Structure and magnetic properties of SmCo thin films on Cr/Ag/Si templates

G. Zangari,[a] B. Lu, D. E. Laughlin, and D. N. Lambeth
Data Storage Systems Center, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213-3890

SmCo thin films were grown onto highly oriented Cr/Ag/Si templates of various orientations and their properties compared to those of SmCo/Cr/glass thin film structures. No conclusive evidence of local crystalline order in SmCo films was observed by microscopy techniques. However, in-plane uniaxial magnetic anisotropy was observed for SmCo films grown onto Si(111) and (110) templates, indicating interfacial effects, while no anisotropy was observed for SmCo on Si(100). It is hypothesized that epitaxial growth of SmCo takes place on Cr(112) surfaces, but local crystalline order disappears with increasing SmCo thickness. Uniaxial SmCo films on Si(110) exhibit magnetic properties superior to those of SmCo on other Si templates. Process optimization could lead to SmCo media largely improved with respect to current SmCo films on glass. © *1999 American Institute of Physics.* [S0021-8979(99)46108-0]

I. INTRODUCTION

High-density recording systems require thin film media with high anisotropy energy density to satisfy the requirement for thermal stability of the recorded data. In particular for recording densities above 10 Gb/in.^{2}, satisfactory SNR requires a grain size approaching the thermal stability limit for hcp Co.[1] This limit can be overcome by the introduction of magnetic media with higher anisotropy. In this respect, rare earth–transition metal alloys and intermetallic compounds are particularly attractive, as they possess the highest known anisotropy values; $SmCo_5$ for example exhibits an anisotropy field $H_K \sim 200$ kOe. High anisotropy materials must generally be prepared at very high processing temperatures, incompatible with many substrates. Hence there is a need to find lower temperature processing routes.[2,3]

In the past, SmCo films have been grown by sputtering onto (110) oriented Cr films, and their properties extensively investigated.[2,4–8] The nanocrystalline state of SmCo films induced by epitaxial defects at the Cr surface[4–8] and the island microstructure of thin films of SmCo on Cr,[5,6] are reported to be at the origin of the hard magnetic properties of SmCo films. Identification of the interfacial epitaxial relationships and of the growth mechanisms would provide a route for control of the crystalline orientation of the magnetic film, and enable an enormous improvement in the magnetic, recording, and noise properties of the medium.[9]

In this article, Ag/Si epitaxial templates were used to grow SmCo/Cr thin film media structures. Epitaxial effects on the crystalline structure, orientation, and magnetic properties of the films were studied, and the possibility of controlling the anisotropy in the plane of the film was investigated. For comparison, similar films were also prepared on Corning No. 7059 glass substrates.

II. EXPERIMENT

Ag, Cr, and SmCo films were sequentially deposited by rf diode sputtering in a Leybold Heraeus Z-400 sputtering system. The SmCo target was a volume cast alloy target with composition $Sm_{23}Co_{77}$ (Johnson Matthey). The base pressure was below 5×10^{-7} Torr. For Ag and Cr deposition, the Ar pressure was 10 mTorr and the sputtering power was 2.3 W/cm^2. SmCo films were sputtered at Ar pressure of 30 mTorr and a sputtering power of 1.1 W/cm^2. No bias was applied during Ag, Cr, or SmCo deposition. A thin (~6 nm) Cr protection overlayer was sputtered on all of the samples, applying a bias of -170 V to promote a dense film.

The Si substrate was stripped of its native oxide just before introduction in the sputtering chamber by immersion in HF 49% for 3 min, then dried under a nitrogen flow,[10] to produce a H-terminated Si surface.

Crystalline structure and orientation were investigated by x-ray diffractometry (XRD), using a Rigaku x-ray diffractometer with Cu K_α radiation, and transmission electron microscopy, using a Philips EM420 TEM. Magnetic measurements were carried out on a Digital Measurement Systems vibrating sample/torque magnetometer, and an alternating gradient magnetometer.

III. RESULTS

Deposition of Cr/Ag templates onto H-terminated Si substrates gives the following template epitaxial relationships:[9–12]

(a) Cr(001)[100]‖Ag(001)[110]‖Si(001)[110],

(b) Cr(110)$[1\bar{1}0]$‖Ag(111)$[11\bar{2}]$‖Si(111)$[11\bar{2}]$,

(c) Cr(112)$[1\bar{1}0]$‖Ag(110)[001]‖Si(110)[001],

as evidenced by XRD and TEM studies.

No evidence of crystallinity for the SmCo layer was obtained by XRD or selected area diffraction, as demonstrated in Fig. 1(a). TEM micrographs of SmCo films [Figs. 1(b)–1(d)], show definite contrast probably caused by thickness variation due to TEM sample preparation. Dark regions are about 25 nm for SmCo films on the template in Figs. 1(b) and 1(d) and boundaries are quite visible. On template 1(c), the SmCo exhibits larger features with lower contrast.

[a]Present address: Metallurgical and Materials Engineering Dept. and MINT Center, University of Alabama, P.O. Box 870202, Tuscaloosa, AL; electronic mail: gzangari@coe.eng.ua.edu

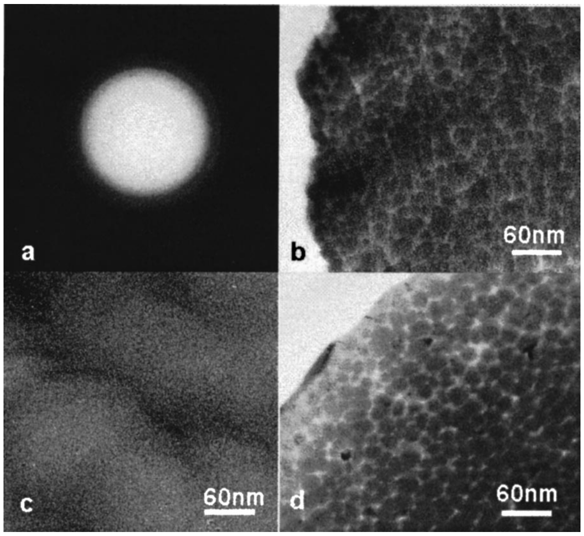

FIG. 1. (a) TEM diffraction pattern for the SmCo layer in Cr/SmCo/Cr/Ag/Si(100). (b), (c), (d) TEM micrographs of the SmCo layer deposited on Cr/Ag/Si(*hkl*): (b) Si(100), (c) Si(111), (d) Si(110).

Figure 2 shows the dependence of coercivity H_c on SmCo and Cr thickness for samples sputtered without intentional heating. Squareness (S) and coercive squareness (S^*) exhibit similar trends. Reference SmCo/Cr structures sputtered on glass exhibit in-plane anisotropy,[2,4] showing a maximum in H_c, S, and S^* between 30 and 120 nm Cr underlayer thickness, and 15–30 nm SmCo layer thickness (Fig. 2). Maximum H_c values are slightly above 2 kOe, squareness values are between 0.7 and 0.9. SmCo/Cr bilayers deposited onto Ag(100 nm)/Si(hkl) templates exhibit different properties. Films sputtered onto Si(100) show a steady increase in H_c, S and S^* with both Cr and SmCo thickness, while on Si(111) and (110) a definite maximum in these values is

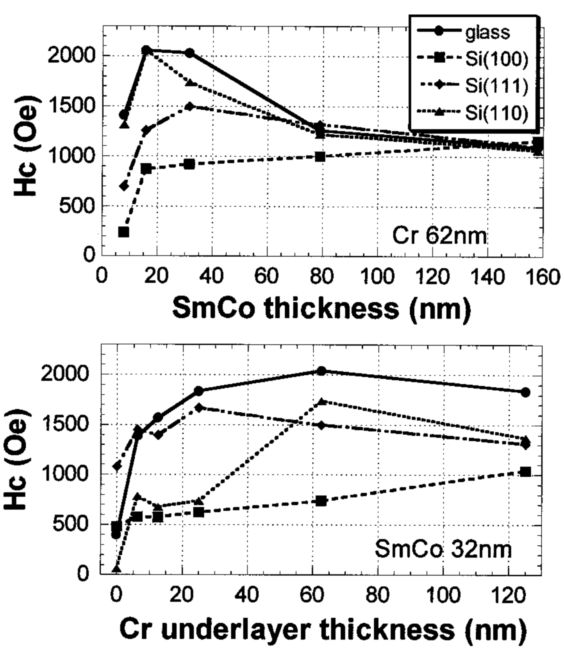

FIG. 2. Coercivity as a function of SmCo thickness, in SmCo(x nm)/Cr(62 nm)/template (top); Cr underlayer thickness, in SmCo(32 nm)/Cr(x nm)/template (bottom). The template is either glass or Ag/Si(*hkl*).

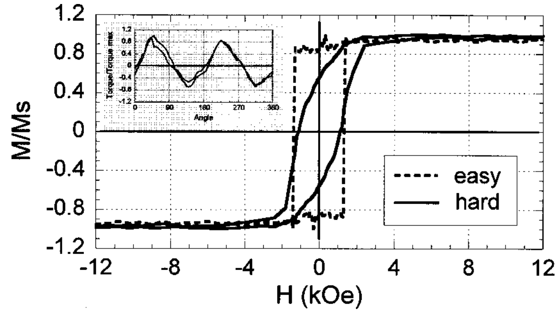

FIG. 3. In-plane hysteresis loops of SmCo/Cr/Ag/Si(111) along the easy and hard directions, as determined by the torque data (inset).

observed, resembling the trend observed for SmCo/Cr/glass. With increasing thickness of the SmCo film [Fig. 2(a)] H_c becomes dominated by the bulk properties of the SmCo film, and independent of the template used.

The orientation of the Si substrate determines the orientation of the Cr and SmCo films through successive epitaxial effects, and influences the magnetic properties of the final structure. Microscopy techniques did not yield any indication of local crystalline ordering for SmCo. However, in-plane torque magnetometry was used to determine magnetic anisotropy in the film plane, and to provide indirect evidence for crystalline ordering or atomic pair correlation. In particular, the existence of any epitaxial relationships at the SmCo/Cr interface was probed.

Similarly to films on glass SmCo/Cr/Ag/Si(100) structures show no in-plane anisotropy, and within the experimental uncertainty the hysteresis loops along perpendicular directions in the film plane coincide. A weak uniaxial anisotropy is instead observed for SmCo deposited on the Si(111) template (Fig. 3, inset) and confirmed by the hysteresis loops taken along the easy and hard axes (Fig. 3). SmCo on Si(110) shows a well defined torque curve [Fig. 4(a), inset], indicating a well developed uniaxial anisotropy. The hard axis loop [Fig. 4(a)] is almost closed, indicating limited distribution of the easy axes. The easy axis of the SmCo phase is oriented parallel to the Si(110)[001] direction. However, the angular dependence [Fig. 4(b)] of the magnetic properties of SmCo on the Si(110) substrate vary periodically with multiple maxima and minima reminiscent of major and minor easy axes.[13]

Assuming a single easy axis and uniaxial anisotropy constant,[1] K_1 for SmCo on the Si(110) substrate can be calculated from the torque curves amplitude. An increase in K_1 was observed with decreasing SmCo thickness. Typically, K_1 varies from 3×10^5 erg/cm^3 for 100 nm thick SmCo to 1.5×10^6 erg/cm^3 for 15 nm thickness. Thickness dependence is consistent with the anisotropy being due to the interfacial effects and contributing only a fraction of the film properties. It is also of interest that the anisotropy values are smaller than those of pure Co or Co films prepared on similar templates.[11]

IV. DISCUSSION

The hard magnetic properties of SmCo thin films are influenced by epitaxial[4,8] and morphological[5,6] effects in-

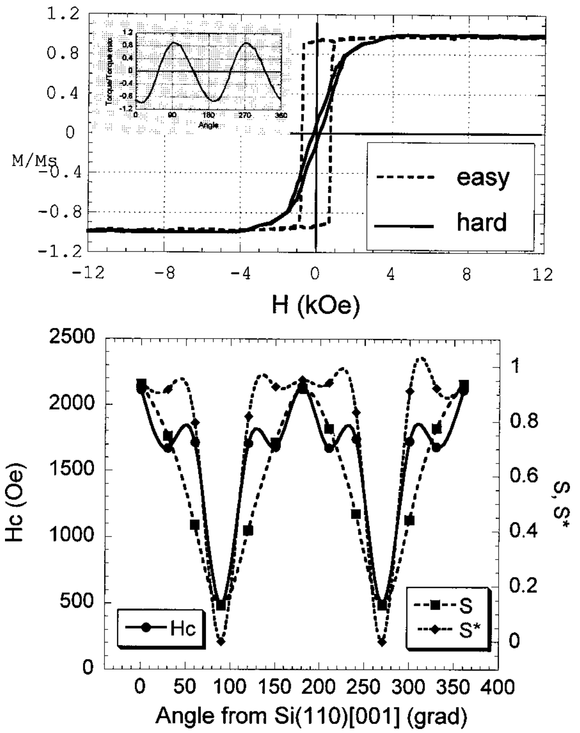

FIG. 4. Top: in-plane hysteresis loops of SmCo/Cr/Ag/Si(110) along the easy and hard directions, as determined by in-plane torque data (inset). The easy axis direction corresponds to the Si[001] direction. Bottom: in-plane angular variation of the magnetic properties.

duced by the underlayer; good epitaxy and a rough underlayer favor the synthesis of hard films. SmCo films on Cr/glass exhibit magnetic properties superior to similar films grown on Si templates. This effect can be ascribed to the different roughness of the Cr surface, surface energy considerations predict which to be higher on glass than on Ag. According to the model in Refs. 4 and 5, SmCo islands are initially more isolated on rougher Cr surfaces but isolated grains tend to become coupled with necessary SmCr. Consequently, film coercivity becomes independent of the template used, as experimentally observed here [Fig. 2(a)].

Assuming the Cr roughness on various Si(*hkl*) substrates is similar, any differences in magnetic properties of SmCo should be ascribed to epitaxial effects. Possible epitaxial relationships for hcp Co alloys on Cr/Ag/Si(*hkl*) templates were summarized in Ref. 9 and two models have been advanced for SmCo on Cr. In Ref. 4 a $SmCo_5$ phase is assumed, and the epitaxial relationship SmCo$(11\bar{2}0)[0001]\|$Cr(110)[001] is hypothesized due to (SmCo) the close lattice matching between the two surfaces. In Ref. 8 the authors assumed a SmCo hcp phase and proposed the epitaxial relationship SmCo$(\bar{1}100)[0001]\|$Cr$(\bar{1}2\bar{1})[\bar{1}01]$. On Si(100), the epitaxial growth of bicrystal Co alloys is expected.[9,10] However, our in-plane anisotropy measurements do not exhibit the expected biaxial anisotropy; we conclude that the growth of SmCo onto Cr(100)/Ag(100)/Si(100) is random, and not influenced by epitaxial effects. Cr(110) grows onto Ag(111)/Si(111) with three possible orientations.[9] On Cr (110), a hcp alloy should grow according to Co alloy $(10\bar{1}1)$/Cr(110), of which there are four variants resulting in 12 different orientations with respect to the substrate. If the orientation described in Ref. 8 is assumed, a threefold in-plane anisotropy should still be observed, due to the multiple Cr orientations. We observe instead only a weak uniaxial anisotropy which we explain by assuming that one of the 12 or three possible anistropy axes is dominant.

In the case of SmCo, on Cr(112)/Ag(110)/Si(110) we observe an easy in-plane axis parallel to Si[001]. The high degree of perfection of this epitaxial relationship is supported by the limited distribution of the easy axes and by the periodic variation of magnetic properties with the in-plane angle (Fig. 4).[8]

The measured low value of the effective anisotropy constant and its decrease with increasing SmCo thickness, are evidence of inhomogeneities along the film thickness. We hypothesize that an initially crystalline SmCo phase, stabilized by epitaxial effects at the interface, but later becomes amorphous due mainly to the difference in atomic volumes of Co and Sm.

Summarizing, the magnetic properties of SmCo films on Cr/Ag/Si templates are inferior to those of SmCo/Cr/glass structures, due possibly to an improved smoothness of the Cr underlayer. SmCo thin films grow epitaxially onto the Cr(112)-surface, generating in-plane anisotropy on Cr(112)/Ag(110)/Si(110) and Cr(110)/Ag(111)/Si(111) templates (where epitaxial growth seems to take place onto side Cr(112) facets).

The easy axis of SmCo films deposited on Cr(112)/Ag(110)/Si(110) is aligned along Si[001] and those films show higher H_c, S, and S^* compared to SmCo deposited on other Si surfaces. Process optimization to induce grain isolation might lead to a SmCo medium largely improved compared to current SmCo films on glass.

ACKNOWLEDGMENT

This work was supported by the National Science Foundation under Grant No. ECD-8907068.

[1] P.-L. Lu and S. Charap, IEEE Trans. Magn. **30**, 4230 (1994); S. Charap, P. Lu, and Y. He, *ibid.* **33**, 978 (1997).
[2] E. M. T. Velu and D. N. Lambeth, J. Appl. Phys. **69**, 5175 (1991).
[3] F. J. Cadieu, T. D. Cheung, L. Wickramasekara, N. Kamprath, H. Hegde, and N. C. Liu, J. Appl. Phys. **62**, 3866 (1987).
[4] E. M. T. Velu and D. N. Lambeth, IEEE Trans. Magn. **28**, 3249 (1992).
[5] E. M. T. Velu, D. N. Lambeth, J. T. Thornton, and P. E. Russel, J. Appl. Phys. **75**, 6132 (1994).
[6] Y. Liu, B. W. Robertson, Z. S. Shan, S. H. Liou, and D. J. Sellmyer, J. Appl. Phys. **77**, 3831 (1995).
[7] E. W. Singleton, Z. S. Shan, Y. S. Jeong, and D. J. Sellmyer, IEEE Trans. Magn. **31**, 2743 (1995).
[8] Y. Liu, D. J. Sellmyer, and B. W. Robertson, J. Appl. Phys. **79**, 5333 (1996).
[9] D. N. Lambeth, W. Yang, H. Gong, D. E. Laughlin, B. Lu, L.-L. Lee, J. Zou, and P. S. Harllee; Mater. Res. Soc. Symp. Proc. (to be published).
[10] W. Yang, D. N. Lambeth, L. Tang, and D. E. Laughlin, J. Appl. Phys. **81**, 4370 (1997).
[11] W. Yang and D. N. Lambeth, J. Appl. Phys. (these proceedings).
[12] H. Gong, M. Rao, D. E. Laughlin, and D. N. Lambeth, J. Appl. Phys. (these proceedings).
[13] Y. Deng, Ph.D. thesis, Carnegie Mellon University, August 27, 1993.