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Magnetism and anisotropy of Tb/Fe multilayers

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Magnetism and anisotropy of Tb/Fe multilayers

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Studies of the layer-thickness dependence of hysteresis loops for Tb/Fe compositionally modulated films (CMF) are reported. The characteristics of magnetic properties, such as magnetization and uniaxial anisotropy, which depend on the FE layer thickness, can be interpreted in terms of the compositional dependence of magnetic properties of the constituent subnetworks and the spatial distribution of the constituent atoms. The magnetic properties of Tb/Fe CMF are analyzed with a micromagnetic model, and the behavior of the anisotropy and constituent magnetization near the compensation point is discussed.

I. INTRODUCTION

The rare earth–transition metal (RE-TM) films have been investigated extensively for reasons both pure and applied. Of these films, Tb-Fe has attracted much attention for its high value of perpendicular anisotropy which is desirable for magneto-optic and vertical recording.

The compositionally modulated films (CMF) have enjoyed considerable attention in recent years.[1-3] The existence of the inhomogeneous (or anisotropic) distribution of Tb and Fe atoms gives the possibility of controlling the local atomic environments and may lead to large anisotropy. However, this inhomogeneous distribution also introduces complexity in studying the magnetic properties analytically in CMF. In the present paper, the layer-thickness dependence of magnetic properties for 4.5 Å Tb/X Å Fe ($X = 2.5$, 3.75, 5, 6.25, 7.5, 8.75, 15, and 20) was investigated experimentally, and the results were analyzed with a micromagnetic model.

II. EXPERIMENT

The Tb/Fe CMF were prepared by a multiple-gun sputtering system as shown in Fig. 1 with the Tb target in an rf gun and Fe target in a dc gun. A specially designed disk (the substrate shutter) is inserted between the substrates and guns. Six substrates are attached to the rotating table, but only one substrate accepts the sputtering deposition through a single window on the shutter. Therefore, six samples can be prepared in one vacuum run by simply rotating the shutter from one substrate to another. This design enables more efficient sample preparation and reduces the fluctuation of magnetic properties due to the change of preparation conditions among different runs.

The structural properties were studied with large- and small-angle x-ray diffraction, and the magnetic properties were measured by vibrating-sample magnetometry at room and low temperature. Here we report only the room temperature results because of space limitations.

III. RESULTS AND DISCUSSION

Large- and small-angle x-ray diffraction studies have been performed for 4.5 Å Tb/X Å Fe CMF ($X = 2.5$–20). The result shows that the structure is amorphous and only the first-order peak is seen corresponding to the bilayer thickness $\lambda < 15$ Å, which means that the atomic distribution of the constituents has the sinusoidal form.[5] Our results are different from those of Sato,[1] who found two low-angle peaks for bilayer thickness $\lambda \simeq 5.9$ Å.

The Fe layer-thickness dependence of the hysteresis loops for 4.5 Å Tb/X Å Fe ($X = 2.5$, 3.3, 3.75, 5, 6.25, 7.5, 8.75, 15, and 20) CMF is shown in Fig. 2 and the corresponding Fe layer thickness dependence of magnetization σ_s and anisotropy K_u' is illustrated in Fig. 3. The following characteristics should be noted:

(i) The saturation magnetization σ_s changes its magnitude and sign regularly as the Fe layer thickness increases: (a) σ_s decreases in magnitude as the Fe layer thickness increases from 2.5 to 3.3 Å because the Tb-subnetwork magnetization dominates in this region and the magnetizations of the Tb and Fe subnetwork are coupled ferrimagnetically. (b) Sample 4.5 Å Tb/3.3 Å Fe is in a state near the compensation point. (c) The magnetization σ_s increases as the Fe layer thickness becomes thicker starting from $X = 3.75$ Å, because the Fe-subnetwork magnetization dominates in this region. But there is one exception, i.e., sample 4.5 Å Tb/8.75

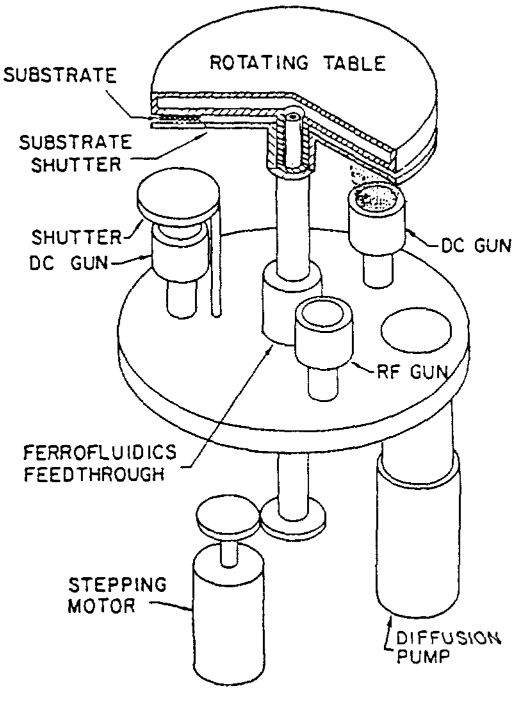

FIG. 1. Schematic of the sputtering apparatus. Only one substrate can accept the sputtering deposition through a single window on the sputtering shutter at a time.

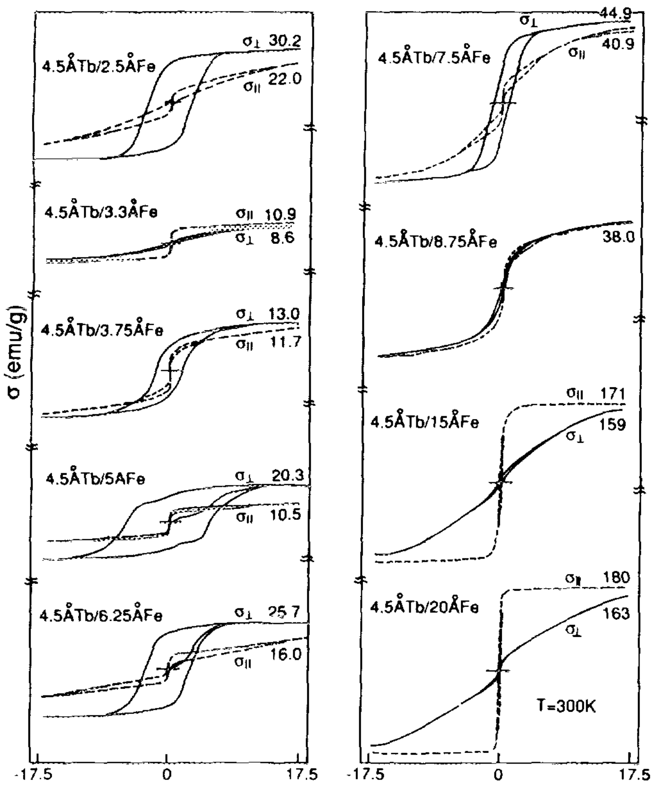

FIG. 2. Hysteresis loops at 300 K for 4.5 Å Tb/X Å Fe series. In this and subsequent figures the layer thicknesses are nominal values based on measurement of sputtering rate.

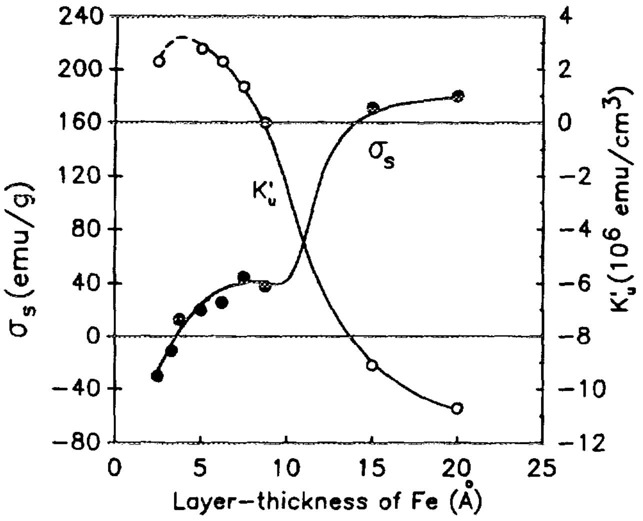

FIG. 3. Fe layer-thickness dependence of apparent anisotropy K'_u and magnetization σ_s for 4.5 Å Tb/X Å Fe at 300 K.

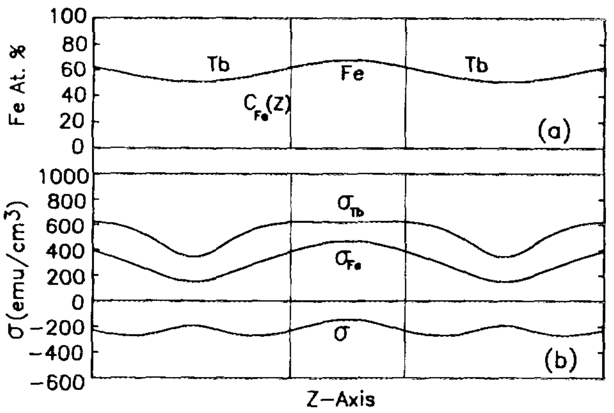

FIG. 4. The distribution of Fe atoms (a) and magnetization (b) along the film normal for 4.5 Å Tb/2.5 Å Fe sample.

Å Fe has a smaller σ_s than that of sample 4.5 Å Tb/7.5 Å Fe. This is because the amorphous Fe is disordered[6] magnetically if the Fe atomic fraction $C_{\rm Fe} > 0.96$; the modeling analysis below shows that this condition is satisfied at the central Fe region for 4.5 Å Tb/8.75 Å Fe. It is this character that causes the sample 4.5 Å/8.75 Å Fe to have a smaller magnetization compared with 4.5 Å Tb/7.5 Å Fe, and also causes a magnetization "kink" around $X = 10$ Å in Fig. 3. This magnetization kink has also been seen in Fig. 4 of our previous paper for Dy/Fe CMF.[7] (d) σ_s increases rapidly as the Fe layer thickness reaches 15 Å since crystalline structure in the Fe region occurs.

(ii) That the behavior of the apparent anisotropy K'_u depends on the Fe layer thickness can be seen from Fig. 2. Here K'_u is defined as the area between the parallel and perpendicular magnetization curves and the intrinsic anisotropy K_u is equal to

$$K_u = K'_u + 2\pi\sigma_s^2 \quad \text{as} \quad \sigma_\perp > \sigma_\parallel,$$

$$K_u = |K'_u| - 2\pi\sigma_s^2 \quad \text{as} \quad \sigma_\perp < \sigma_\parallel. \qquad (1)$$

It is noticed: (a) The sample has $\sigma_\perp < \sigma_\parallel$ (or $K'_u < 0$) for $X \geqslant 15$ Å and $\sigma_\perp > \sigma_\parallel$ (or $K'_u > 0$) for $X \leqslant 7.5$ Å except near the compensation point. That is, the samples with thinner Fe layers of $2.5 < X < 7.5$, which will produce the anisotropic distribution of constituent atoms, favors the perpendicular anisotropy. Sample 4.5 Å Tb/8.75 Å Fe shows $K'_u \simeq 0$, but it possesses perpendicular anisotropy ($K_u > 0$) when the demagnetization anisotropy, $2\pi\sigma_s^2$, is considered. (b) The anisotropy behavior near the compensation point was ambiguous: Sato[1] claimed that the anisotropy K_u vanished at the compensation point, however Van Dover[8] emphasized that K_u was not zero, but changed smoothly through the compensation point. Our more detailed analysis concluded[9] that the method to determine K'_u in terms of the area between the $\sigma_\parallel$ and $\sigma_\perp$ curves is unsuitable for the ferrimagnetic media near the compensation point, but for Tb/Fe CMF with thin Fe layers, in which the main origin of perpendicular anisotropy is single-ion anisotropy of Tb ions,[5] the K'_u should change smoothly through the compensation point. (c) Samples of 4.5 Å Tb/15 Å Fe and 4.5 Å Tb/20 Å Fe show large $|K'_u|$, and a calculation indicates that K'_u originates mostly from the demagnetization anisotropy.

IV. MODELING ANALYSIS

The behavior of the layer-thickness dependence of magnetic properties is analyzed in terms of a micromagnetic model. Compared with the homogeneous RE-TM alloys the modeling analysis for CMF will be more complicated since the atomic distribution of the constituents in CMF are compositionally modulated along the film normal. We have developed a model for the magnetization and anisotropy analy-

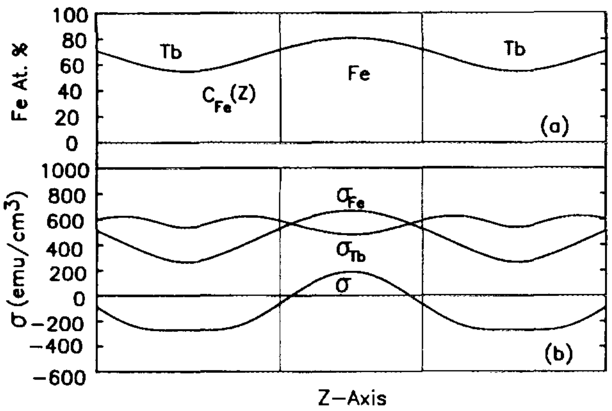

FIG. 5. The distribution of Fe atoms (a) and magnetization (b) along the film normal for 4.5 Å Tb/3.3 Å Fe sample.

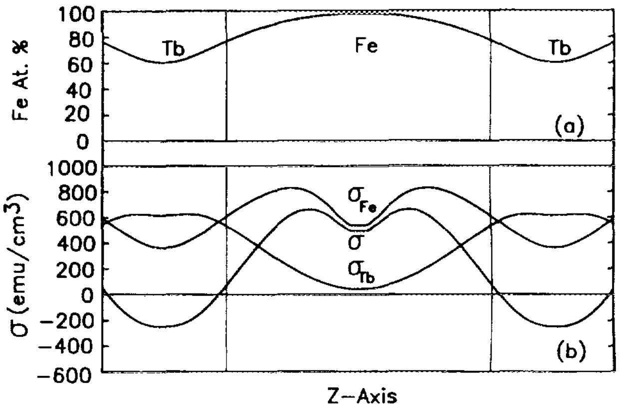

FIG. 6. The distribution of Fe atoms (a) and magnetization (b) along the film normal for 4.5 Å Tb/8.75 Å Fe sample.

ses in CMF. Some results are given in Figs. 4–6 for Tb/Fe CMF. A brief discussion of the procedure is given in Ref. 5.

Figures 4, 5, and 6 illustrate the distributions of Fe atoms and magnetization (the total, Tb- and Fe-subnetwork magnetization) along the film normal for the samples of 4.5 Å Tb/X Å Fe ($X = 2.5$, 3.3, and 8.75, respectively). These curves present a microscopic picture and help to resolve some of the ambiguities mentioned above.

Figure 4 indicates: (a) The Fe atom distribution $C_{\mathrm{Fe}}(Z)$ has small fluctuations with $C_{\mathrm{Fe(max)}} = 0.68$ and $C_{\mathrm{Fe(min)}} = 0.51$ for 4.5 Å Tb/2.5 Å Fe. (b) The magnetization of the Tb subnetwork dominates through the whole sample.

Figure 5 shows: (a) Compared with the curve in Fig. 4(a), the Fe atom distribution C_{Fe} (Z) has relatively large fluctuations with $C_{\mathrm{Fe(max)}} = 0.81$ and $C_{\mathrm{Fe(min)}} = 0.54$ for 4.5 Å Tb/3.3 Å Fe in Fig. 5(a). (b) As was pointed out in Figs. 2 and 3, this sample is near the compensation point. However, it is seen clearly that both σ_{Fe} and σ_{Tb} are not zero through the whole sample. The apparent compensation behavior follows from the σ_{Tb} domination in the Tb region and σ_{Fe} domination in the Fe region, so the net magnetization becomes very small.

Figure 6 exhibits the distribution of Fe atoms and magnetization for 4.5 Å Tb/8.75 Å Fe. The analogous discussion as was done for Figs. 4 and 5 is omitted. One point worthy of mention is that there is a σ_{Fe} valley and consequently a σ valley in the central Fe region. This behavior follows because the Fe atomic fraction there is close to unity and the amorphous Fe is disordered magnetically. This is the reason why sample 4.5 Å Tb/8.75 Å Fe possesses smaller σ_s than that of 4.5 Å Tb/7.5 Å Fe and there is a magnetization kink around $X = 10$ Å in Fig. 3.

In summary, the dependence of the magnetic properties of Tb/Fe CMF on the layer thickness can be interpreted in terms of both the compositionally modulated distribution of Tb and Fe atoms and their ferrimagnetic coupling. The experimental data show that the magnetic behavior results from a statistical average over the whole sample; however, the modeling analysis offers information about the micromagnetic structure. The results from the modeling analysis agree with the experiment reasonably well. Details of the layer-thickness dependence of the anisotropy for Tb/Fe CMF can be understood by the model developed recently, which will be published elsewhere.[10]

ACKNOWLEDGMENTS

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