Structure and ferromagnetic resonance of Tb/FeCo multilayer thin films

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Multilayer thin films of Tb and Fe₉₅Co₅ were prepared by thermal evaporation from two sources. The films were studied by x-ray diffraction, Auger electron spectroscopy, and ferromagnetic resonance. The low-angle x-ray diffraction and Auger analysis showed that a multilayer structure was achieved for films with a modulation wavelength $\Lambda \geq 31.5 \text{ \AA}$. FMR results were consistent with the structural data. The films with $\Lambda < 31.5 \text{ \AA}$ had similar H_{Keff} , line width, and line shape to those of a coevaporated alloy with the same composition. The films with $\Lambda > 31.5 \text{ \AA}$ had an H_{Keff} greater than or equal to that of an Fe₉₅Co₅ film. A film with H_{Keff} greater than that of the Fe₉₅Co₅ film had multiple resonances. Interfacial stress due to incoherent matching of the Tb and Fe₉₅Co₅ layers is thought to give rise to differences in H_{Keff} in the various layers.

I. INTRODUCTION

Compositionally modulated or multilayer thin-film magnetic materials are of interest for applications and in fundamental studies of the magnetic properties of thin magnetic layers. We discuss some studies by x-ray diffraction, Auger electron spectroscopy, and ferromagnetic resonance (FMR) of Tb and Fe₉₅Co₅ multilayers in this report.

II. SAMPLE PREPARATION

The samples were prepared by thermal evaporation of Tb and Fe₉₅Co₅ alloy at ambient temperature ($\sim 313 \text{ K}$) in a vacuum of about 1×10^{-6} Torr. The modulated structure was achieved by alternately exposing the substrate to each of the two sources via a rotating substrate holder at a speed of 0–70 rpm. The sublayer thicknesses were monitored by quartz-crystal sensors. Although the modulation wavelength was varied, the ratio of sublayer thicknesses of the Tb and Fe₉₅Co₅ was kept constant in all samples. The composition, Tb₂₁(Fe₉₅Co₅)₇₉, was confirmed by inductively coupled plasma spectrometry. The number of bilayers was reduced with increasing modulation wavelength to obtain films with total thicknesses in the range 1400–2100 Å.

III. RESULTS AND DISCUSSION

A. Structural characteristics

The growth parameters of the compositionally modulated Tb/FeCo films studied here are listed in Table I. Figure 1 shows θ – 2θ scans at high angle for samples with $\Lambda = 4.2$, 31.5, and 175 Å. The featureless diffraction pattern for the

$\Lambda = 4.2 \text{ \AA}$ sample implies an amorphous phase. Two broad peaks around $2\theta = 30^\circ$ and 45° appeared for the $\Lambda = 31.5 \text{ \AA}$ sample, and they became more distinct for the sample with $\Lambda = 175 \text{ \AA}$. These peaks correspond to diffractions from Tb (102) and Fe₉₅Co₅ (110) planes, respectively. The modulated structure of the sample with $\Lambda = 70 \text{ \AA}$ was confirmed directly by Auger electron spectroscopy.

Figure 2 shows the results of the low-angle, $2\theta < 10^\circ$, x-ray diffraction experiments on samples with $\Lambda = 21 \text{ \AA}$ and $\Lambda = 31.5 \text{ \AA}$. The sample with $\Lambda = 21 \text{ \AA}$ did not have any low-angle diffraction peaks, which suggests that the composition modulation was destroyed by interdiffusion. Two dif-

FIG. 1. High angle θ – 2θ scans for (a) $\Lambda = 4.2 \text{ \AA}$, (b) $\Lambda = 31.5 \text{ \AA}$, and (c) $\Lambda = 175 \text{ \AA}$ samples.

TABLE I. Growth parameters of compositionally modulated TbFeCo films.

Sublayer thickness (Å)		Modulation Wavelength (Å) Λ	Number of Bilayers
(Tb)	(FeCo)		
1.8	2.4	4.2	320
9	12	21	67
13.5	18	31.5	66
30	40	70	20
75	100	175	10

FIG. 2. Low-angle x-ray diffraction patterns for (a) $\Lambda = 21 \text{ \AA}$ and (b) $\Lambda = 31.5 \text{ \AA}$ samples.

fraction peaks were seen in the low-angle diffraction of the sample with $\Lambda = 31.5 \text{ \AA}$ showing the artificial periodicity of the layer structure. Although Sato reported a modulated structure with $\Lambda = 5.9 \text{ \AA}$ in TbFe films using a water-cooled substrate,¹ we could not produce the layer structure for films with $\Lambda < 31.5$ by our preparation method.

B. FMR spectra

We studied the ferromagnetic resonance (FMR) of these multilayer films at room temperature ($\sim 294 \text{ K}$) using a conventional spectrometer at about 9-GHz microwave frequency. For comparison we also studied the FMR spectra of a film of the $\text{Fe}_{95}\text{Co}_5$ alloy and a film prepared by coevapora-

FIG. 3. Perpendicular FMR spectra of (a) $\Lambda = 4.2 \text{ \AA}$, (b) $\Lambda = 21 \text{ \AA}$, and (c) $\Lambda = 31.5 \text{ \AA}$ samples. Note the secondary resonance near 9000 Oe, which might be an oxidation product.

FIG. 4. Perpendicular FMR spectra of (a) $\Lambda = 70 \text{ \AA}$, (b) $\Lambda = 175 \text{ \AA}$, and (c) the $\text{Fe}_{95}\text{Co}_5$ film.

TABLE II. Summary of FMR data at 9.51 GHz and 294 K.

Sample	$H_{\perp}$ (Oe)	$H_{\parallel}$ (Oe)	H_{Keff} (KOe)	g_{eff}	Line width $\Delta H_{\perp}$ (Oe)
I	10200	860	-7.5	2.53	1400
II	9170	1080	-6.3	2.40	1000
III	8760	1080	-6.0	2.34	850
IV	12850	880	-9.8	2.13	1200
V	13000	880	-9.9	2.22 ^a	200
	14250	880	-11.0	2.11 ^a	
	14980	880	-11.7	2.16 ^a	
	15360	880	-12.0	2.02 ^a	
	16500	880	-13.0	1.95 ^a	
	17450	880	-13.9	1.89 ^a	
	> 19000	880	> -15.2	1.81 ^a	
Fe ₉₅ Co ₅	13000	880	-9.9	2.21	1400
	16630	880	-13.1	1.94	300
Tb ₂₁ (Fe ₉₅ Co ₅) ₇₉	10300	820	-7.7	2.57	1200

^a It may not be reasonable to calculate a g_{eff} for these modes since we do not clearly understand their origin.

tion having composition Tb₂₁(Fe₉₅Co₅)₇₉. The samples were all cut to the same shape and mounted in the same position in our microwave cavity by a quartz rod to which they were glued. We studied the spectra with the external magnetic field applied parallel and perpendicular to the film surface to obtain the effective anisotropy field

$$H_{\text{Keff}} = [-H_{\parallel} - 2H_{\perp} + (4H_{\parallel}H_{\perp} + 5H_{\parallel}^2)^{1/2}]/2$$

and g_{eff} . $H_{\perp}$ and $H_{\parallel}$ are the resonance fields with the external field applied perpendicular and parallel, respectively. The perpendicular spectra of several of the samples are shown in Figs. 3 and 4 and the results are summarized in Table II.

Several points of interest resulted from the spectra. The spectra of films with $\Lambda \leq 31.5$ Å were nearly identical in H_{Keff} , line shape, and linewidth to the spectrum of the sample prepared by coevaporation. These spectra may be contrasted with those of the Fe₉₅Co₅ film and films with $\Lambda > 31.5$ Å (Fig. 4 and the data summary in Table II). We found that all of our films had negative H_{Keff} , meaning that the easy magnetization direction was in-plane.

The Fe₉₅Co₅ film had a secondary, less intense mode at a higher field than the main mode. These characteristics are like those expected for a surface spin-wave mode.² The value of H_{Keff} of this mode was near to the value obtained in some of the multilayer films (Table II). The linewidth of the FeCo film was quite large and could be due to stress in the film.

There were also differences in g_{eff} between the modulated films and the Fe₉₅Co₅ film. The data of Table II show that g_{eff} decreased as the modulation wavelength increased and obtained a value equal to that of the Fe₉₅Co₅ film in the films with $\Lambda > 31.5$ Å, while the g_{eff} of films with $\Lambda \leq 31.5$ was like that of the evaporated film. Based on these FMR data we conclude that TbFeCo alloy was formed in the films with $\Lambda \leq 31.5$ Å. In films with $\Lambda > 31.5$ Å the magnetic properties were due to FeCo.

The structural and FMR data agree well with this hypothesis except when $\Lambda = 31.5$ Å. The low-angle x-ray data showed that this film had structure modulation, while the FMR data are similar to those of the coevaporated alloy. This is the first film in which we see any modulation in the structure, and so apparently the long-range magnetic order is dominant in determining the magnetic properties. Also the high-angle x-ray results showed that this film is mostly amorphous since the polycrystalline peaks were not very intense [Fig. 1(b)].

The film with $\Lambda = 70$ Å had a value of H_{Keff} that was almost identical with that of the Fe₉₅Co₅ film, while the perpendicular spectrum of the film with $\Lambda = 175$ Å showed multiple resonance modes. The FMR spectra of some other types of multilayer structures, notably those of Co/Nb and Ni/Mo, also showed multiple resonances in their perpendicular FMR spectra.³⁻⁵ The modes were observed all had values of H_{Keff} greater than that observed for the main mode of the Fe₉₅Co₅ film.

These modes could arise from composition or magnetic variations, perhaps caused by interdiffusion. Another possibility is that these modes were related to incoherent matching in the interface planes. A transition between coherent and incoherent matching could occur as Λ is increased, owing to the differences in lattice parameters of Tb and FeCo. The increase in H_{Keff} could be related to interfacial stress and modulations due, for example, to misfits and dislocations.

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