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Magnetic properties of Fe/Nd multilayer films

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Measurements are reported on the relationship between magnetic properties and microstructure in thin amorphous and crystalline Fe/Nd multilayer films. The samples, denoted by $(X\,\text{Å}\text{Fe}/Y\,\text{Å}\text{Nd}) \equiv (X/Y)$, were prepared in a multiple-gun sputtering chamber with a microprocessor-controlled rotating table. For X and Y values less than about 20 Å an amorphous compositionally modulated structure is obtained, with magnetic properties characterized by speromagnetic ordering associated with strong Nd random anisotropy. The net magnetization in general lies in the plane of the film. The temperature and composition dependence of the coercivity, magnetization, and transition temperatures are discussed.

INTRODUCTION

In recent years great interest has been associated with amorphous rare-earth–transition-metal alloys. This follows from the novel types of random magnetism[1] and phase transitions[2] induced by local random anisotropy, and also because certain of these alloys in thin-film form exhibit perpendicular magnetic anisotropy which gives them potential as erasable magneto-optic storage media.[3] An understanding of the origin of the perpendicular anisotropy has been difficult to achieve, but one of the favored models is that of a microstructure which includes significant *anisotropic* short-range pair ordering.

Given this situation it is intriguing to consider how modern deposition techniques[4] for producing compositionally modulated alloys (CMA) might be brought to bear on this question. If one constructs a CMA of the form A/B with individual layers of only one or two atomic layers, one in effect has created an artificially structured material with highly anisotropic pair correlations; these are excess AA and BB pairs in the plane of the film and AB pairs perpendicular to the plane of the film. Since it is possible to produce random homogeneous glasses by rapid rotation of a substrate over two sputtering guns, for example, it is possible also to introduce in a controlled way a given amount of anisotropic pair ordering by holding the substrate over a gun long enough for, say, one or two atomic layers to form.

The present work was motivated by the above considerations and with particular reference to Fe/Nd multilayers. Because Nd is a light rare earth there is a ferromagnetic coupling between the Fe and Nd moments, and the Nd has a significant random magnetic anisotropy (RMA). Thus one goal of this study was to compare the effects of the ferromagnetic coupling and random anisotropy *vis-à-vis* a magnetic multilayer system such as Fe/Ta,[5] where the second element is nonmagnetic.

EXPERIMENT

The Fe/Nd films were prepared with a multiple-gun sputtering system employing a microprocessor-controlled, water-cooled substrate. dc and rf guns were operated in 5 mTorr of flowing high-purity argon gas, after the system was pumped to 2×10^{-7} Torr. Mylar substrates were used and the total thickness of the samples was typically 3000 Å. A standard notation is adopted in which $(X\,\text{Å}\text{Fe}/Y\,\text{Å}\text{Nd})$ also is written as (X/Y). The films were characterized with small- and large-angle x-ray diffraction, low and high-field vibrating sample magnetometry, and ac susceptibility measurements between 4.2 and 300 K.

RESULTS AND DISCUSSION

Figure 1 shows diffraction data typical of samples with large and small modulation wavelength, $\lambda \equiv X + Y$. The (20/20) sample exhibits only a broad peak near 29° which is indicative of an in-plane amorphous structure. For a larger λ sample, (100/100), broadened Nd crystalline peaks are observed from about 26–30°, and a very small (110) bcc Fe peak (not shown) near 44°. The wavelength modulation of the (10/10) sample is seen in Fig. 2 which shows peaks corresponding to first- and second-order diffraction from structure with $\lambda = 26.6$ Å. There is thus rough agreement with the nominal wavelength of 20 Å based on measured sputtering rates. In general, when the individual layer thicknesses get below (above) 15–20 Å, the resulting CMA structure in the film plane is amorphous (crystalline).

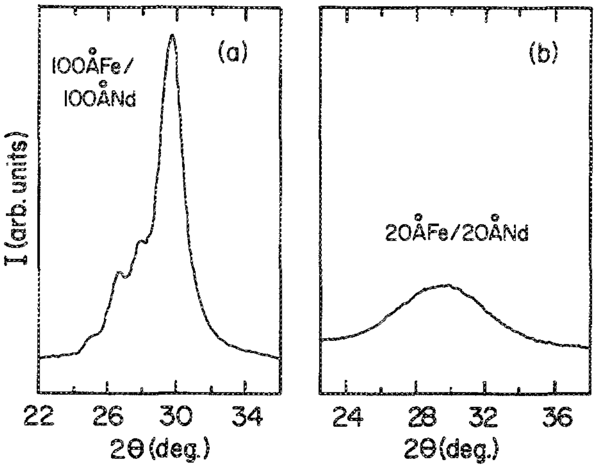

FIG. 1. Cu$K\alpha$ diffraction intensity as a function of angle for (100/100) and (20/20) films. In (a) peaks at 28° and 30° are due to Nd (100) and (004) planes.

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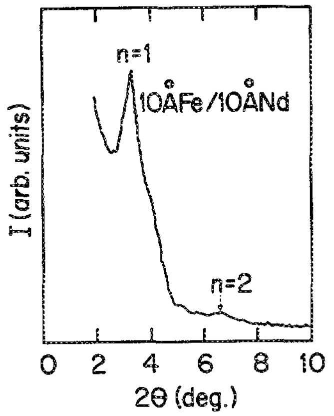

FIG. 2. Small-angle Cu$K\alpha$ diffraction intensity vs angle for a (10/10) sample.

Figure 3 exhibits several examples of low-field, room-temperature and high-field, helium-temperature hysteresis loops. Of interest here is the apparent difficulty of achieving saturation in the (15/15) film which presumably stems from the RMA of the Nd. In addition there is no clear tendency towards perpendicular anisotropy as λ gets small, as there is in the Fe/Ta system.[5] The 4.2 K loop to 80 kOe for the (30/30) film shows a constricted loop characteristic of a system with two magnetic phases.

Figure 4 shows the saturation magnetization obtained by extrapolating high-field data to $H = 0$. Data for two series of samples are shown: (100/X) and (X/X). The falloff in σ_s in the latter series for $x \cong 20$ Å is attributable to the amorphous structure and the RMA associated with Nd. Figures 5 and 6 show the behavior of the apparent anisotropy field, H_K at 300 K and the coercivity H_c, at 300 and 4.2 K. H_K is determined by the standard extrapolation of $\sigma(H_\perp)$ to the field where it intersects the saturated $\sigma(H_\parallel)$. For the (100/X) series, H_K remains independent of X and thus does not follow the behavior expected for a simple soft magnetic film where $H_K = 4\pi M_s$, where M_s is the average spontaneous magnetization. At 300 K, H_c for both series with $X \cong 60$ Å is 300–400 Oe. However, at 4.2 K the (X/X) series tends towards very large H_c values (~ 10 kOe) as $X \to 20$ Å. Again this is clearly associated with a speromagnetic structure (spin-glass-like) with strong RMA and a glassy, compositionally-modulated structure.

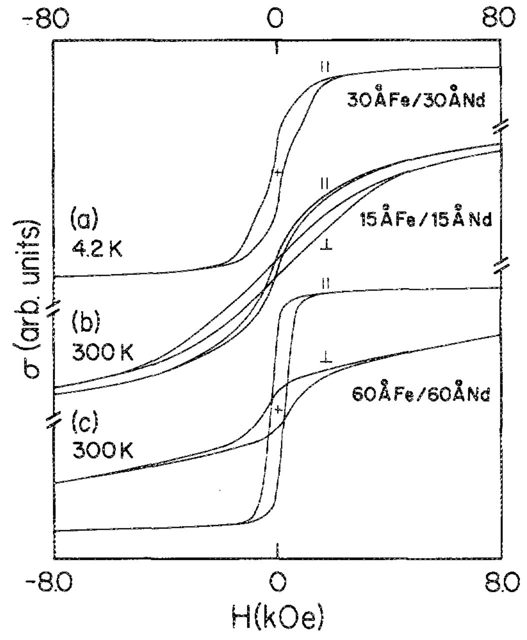

FIG. 3. Magnetization loops at 4.2 or 300 K for three samples. Field axis for upper curve is on the upper abscissa and for the lower two curves on the lower abscissa.

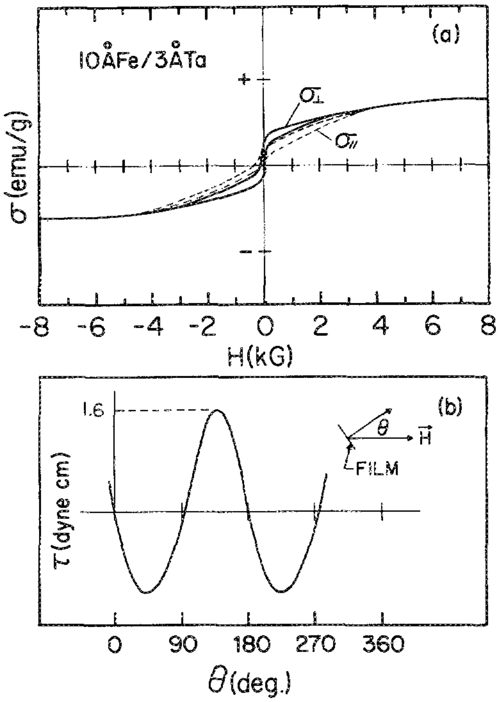

FIG 4. Extrapolated ($H = 0$) saturation magnetization for (100/X) and (X/X) series.

ac susceptibility results are shown in Fig. 7 for two of the films with rather small X values in the (X/X) series. For the (5/5) sample there is an apparent speromagnetic transitions at $T_g \cong 230$ K and for the (10/10) sample this transition appears to be above room temperature. For larger X values, e.g., (100/100), where the Fe and Nd individual layers are

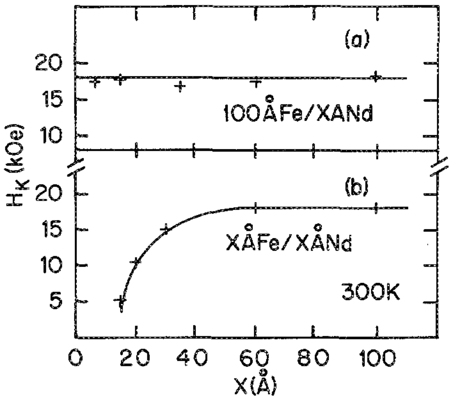

FIG. 5. Apparent anisotropy field, obtained in text for (100/X) and (X/X) series.

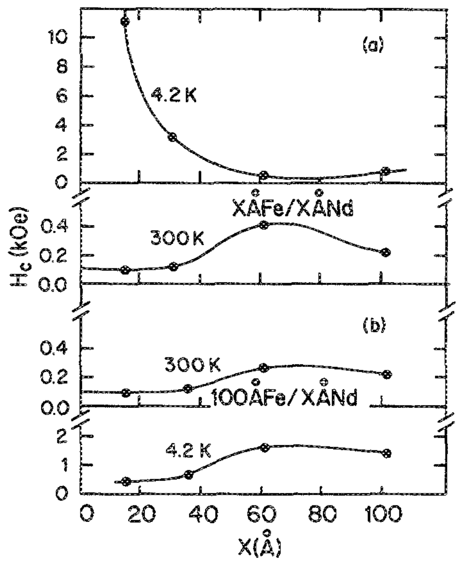

FIG. 6. Coercive field H_c at 4.2 and 300 K for the two series indicated.

polycrystalline, we observe a large, temperature-independent χ_{ac} from 300 down to 4.2 K. This is surprising since one might expect to see one or more transitions in the Nd layers in the region below 19 K, where antiferromagnetism sets in.[6]

In this work the effects of RMA associated with Nd are clearly seen in the difficulty in achieving saturation of the magnetization and in large coercivities particularly for (X/X) multilayers as X decreases below about 20 Å. However, no clear evidence for perpendicular anistropy has been observed, and this is in contrast to recent work reported on sputtered Fe/Tb multilayers.[7] The structure of these films is expected to be similar to that of the present Fe/Nd films. In addition, Fe-Nd films[8] sputtered onto substrates, heated to 250 °C, as well as FeNdTi sputtered films,[9] do show perpendicular anisotropy. Thus the relationship between uniaxial anisotropy and microstructure is very delicate matter in Fe/rare-earth films. Further measurements, including microstructure and torque measurements, are planned for these systems.

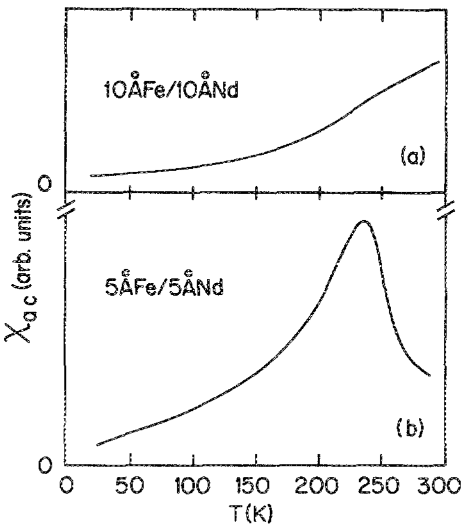

FIG. 7. ac susceptibility (280 Hz, $H_{ac} \approx 0.1$ Oe) for (10/10) and (5/5) films.

ACKNOWLEDGMENTS

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[1] See K. Moorjani and J. M. D. Coey, *Magnetic Glasses* (Elsevier, New York, 1984).
[2] D. J. Sellmyer and S. Nafis, Phys. Rev. Lett. **57**, 1173 (1986).
[3] G. A. N. Connell, J. Magn. Magn. Mater. **54–57**, 1561 (1986).
[4] See C. M. Falco, W. R. Bennett, and A. Boufelfel, in *Dynamic Phenomena at Surfaces, Interfaces and Superlattices* (Springer, Berlin, 1985), p. 35 and references therein.
[5] Z. S. Zhan, Z. R. Zhao, J. G. Zhao, and D. J. Sellmyer (these proceedings).
[6] See J. J. Rhyne, in *Magnetic Properties of Rare Earth Metals*, edited by R. J. Elliott (Plenum, New York, 1972), p. 143.
[7] N. Sato, J. Appl. Phys. **59**, 2514 (1986).
[8] T. Suzuki, J. Magn. Magn. Mater. **54–57**, 1407 (1986).
[9] K. Tsutsumi and H. Sugahara, Jpn. J. Appl. Phys. **23**, L169 (1984).