magnetic characterizations of the cap on the 160 nm particle reveal a (110) texturing for the Cr seed layer resulting in the (111) texturing for the FePt, leading to the random orientation of the easy axis of the magnetization. Therefore, further optimization of the growth conditions is required.

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