Magnetic studies of Fe-Y compositionally modulated thin films

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Compositionally modulated thin films of Y/Fe have been studied by using SQUID magnetometry. Samples were grown by electron-beam evaporation onto Kapton substrates. In the low applied field regime, the samples show irreversible behavior when they are submitted to ZFC-FC magnetization processes, increasing the irreversibility zone as the thickness of the Fe layers increases. In the high applied magnetic field regime ($H \geqslant 10\,000$ Oe), samples show ferromagnetic behavior. The temperature dependence of the saturation magnetization has been studied, and it was found that both spin-wave excitations and Stoner excitations occur at temperatures higher than 40 K, and a marked deviation from the $T^{3/2}$ law was noted below 30 K.

INTRODUCTION

Multilayered samples of rare-earth and transition-metal atoms are ideal systems to study the competition between exchange interaction and local random anisotropy because of the strong magnetocrystalline anisotropy of the non-*s*-state rare-earth ions, which is predominantly single ion in nature. The problem of random magnetic anisotropy has been the subject of several papers in the last decade[1-3] due to the technological interest of transition-metal (Fe,Co) rare-earth magnets as promising systems for thermomagnetic and magneto-optical recording. Chudnovsky *et al.*[2,3] have shown that the magnetic properties of system with local random anisotropy (LRA) and ferromagnetic exchange are dominated by the parameter $\Lambda_r = \lambda_r (R_a/a)^2$, where $\lambda_r \simeq D/J$ is the relation between LRA strength and exchange, R_a is the distance over which the local easy axis is correlated, and a is the interatomic distance.

In this paper we study the magnetic properties of the Y/Fe multilayer system as a function of the iron layer thickness. The interlayer surface roughness and the Y atom diffusion on the Fe layers produce a polarization of the net magnetization of each Fe layer[4] which can be considered as a source for the random anisotropy that has been observed in our samples in the low applied field regime.

EXPERIMENTAL RESULTS AND DISCUSSION

We have investigated the magnetic properties of four Y/Fe compositionally modulated thin films having different Fe layer thickness. The samples were grown onto Kapton and glass substrates by means of electron gun evaporation. The system uses a shutter to alternate the evaporation of the two elements from two separate *e*-guns and to build the multilayer structure. The pressure before evaporation was 10^{-7} Torr and increases until 2×10^{-7}. The thickness of the layer was measured *in situ* using a quartz-crystal sensor and was later measured again using the Tolansky method[5] with an error less than 5% (see Table I). We began growing a thick buffer of about 650 Å of Y onto the substrate to smooth the surface roughness. The substrate temperature was held at 300 °C during the growth of this buffer, and then it was reduced to 200 °C. Onto the buffer layer we grew the Fe and Y structure, finishing with an Y layer. Finally, we grew a cover layer of 500-Å Al to protect the sample against oxidations.

Our low-angle x-ray spectra show peaks that correspond to the modulation of the multilayer (Fig. 1). The high-angle x-ray spectra show a large peak that corresponds to Y with preferred orientation in the [002] direction. The peaks corresponding to the Fe are smaller and do not show any preferred orientation.

We have also observed the samples with transmission electron microscopy, and we can see a grain structure. The electron diffraction pattern shows evidence of a polycrystalline structure.

A commercial SHE SQUID magnetometer has been used to study the dependence on temperature and field of the magnetization. First, we have measured the zero-field-cooled and the field-cooled behavior at low fields for the four samples. The applied field was just high enough to have a good signal, and it was applied parallel to the sample plane. For sample 1 we observe a spin-glass-like behavior (Fig. 2). In fact, this behavior is not far away from the one observed for the Y-Fe amorphous alloy.[4] Those alloys show asperomagnetic behavior, and it is due to the competition of differ-

TABLE I. Structural parameters of the samples.

Sample	Fe (Å)	Y (Å)	No. layers
1	13	38	23
2	26	39	44
3	38	35	41
4	47	38	19

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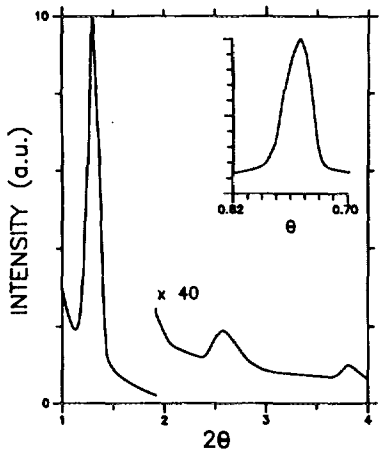

FIG. 1. Low-angle x-ray pattern for sample 2 showing the peak coming from the multilayer structure. The rocking curve of the first-order peak is shown in the inset.

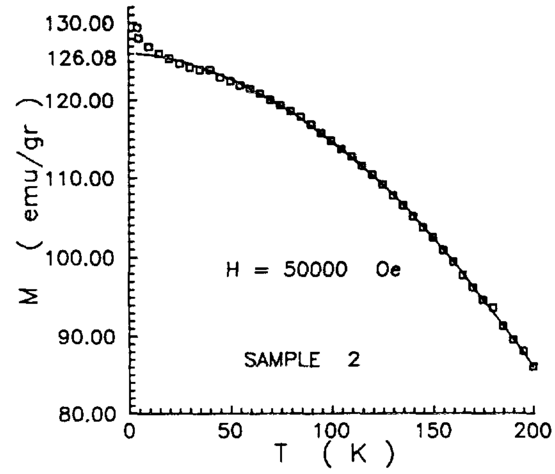

FIG. 3. Variation of the saturation magnetization with temperature at constant applied field $H = 50\,000$ Oe for sample 2.

ent sign interactions caused by the dilution of Fe into Y. This suggests that we have some diffusion at the interface, and this creates an amorphous Y-Fe alloy. As the Fe layer thickness increases, the behavior of the samples changes from the one described by Coey *et al.*,[4] and the irreversibility starting point moves toward higher temperatures. We have investigated the thermal demagnetizing processes by applying a field of 50 000 Oe parallel to the substrate at 4.2 K and then raising the temperature, keeping the field constant (Fig. 3).

We have fitted the experimental data using the equation.

$$M_s(T) = M_0(1 - BT^{3/2} - AT^2), \tag{1}$$

where the $T^{3/2}$ term shows the existence of spin waves, and the T^2 term account for Stoner exitation. The data were fitted first doing $A = 0$ and then with the complete expression. The fit is better when the complete expression is used.

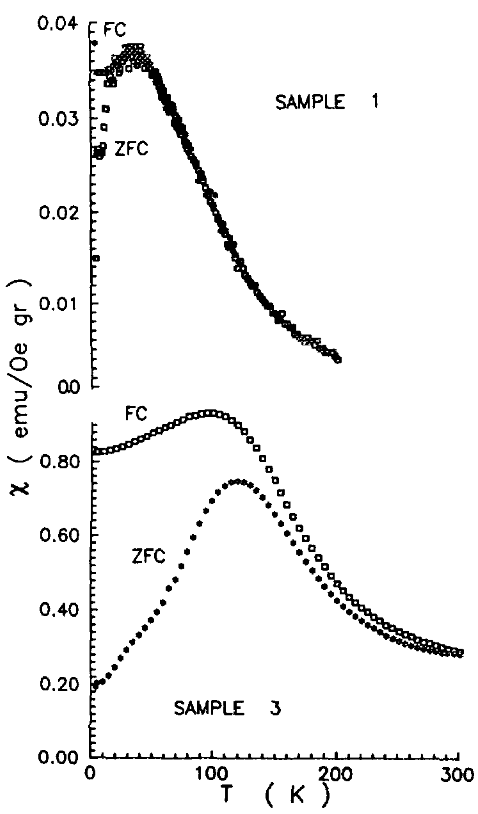

FIG. 2. ZFC-FC low-field susceptibility for different samples.

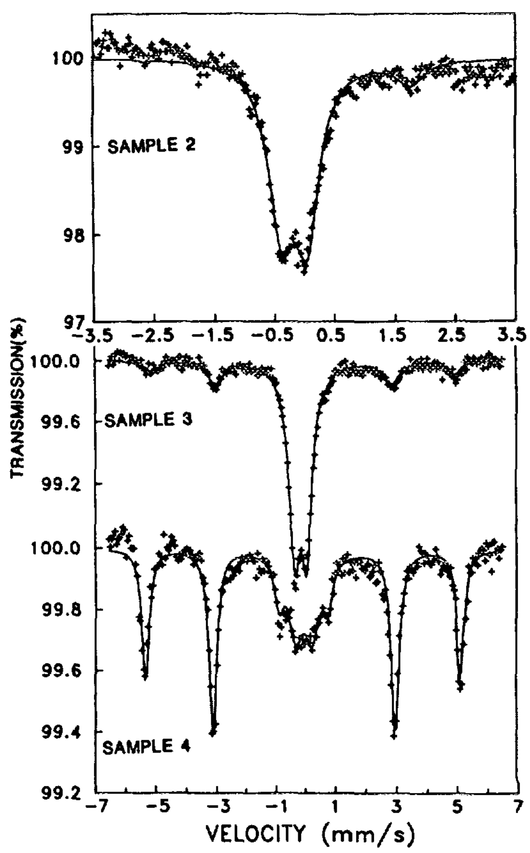

FIG. 4. Mössbauer spectra at room temperature for samples 2, 3, and 4.

TABLE II. Values of the saturation magnetization and the B parameters of Eq. (1) for the four samples.

Sample	$M = M_0(1 - BT^{3/2})$		$M = M_0(1 - BT^{3/2} - AT^2)$		
	M_0 (emu/g)	B (K$^{-3/2}$)	M_0 (emu/g)	B (K$^{-3/2}$)	A (K^{-2})
1	48.20	2.29×10^{-4}	51.70	3.92×10^{-4}	-1.08×10^{-5}
2	129.22	1.15×10^{-4}	126.08	3.55×10^{-5}	5.43×10^{-6}
3	155.57	7.56×10^{-5}	154.72	6.44×10^{-5}	6.43×10^{-7}
4	225.65	3.42×10^{-5}	225.14	2.95×10^{-5}	2.63×10^{-7}

The coefficient A is always one order of magnitude smaller than B. In Table II we summarize the values of the coefficients M_0, B, and A for all samples and for the two kinds of fittings done. As expected, we can see how M_0 increases when the iron layer thickness increases. The phenomenon of the deviation from the $T^{3/2}$ law[6] in the very low-temperature regime ($T < 30$ K) can be accounted for by Kaneyoshi's theory[7,8] for the spin-wave excitation in the amorphous asperomagnetic alloy. In our case, we have this effect, due to the interface, superposed to the ferromagnetism of the single iron layer.

Finally, we have used SQUID magnetometry to measure the approach to saturation. The field was applied parallel and perpendicular to the sample. At 4.2 K we do not reach saturation for any of the samples even at applied fields of 50 000 Oe. The coercive field and the remanent magnetization are both very small, obtaining quasireversable hysteresis loops (see Table III). This behavior can be interpreted in the theory of Chudnovsky, Saslow, and Serota[3] as the one corresponding to the correlated spin glass whose main macroscopic features are the absence of hysteresis and the large zero-field susceptibility. In our case, the source of the random anisotropy is the polarization of the Fe layers by the diffused Y atom and the surface roughness. From the comparison of the M-vs-H curves when the field is applied parallel and perpendicular to the sample, we can conclude that the magnetization is in-plane.

TABLE III. Values of remanence (M_r) and coercivity (H_c) for samples 2, 3, and 4 with the applied field parallel to the sample plane.

Sample	M_r (emu/g)	H_c (Oe)
2	55.33	750
3	93.54	530
4	156.81	350

We have done Mössbauer spectroscopy at room temperature, and all the spectra show a large quadrupolar doublet associated to the iron diluted in the yttrium at the interfaces (Fig. 4).[9] As the Fe layer thickness increases, a six-line pattern starts to appear due to the ferromagnetic order in the pure iron layer. For sample 4 we can see a large sextet superimposed to this quadrupolar term. This sextet is strongly reduced for sample 3. For sample 2 we can hardly guess the presence of the sextet.

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