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Magnetic properties, anisotropy, and microstructure of sputtered rare-earth iron multilayers

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Magnetic properties, anisotropy, and microstructure of sputtered rare-earth iron multilayers

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A study of compositionally modulated magnetic films of the form Fe/RE, particularly for RE = Nd and Dy, has been performed by vibrating sample magnetometry, ac susceptibility and x-ray diffraction. The relationship between the magnetic properties and the layer thickness was studied systematically for X-Å Fe/Y-Å Dy, as the layer thicknesses X and Y were varied from 1.8 to 20 Å. The ranges of layer thicknesses required for perpendicular anisotropy were determined. The interface and volume anisotropy energies were estimated for X-Å Fe/Y-Å Nd and the differences in the magnetic properties between X-Å Fe/7-Å Dy and X-Å Fe/7-Å Nd are discussed.

INTRODUCTION

Artificially structured magnetic multilayers are an interesting new class of materials.[1] When the layer thicknesses approach the nanometer region there clearly is the opportunity to control the chemical short-range order and its anisotropy. Interfacial atomic interactions become increasingly significant and new thin-film properties, some with technological importance, are likely to arise. Previously we have studied Fe/Nd (Ref. 2) and Fe/Ta (Ref. 3) multilayers and have found that the single-ion anisotropy of the Nd ions plays a major role.

The purpose of this work is to investigate the range and the origins of perpendicular magnetic anisotropy in Fe/RE multilayers. Five series of samples, Fe/Nd, Co/Nd, Fe/Dy, Co/Dy, and Fe/Er, have been prepared and measured. In this paper we shall focus on some of the magnetic properties of Fe/Nd and Fe/Dy multilayer films only. A more detailed discussion of the other systems will be published elsewhere.

EXPERIMENT

Fe/RE multilayers were prepared in a multiple-gun sputtering system with a water-cooled rotating table. The substrate was mylar. The RE (Dy or Nd) was sputtered with an rf gun and the Fe with a dc gun. The layer thickness was controlled by programming the time that the substrate was stationary above the corresponding target. The base pressure of the system was 2×10^{-7} Torr and the pressure during sputtering was held at 5 mTorr in a continuous flow of high-purity argon gas. The total thickness of the samples was about 3000 Å. The multilayers were studied with x-ray diffraction, low- and high-field vibrating sample magnetometry, and ac susceptibility measurements.

RESULTS AND DISCUSSION

X-ray diffraction measurements have been made on selected multilayers and some examples are given in Ref. 2. Briefly, the structure is polycrystalline for individual layer thickness greater than about 15 Å. For thinner layers the structure is amorphous in the direction normal to the film plane but the composition is modulated with the wavelength of the bilayer thickness.

The magnetization and anisotropy characteristics of X-Å Fe/7-Å Nd samples at 300 K are shown in Fig. 1. Several characteristics are noticed: (i) The films exhibit perpendicular anisotropy, i.e., $\sigma_\perp > \sigma_\parallel$, for $X = 5$ Å, 7.5, and 10 Å. The perpendicular anisotropy property gets stronger for X ranging from 2.5 to 5 Å, then gets weaker as the Fe layer thickness increases and finally $\sigma_\parallel$ becomes greater than $\sigma_\perp$ as X becomes larger than 10 Å. We should point out that 5-Å Fe/7-Å Nd and 7.5-Å Fe/7-Å Nd have a high density of Fe-Nd pairs oriented perpendicular to the films. (ii) Fe/Nd multilayer films possess narrow hysteresis loops, and low values of coercivity and remanence, typically of the order of 100 Oe and 1 emu/g, respectively. (iii) Both of $\sigma_\perp$ and $\sigma_\parallel$ increase as X increases and more detailed features will be discussed later. The X-Å Fe/14 Å Nd and X-Å Fe/28-Å Nd samples also have similar characteristics.

The temperature dependence of the hysteresis loops for 2.5-Å Fe/10-Å Nd is shown in Fig. 2. Of interest here is that

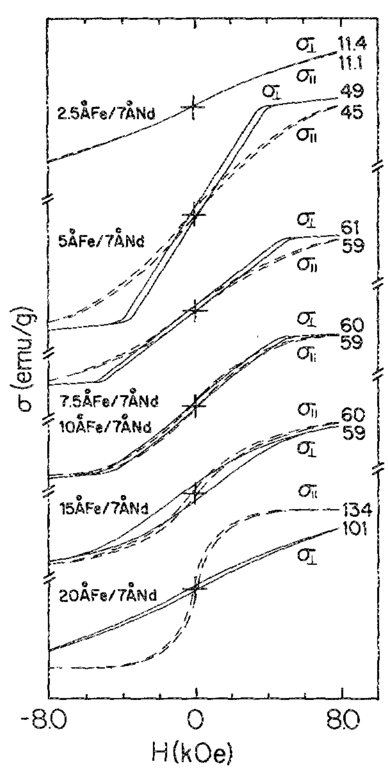

FIG. 1. Magnetization loops at 300 K for X-Å Fe/7-Å Nd series. In this and subsequent figures the layer thicknesses are nominal values based on measurements of sputtering rate.

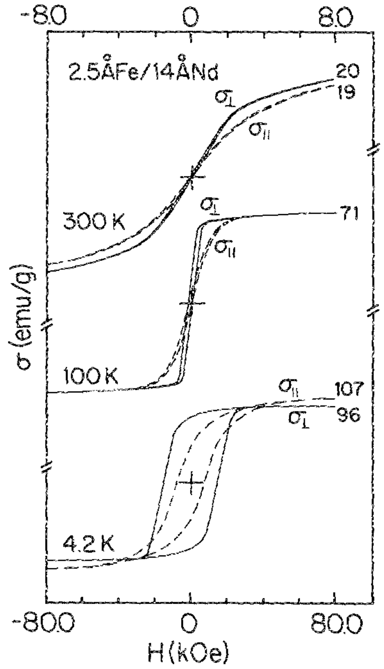

FIG. 2. Magnetization loops of sample 2.5-Å Fe/10-Å Nd at $T = 300$, 100, and 4.2 K. Field axis for upper curve is on the upper abscissa and for the lower two curves on the lower abscissa.

both the coercivity and the remanence increase rapidly as the temperature approaches 4.2 K. We notice that $H_{c\parallel} = 8$ kOe, $H_{c\perp} = 15$ kOe, and $\sigma_\perp \simeq \sigma_\parallel \simeq 100$ emu/g which is close to the calculated value assuming that all Fe and Nd moments are aligned.

Using the formula[4]

$$K_u = -[2K_i + (K_v + 2\pi M_0^2)X]/\lambda,$$

where, M_0, X, λ, K_u, K_v, and K_i are saturation magnetization of Fe, Fe layer thickness, bilayer thickness, and anisotropy energies corresponding to the bilayers, Fe layers, and interfaces, respectively. K_i and K_v can be determined from the experimental data. Figure 3 shows the λK_u vs X curve. Several results are obtained: (i) The perpendicular magnetization occurs for $X < 11$ Å. (ii) From the $X = 0$ intercept, we obtain $K_i = -0.18$ erg/cm^2. (iii) The bulk saturation magnetization data of $M_0 = 1714$ emu/cm^3 for Fe leads to $K_v \simeq -1.5\times10^7$ erg/cm and this is larger than the bulk value of Fe which is 4.8×10^5 erg/cm^3. (iv) For Fe layer thickness less than 6-Å λK_u decreases as the Fe thickness decreases. This is because, as the Fe layer thickness becomes less than about 2 at. diam, significant mixing of the Nd into the Fe layer occurs. Thus, a well-defined Nd/Fe interface is lost.

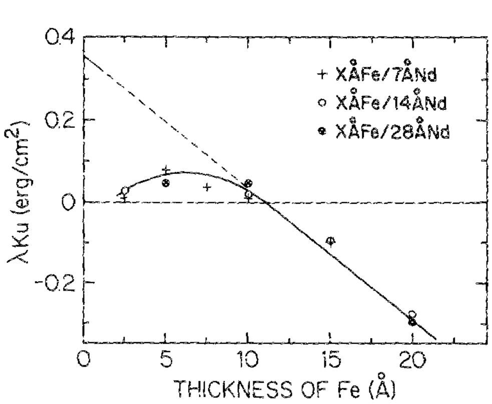

FIG. 3. Total anisotropy energy K_u multiplied by the bilayer thickness vs the Fe layer thickness.

In Fig. 4 the hysteresis loops for X-Å Fe/3.5-Å Dy as a function of the Fe layer thickness are shown. Several interesting features are found: (i) The samples of X-Å Fe/3.5-Å Dy with $X = 6$, 7.5, 9, and 12 Å clearly possess perpendicular anisotropy. As the Fe layer thickness increases further the magnetization in the film plane becomes dominant, i.e., $\sigma_\parallel > \sigma_\perp$. (ii) Comparing with Fig. 1, the hysteresis loops with perpendicular anisotropy here are much broader; that is, these films possess larger values of coercivity and remanence. The coercivity, remanence and the ratio of the remanence perpendicular to the film plane to that parallel to the film plane are listed in Table I. It is seen clearly from these data that Fe/Dy multilayer film could be a potential candidate for a perpendicular recording material.

To determine the range of layer thickness required for perpendicular anisotropy, the Fe/Dy multilayer films were prepared systematically by increasing the layer thicknesses of Fe and Dy approximately one atomic layer at a time. Hysteresis loops were measured and some of the hysteresis loops are shown in Fig. 4. The results are summarized in Fig. 5. The rather broad region possessing perpendicular anisotropy also suggests that Fe/Dy multilayers should be promising for perpendicular recording.

The magnetization for X-Å Fe/7-Å Nd and X-Å Fe/7-Å Dy samples as a function of Fe layer thickness X are shown in Fig. 6. We notice the following. (i) The 8-kOe magnetizations $\sigma_\parallel^*$ and $\sigma_\perp^*$ of X-Å Fe/7-Å Nd are much larger than those of X-Å Fe/7-Å Dy and this is associated with the character of the RE-TM moment coupling: Fe and Nd moments

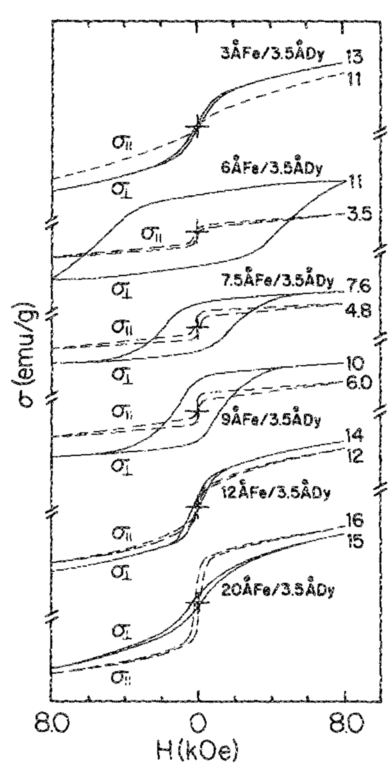

FIG. 4. Magnetization loops at 300 K for X-Å Fe/3.5-Å Dy series.

TABLE I. Coercivity and remanence of some X-Å Fe/3.5-Å Dy samples. $H_{c\perp}$ is the coercivity in the direction perpendicular to the film plane. $\sigma_{r\perp}$ and $\sigma_{r\parallel}$ are the magnetization at $H = 0$ Oe in the direction perpendicular and parallel to the film plane, respectively.

Samples	$H_{c\perp}$ (kOe)	$\sigma_{r\perp}$ (emu/g)	$\sigma_{r\perp}/\sigma_{r\parallel}$
6-Å Fe/3.5-Å Dy	5.2	7.0	12
7.5-Å Fe/3.5-Å Dy	1.9	4.9	2.6
9-Å Fe/3.5-Å Dy	1.2	6.5	4.3
12-Å Fe/3.5-Å Dy	0.18	1.5	0.95
20-Å Fe/3.5-Å Dy	0.20	1.0	0.22

are parallel and for Fe and Dy they are antiparallel. (ii) For X-Å Fe/7-Å Nd the shape of the magnetization curve shows that as X increases from 2.5 to 7.5 Å, $\sigma_{\parallel}^{*}$ and $\sigma_{\perp}^{*}$ also increases presumably due to a decrease in the intermixing of the Fe and Nd layers so that the magnetic structure evolves from speromagnetic towards ferromagnetic. As X increases from 7.5 to 16 Å, $\sigma_{\parallel}^{*}$ and $\sigma_{\perp}^{*}$ remain constant, but a microscopic model for this behavior has yet to be developed. For $X \gg 16$ Å, the magnetization increases rapidly and this is associated with the Fe layers becoming crystalline. (iii) It is of interest that there is a small depression of the magnetization curve at about $X = 10 \sim 12$ Å for X-Å Fe/7-Å Dy. This may be associated with the moment directions of Fe and Dy which are expected to be antiparallel.

In summary, for Fe/Dy and Fe/Nd multilayers the perpendicular anisotropy and its dependence on the layer thicknesses of Fe or RE layer have been determined. The Fe/Dy multilayers, in particular, possess excellent magnetic properties in a rather broad region exhibiting strong perpendicular anisotropy and are suggested to be a potential candidate for perpendicular recording. The fact that the multilayers with higher density of Fe-Dy (or Fe-Nd) pairs oriented perpendicular to the films exhibits stronger perpendicular anisotropy suggests that such pairs are one of the important origins of the perpendicular anisotropy. However, further systematic studies will be required to determine the microscopic origin and other possible sources[5] of the anisotropy. The TM-RE moment coupling for Fe/Nd and Fe/Dy thin multilayers has been observed clearly. The volume anisotropy energy K_v found here is much larger than that of crystalline Fe. One may speculate that this results from an amorphous or monocrystalline Fe structure of $X \lesssim 15$ Å, but detailed microstructure studies will be required to test this hypothesis.

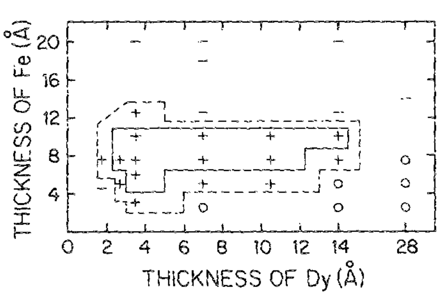

FIG. 5. The range of layer thicknesses exhibiting perpendicular or parallel anisotropy characteristics for Fe/Dy multilayer films. + means $\sigma_{\perp} > \sigma_{\parallel}$, O means $\sigma_{\perp} \simeq \sigma_{\parallel}$, and − means $\sigma_{\perp} < \sigma_{\parallel}$. The region surrounded by the solid line possesses $(\sigma_{r\perp}/\sigma_{r\parallel}) > 1.8$.

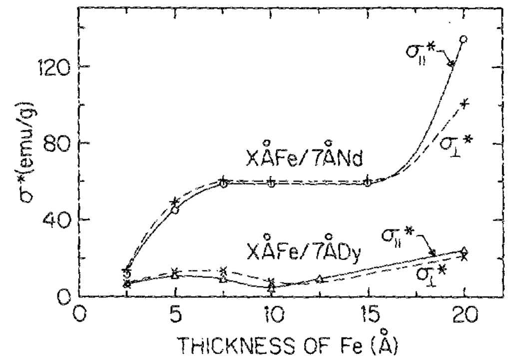

FIG. 6. Comparison of magnetization at 8 kOe for X-Å Fe/7-Å Nd and X-Å Fe/7-Å Dy.

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