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Co-Sm ($\bar{1}100$)[0001]//Cr ($\bar{1}2\bar{1}$)[$\bar{1}01$] epitaxy and its effects on magnetic properties of Co-Sm//Cr films

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Co-Sm $(\bar{1}100)[0001]$//Cr $(\bar{1}2\bar{1})[\bar{1}01]$ epitaxy and its effects on magnetic properties of Co-Sm//Cr films

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It is well known that the Cr underlayer plays a critical role in generating large in-plane coercivity in Co-based magnetic thin films. In this paper we report in detail the Co-Sm $(1100)[0001]$//Cr $(121)[10\bar{1}]$ epitaxy revealed by high resolution electron microscopy. The lattice mismatch between Co-Sm (1100) and Cr (121) is less than 2%, suggesting an energetically favorable configuration. The high anisotropy observed in Co-Sm films is discussed by this epitaxial relation. © *1996 American Institute of Physics.* [S0021-8979(96)15308-6]

I. INTRODUCTION

In pursuing Co-based magnetic thin films for high density recording, it is well known that the Cr underlayer plays a critical role in generating large in-plane coercivity in Co-based magnetic thin films. The Co-based thin films have the hexagonal close-packed (HCP) structure which can grow on Cr underlayer epitaxially. Three kinds of microstructures in Co-based magnetic thin films with large in-plane anisotropy have been reported, which are all based on the epitaxial relation Co-alloy $(11\bar{2}0)[0001]$//Cr $(001)[110]$. The first kind has (001) texture of the Cr underlayer with the [010] direction randomly distributed in the film plane. Consequently the easy axes of the crystallites in the Co alloy magnetic thin films are randomly distributed in the film plane.[1,2] The second kind has a single crystalline Cr underlayer with the (100) in film plane. The *c* axes of the hexagonal crystallites in the magnetic film are epitaxially grown in two perpendicular directions [110] and $[1\bar{1}0]$ of the Cr underlayer. Such structure has been named bicrystal.[3,4] The third kind of microstructure is produced by depositing the Co alloy on a scratched (100) Cr single crystal. As a result, the *c* axis of the crystallites are aligned in one [110] direction only and the film has uniaxial anisotropy.[5]

Recently it has been shown that Co-Sm films with a nominal composition from Co_4Sm to Co_7Sm_2 exhibit high coercivity and in-plane anisotropy.[6,7] Transmission electron microscopy studies of Co-Sm films have shown that the microstructure of a Co-Sm thin film is composed of the amorphous matrix and crystallites with a grain size of about 5 nm.[8] The crystallites in the as-deposited Co-Sm films have a close-packed structure.[9] Each crystallite has a particular stacking mode which consists of local random stacking, occasionally a few unit cells of two layer stacking *AB*, three layer stacking *ABC*, and four layer stacking *ABAC*. However, the epitaxy relation between the Co-Sm crystallites and the Cr, if any, remains a mystery. In this paper we report our discovery of a new epitaxial relation between the Co-Sm crystallites and the Cr underlayer, that is, Co-Sm $(\bar{1}100)$//Cr (121) and Co-Sm $[11\bar{2}0]$//Cr $[\bar{1}11]$ (equivalent to Co-Sm $[0001]$//Cr $[\bar{1}01]$. This epitaxy relation is responsible for the high in-plane coercivity of Co-Sm films grown on Cr underlayer with {110} texture. We think the discovery of this epitaxy relation is important also because it will now be possible to grow uniaxial anisotropic Co-Sm films (true for Co-based alloy with hexagonal close-packed structure) on single crystalline Cr of (121) surface. The resultant film will have the magnetic easy axis aligned in one direction and will have the highest anisotropy. Much higher coercivity, and coercive squareness can be expected from the uniaxial anisotropic Co-Sm films compared to current Co-Sm films.

II. EXPERIMENTAL PROCEDURE

The Co-Sm target used for deposition has a nominal composition of Co_7Sm_2. The films were deposited by dc magnetron sputtering under an Ar pressure of 5 mTorr at room temperature. The film configuration from substrate to film is 220 μm glass, 80 nm Cr, 30 nm Co-Sm and 10 nm Cr. Cross sectional transmission electron microscope (TEM) samples were prepared by embedding the strips of the films into a 3-mm-diam Cu tube with EMbed 812 (supplied by Electron Microscopy Sciences, P.O. Box 251, Ft. Washington, Pa 19034). The Cu tube with the films was cross-sectioned into about 0.3 mm slices. The slices were dimpled to 50 μm at the center and then ion milled until perforation. The high resolution electron microscopy (HREM) and diffraction work was performed using a JEOL 2010 transmission electron microscope operating at 200 kV.

III. RESULTS

Figure 1 shows the cross sectional HREM image of a Co-Sm film on Cr. Two Cr grains are observed. The Cr grain on the left side (marked G1) is on a random orientation and no lattice fringes are observed. The orientations of the Co-Sm crystallites with a grain size of about 5 nm grown on

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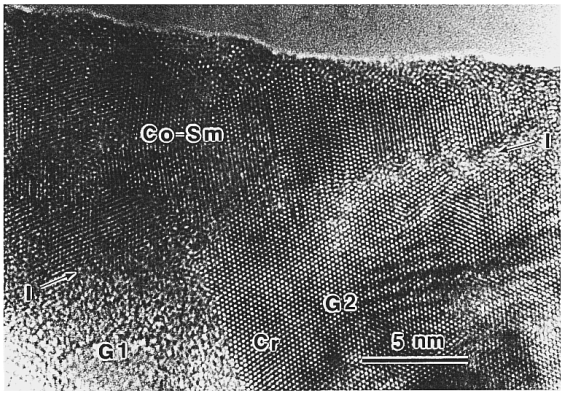

FIG. 1. HREM image of a cross-sectional Co-Sm film. A Cr grain is aligned on [111] zone axis while the Co-Sm crystallite is aligned on [11$\bar{2}$0] zone axis. The epitaxy is Cr (121)//Co-Sm (1100) and Cr [111]//[11$\bar{2}$0]. The interface is indicated by letter *I*.

this Cr grain are not identified. The Cr grain on the right side (marked G2) is aligned on the [111] zone axis. The Co-Sm film grown on this Cr grain is on the [11$\bar{2}$0] zone axis. The epitaxy is Cr (121)//Co-Sm (1100) and Cr [111]//Co-Sm [11$\bar{2}$0]. The interface between the Cr underlayer and the Co-Sm film is indicated by letter I. Figure 2 is the magnified interface region shown in Fig. 1. The crystal structures of the Cr underlayer and the Co-Sm crystallite are well revealed by the optical diffraction patterns, which are attached to the corresponding regions. The optical diffraction patterns clearly show that the Co-Sm has the close-packed structure and the Cr the *BCC* structure. The Co-Sm layer is basically a two-layer stacking, *ABAB*, with a stacking fault. The stacking sequence is well defined by drawing three lines corresponding to *A* layers, *B* layers, and *C* layers. The stacking sequence is *BABA* on the left side and then switched to *CACA* as indicated by the arrows. Simulated images based on the above stacking sequence for the Co-Sm crystallite and the *BCC* structure for the Cr underlayer show excellent match to the HREM image.

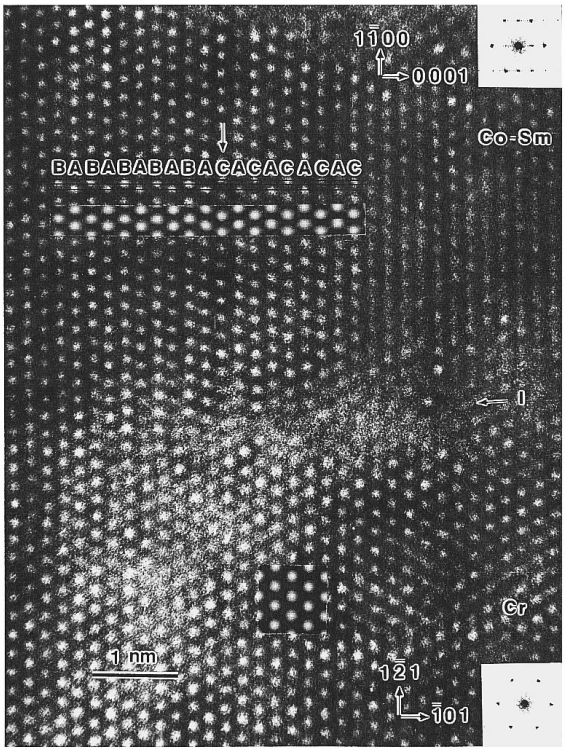

FIG. 2. Magnified interface region of Co-Sm on Cr underlayer. The stacking sequence in the Co-Sm film is well identified by the HREM image.

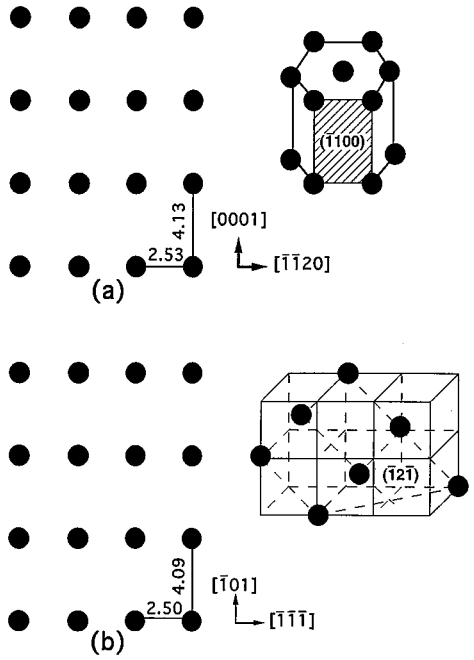

FIG. 3. Schematic illustration of atomic planes of (a) (1$\bar{1}$00) in Co-Sm of hexagonal unit cell with lattice parameters $a=0.253$ nm, $c=0.413$ nm. (b) (12$\bar{1}$) in BCC Cr with lattice parameter $a=0.289$ nm.

Figure 3 schematically illustrates the atomic planes of Co-Sm (1100) and Cr (121). The distances between atoms were deduced according to the lattice parameters $a=0.253$ nm, $c=0.413$ nm for the Co-Sm crystallite, and $a=0.289$ nm for Cr. Note that the lattice mismatch between the Co-Sm phase and the Cr is very small ($\sim$1%). Therefore such epitaxy is energetically favorable.

IV. DISCUSSION

The magnetic films fabricated using Co-based alloys have been available for magnetic recording for many years. The films also have the hexagonal close packed structure grown on the Cr underlayer. The epitaxy reported for the Co-alloy film on Cr underlayer is limited to Co-alloy (11$\bar{2}$0)[0001]//Cr (00$\bar{1}$)[1$\bar{1}$0]. The reason that Co-alloy (1100)[0001]//Cr (121)[101] epitaxy was not discovered by earlier researchers, if it existed in Co alloy films, is that when a ⟨111⟩ direction of Cr is aligned parallel to the electron beam, the Co-Sm (1100)[0001]//Cr (121)[101] epitaxy is not necessarily to be seen. This is because HREM images are only obtainable for certain directions of Cr and Co-Sm crystallites. HREM images contain structural information only when the projections of the atoms are within the microscope resolution limit which is 0.14 nm for the JEOL

2010. If the projection of the atomic columns in a zone axis has a smaller spacing than 0.14 nm, no clear HREM images can be obtained. Therefore, for the Co-Sm $(1100)[1120]$// Cr $(121)[111]$ epitaxy, if the $[111]$ zone axis of the Cr grain is aligned parallel to the electron beam, both the Cr $[111]$ zone axis HREM image and the Co-Sm $[1120]$ zone axis image will be a projection of the structure and the epitaxy will be observed. However, for the same Co-Sm $(1100)[1120]$//Cr $(121)[111]$ epitaxy, if any of the other three $\langle 111\rangle$ zone axis of the same Cr grain ($[111]$, $[111]$ or $[1111]$) is aligned parallel to the electron beam, the corresponding zone axis of Co-Sm crystallite is a high index zone axis but not a $[1120]$ type zone axis. In this case, high resolution image will be obtained for the Cr grain but not for the Co-Sm crystallite and the epitaxy will not be revealed. Therefore, if an arbitrary $\langle 111\rangle$ type direction of Cr is chosen for high resolution imaging, the chance of seeing Co-Sm $(1100)[1120]$//Cr $(121)[111]$ epitaxy is one out of four.

In the x-ray diffraction spectrum of the Cr underlayer in the Co-Sm films, only strong {110} peak is observed, suggesting an {110} texture. The in-plane anisotropy of Co-Sm films on {110} textured Cr underlayers can also be explained by this epitaxy relation. Figure 4 depicts the Co-Sm hexagonal structure grown on Cr underlayer with {110} texture. The growth direction of the Cr underlayer is $[110]$. The two {112} planes have a 30° angle with the (110). Such a structure is a close approximation for the Cr underlayer morphology grown by sputtering as revealed by atomic force microscopy [10]. The Co-Sm crystallites lie on the two {112} planes with the *c* easy axis 30° from the (110) plane. However, even larger anisotropy of Co-Sm films will be expected if the $[0001]$ easy axis of Co-Sm crystallites lie in the film plane which could be achieved by depositing Co-Sm films on Cr single crystal with a (121) surface.

V. CONCLUSIONS

HREM study has clearly shown the existence of Co-Sm $(1100)[1120]$//Cr $(121)[111]$ epitaxy with a lattice mismatch of less than 2%. Such epitaxy makes it possible to grow uniaxial anisotropy Co-Sm//Cr films.

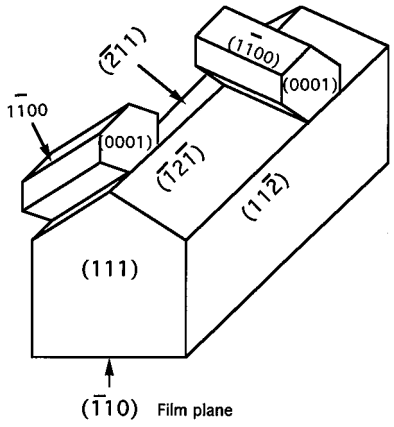

FIG. 4. Co-Sm $(1\bar{1}00)[11\bar{2}0]$//Cr $(\bar{1}\bar{2}1)[111]$ epitaxy shown on a Cr grain.

ACKNOWLEDGMENTS

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