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Structure and magnetic properties of nanostructured Dy/transition-metal multilayered films

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We report the results of magnetic and microstructural studies for T/Dy (T = Fe, Co, Ni) compositionally modulated films prepared in a multiple-gun sputtering system. The perpendicular anisotropy and magnetization were measured systematically for X-Å Fe/Y-Å Dy and X-Å Co/Y-Å Dy films. The layer-thickness dependence of the magnetization for Co/Dy and Fe/Dy was interpreted in terms of the antiparallel coupling between transition-metal and Dy magnetic moments. For Co/Dy films the ranges of X and Y required for perpendicular anisotropy were determined. A comparision of the structural and magnetic properties of Ni/Dy, Co/Dy, and Fe/Dy is given and the origin of the perpendicular anisotropy is discussed.

INTRODUCTION

Compositionally modulated films have been studied extensively for both physical and technological reasons. Some films[1-3] are of great interest for their strong perpendicular anisotropy. They could be the materials of choice for investigating solid interfaces or candidates for perpendicular recording. Previously we have studied Fe/Ta, Fe/Dy, and Fe/Nd multilayered films,[4-6] and the present work represents an extension to Co/Dy, Fe/Dy, and Ni/Dy systems. The layer-thickness dependence of the magnetization and perpendicular anisotropy was investigated systematically. In this paper we shall only report some of the magnetic properties at room temperature. A more detailed discussion of the temperature dependence of the magnetic properties and the origin of the perpendicular anisotropy will be published elsewhere.

EXPERIMENT

We have prepared a variety of samples of the form X-Å T/Y-Å Dy (T = Fe, Co, and Ni). Here X and Y are the layer thicknesses of the transition metal and Dy. In this work X and Y range from 2.5 to 160 Å and 1.75 to 224 Å, respectively. In order to study the layer-thickness dependence of magnetic properties systematically, in the region of 2.5 Å $<X<$ 20 Å and 3.5 Å $<Y<$ 14 Å the interval for X and Y is about one atomic diameter, i.e., 2.5 Å for T and 3.5 Å for Dy. In some regions the interval is only 1.25 Å to probe the change of the magnetic properties more precisely. Totally about 150 samples have been prepared.

The samples were prepared with the multiple-gun sputtering system. The preparation conditions here are the same as those mentioned in Ref. 6. In this system six samples can be made in one vacuum run by means of a specially designed mechanism which can be rotated to move the substrate shutter from one position to another. This design enables the sample preparation to be done much more efficiently and reduces the fluctuation of magnetic properties due to the change of preparation conditions among different runs.

The measurements of the magnetic properties, such as the magnetization in the direction perpendicular and parallel to the film plane, coercivity, and anisotropy energy, etc., were performed with vibrating sample magnetometry. The atomic structure was studied with large and small-angle x-ray diffraction.

RESULTS AND DISCUSSION

Four examples of large-angle x-ray diffraction patterns are shown in Fig. 1, and three examples of small-angle x-ray diffraction in Fig. 2. We notice that 40-Å Fe/56-Å Dy film has much sharper diffraction peaks than those of the 40-Å Co/56-Å Dy film. Therefore, in rough terms, 40-Å Fe/56-Å Dy has crystalline structure and 40-Å Co/56-Å Dy has microcrystalline structure, whereas for 15-Å Fe/14-Å Dy and 10-Å Co/14-Å Dy films, the structure is amorphous. The small-angle x-ray diffraction patterns only show the first-order peaks for 40-Å Fe/14-Å Dy and 50-Å Co/14-Å Dy, but also the second-order peak for 30-Å Ni/7-Å Dy. This implies that the compositionally modulated structure has the sinusoidal form for 40-Å Fe/14-Å Dy and 50-Å Co/14-Å Dy, and a sharper interface boundary for 30-Å Ni/7-Å Dy.

The layer-thickness dependence of magnetic properties was probed in terms of the measurements of hysteresis loops for all samples. One series of samples for Co/Dy is shown in Fig. 3. In this figure Dy layer thickness is fixed at 5 Å and the Co layer thickness changes from 3.5 to 10 Å. It is seen clearly that: (i) The samples with X = 3.5, 6, and 8 Å have strong

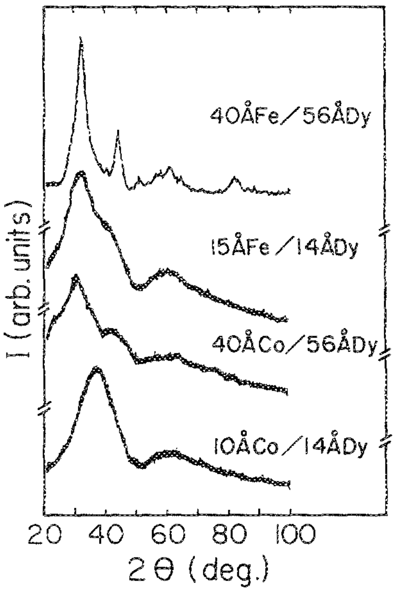

FIG. 1. Cu$K\alpha$ large-angle diffraction intensity as a function of 2θ for four Fe/Dy and Co/Dy samples.

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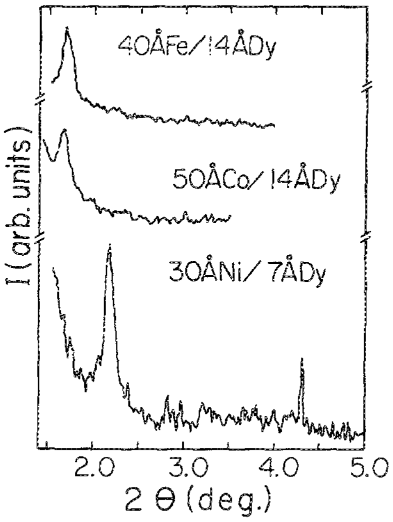

FIG. 2. Cu$K\alpha$ small-angle diffraction intensity as a function of 2θ for three Fe/Dy, Co/Dy, and Ni/Dy samples.

perpendicular anisotropy, i.e., $\sigma_\perp > \sigma_\parallel$. But as the Co layer thickness reaches 10 Å, $\sigma_\parallel$ becomes larger than $\sigma_\perp$. (ii) The values of covercivity H_c and magnetization σ (8 kOe) shown on the figure are changed correspondingly as the Co layer thickness increases, and this will be discussed in more detail in the following. (iii) The sample of 6-Å Co/5-Å Dy has interesting character for its "square hysteresis loop," larger coercivity of 2.6 kOe, and stronger perpendicular anisotropy. The fact that the samples with thinner Co layer have stronger perpendicular anisotropy means the interfaces play an important role for perpendicular anisotropy. The interface possesses reduced symmetry which favors perpendicular anisotropy as indicated in Ref. 7.

Based on systematic measurements, the layer-thickness dependence of the magnetization $\sigma_\perp$ at 8 kOe for Co/Dy films is summarized in Fig. 4. The effect of the antiferromagnetic coupling between Co and Dy magnetic moments is shown clearly in this figure: (i) For example, the magnetization of X-Å Co/8-Å Dy is saturated for thick Co layer because of the Co magnetization dominance in this region. As the Co layer becomes thinner $\sigma_\perp$ decreases, passes through the compensation point, and changes the sign since the Dy magnetization dominates. At very small Co thickness $|\sigma_\perp|$ decreases, presumably because both the atomic and magnetic structures become highly disordered. (ii) As the Dy layer gets thicker the compensation point moves towards larger Co layer thickness, which is reasonable.

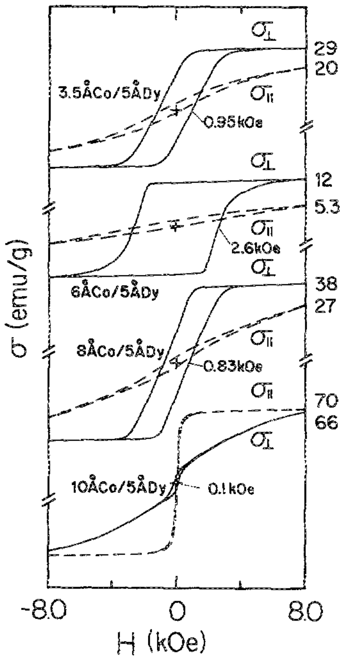

FIG. 3. Magnetization loops at 300 K for X-Å Co/5-Å Dy series.

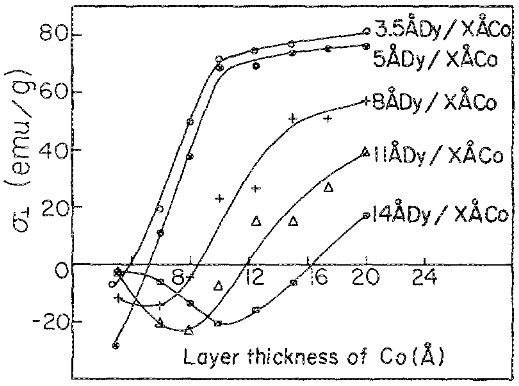

FIG. 4. Layer-thickness dependence of magnetization $\sigma_\perp$ at room temperature.

It is useful to determine the ranges of Co and Dy layer thickness exhibiting perpendicular anisotropy. The result is shown in Fig. 5. The rather broad region exhibiting perpendicular anisotropy suggests that Co/Dy films could be promising for perpendicular recording.

It is of interest to ask whether the thickness dependence of the magnetic properties discussed above could be explained entirely on the basis of a model in which one assumes a composition dependence of an essentially homogeneous glassy alloy. Figure 6 gives a negative answer to this question. The hysteresis loops of four samples, which have identical chemical ratios of Co and Dy, change their shape regularly as the nominal layer thickness of Co and Dy increase. This feature means the compositionally modulated structure clearly exists and controls the magnetic properties.

A similar character of the layer-thickness dependence of magnetic properties, as shown in Figs. 3–5, is also found for Fe/Dy films. Some of these figures were shown in our previous paper.[6]

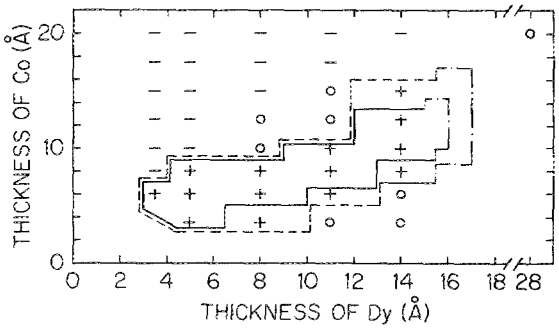

FIG. 5. The range of layer thickness exhibiting perpendicular or parallel anisotropy characteristics for Co/Dy films. $+ = \sigma_\perp > \sigma_\parallel$; $\bigcirc = \sigma_\perp \approx \sigma_\parallel$; and $-- = \sigma_\perp > \sigma_\parallel$. The region surrounded by the solid line possesses $(\sigma_\perp/\sigma_\parallel) > 2$ at $H = 0$.

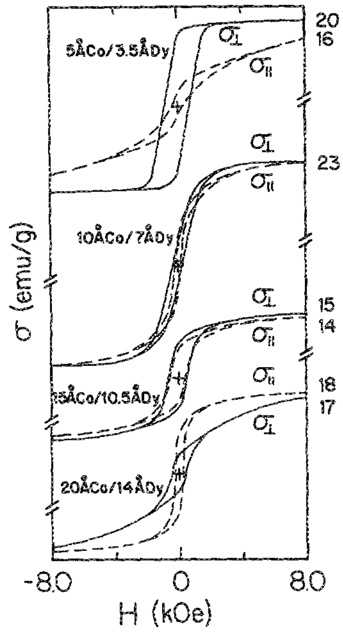

FIG. 6. The hysteresis loops of the Co/Dy films which have the identical chemical ratio of Co and Dy, but increasing layer thickness.

Two series of Ni/Dy samples, the *X*-Å Ni/3.5-Å Dy and *X*-Å Ni/7-Å Dy ($X = 2.5, 5, 7.5, 10, 15, 20$, and 30 Å), have been studied. The magnetizations at room temperature are much weaker than those of Fe/Dy and Co/Dy films. This follows from the weaker exchange coupling in Ni as compared to Fe and Co. Low-temperature studies of the Ni/Dy system are now under way.

The magnetic structure and origin of the perpendicular anisotropy for the compositionally modulated films are interesting but complicated. Many models, such as stress induced anisotropy,[8] single-ion anisotropy,[9] exchange anisotropy,[10] anisotropic ordering of atomic pairs,[3] etc., have been proposed to interpret the perpendicular anisotropy. In this paper we have pointed out that the interface is the main source for the perpendicular anisotropy, but a microscopic model suitable for the compositionally modulated films remains to be developed. For the T/Dy (T = Fe, Co, and Ni) films the following conclusions can be stated: (i) Stress induced anisotropy is not important based on our experiment that the 5-Å Fe/5-Å Dy film deposited on Mylar, Ta, Cu, and mica substrates exhibited almost same magnetic properties (not shown in this paper). (ii) The model of anisotropic ordering of the atomic pairs is appealing for explaining the perpendicular anisotropy, as is qualitatively discussed in Ref. 3. (iii) The single-ion model is successful in calculating the perpendicular anisotropy for nonmultilayered $(Gd_{0.75}R_{0.25})_{19}Co_{81}$.[9] This may be a promising model, but the anisotropic distribution of the atoms in the interface must be determined carefully. In particular, the interactions of the rare earth with both its rare-earth and transition-metal neighbors must be accounted for properly.

In summary, the systematic studies of the layer-thickness dependence of the magnetization and perpendicular anisotropy have been performed for Co/Dy and Fe/Dy compositionally modulated films. The values of magnetization and perpendicular anisotropy are controllable. Thus, these films may be the potential candidates for perpendicular and/or magneto-optic recording. The origins of the perpendicular anisotropy have been discussed and a detailed model suitable for the compositionally modulated films presently is being investigated.

ACKNOWLEDGMENTS

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