Magnetic properties of amorphous Fe-Si compositionally modulated thin films

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The present paper reports on a magnetometric study of Fe-Si compositionally modulated thin films. The low-temperature dependence of the magnetization exhibit Bloch's $T^{3/2}$ dependence with a minor $T^{5/2}$ correction term. The spin-wave stiffness constant deduced from the temperature coefficient depends on the characteristic modulation length and its values are much lower that in glassy alloys.

INTRODUCTION

For both crystalline and glassy ferromagnets, the magnetization as $T=0$ K varies as

$$M(T)/M(0) = 1 - BT^{3/2} - CT^{5/2}. \tag{1}$$

The B coefficients for glassy ferromagnets are of about 10^{-4} $K^{-3/2}$ and a factor 10 smaller for the crystalline case. The C coefficients are comparable in both cases.[1]

The properties of the collective excitations in superlattices have been a subject of increasing interest in recent years. In the case of magnetic superlattices, in which one has a set of magnetic films separated from each other by a nonmagnetic material, the spin waves appearing as $T=0$ K in the different magnetic films may couple either through the long-range dipole fields, which accompany a spin wave or through exchange coupling.[2] For separations greater than 20 Å the dipolar fields alone allow the spin-wave existence, and, when the magnetic films are close, the exchange interactions existing between spins of different materials explain the spin waves presence. Many theoretical attempts have been recently published with the aim to study the magnetostatic spin-wave modes for ferromagnetic multilayers.[3–5]

EXPERIMENT

The Fe-Si compositionally modulated thin films were prepared in a special triode sputtering system on glass substrates held at room temperature. The thin films are formed by single layers of an amorphous alloy of composition $Fe_{75}Si_{25}$ with different thicknesses separated by amorphous layers of Si. The total thicknesses of the samples, determined by using a Tolansky interferometer, are about 1000 Å.

The amorphous character of the samples was verified by means of x-ray diffraction and, using low angle x-ray scattering, we tested the modulated structure of the samples.

In Table I we summarize the thickness and composition of the samples. The magnetization measurements were recorded using a SQUID magnetometer in applied magnetic fields up to 5.5 T working in the temperature range between 1.8 and 300 K.

TABLE I. Thickness and composition of the different samples.

Sample	$Fe_{75}Si_{25}$ layer thickness (Å)	Amorphous Si single layer thickness (Å)	Characteristic modulation length λ (Å)
1	4.4	2.2	6.6
2	8.8	4.4	13.2
3	17.6	8.8	26.4
4	35.2	17.6	52.8

RESULTS AND DISCUSSION

In Figs. 1 and 2 we show the magnetization dependence, at constant temperature $T=4.2$ K, on the external field for the easy direction contained in the substrate plane, $M_{\parallel}$, and in the perpendicular direction to the substrate, $M_{\perp}$. In both cases the curves are clearly not saturated at external applied fields, H, of 5.5 T. This can be correlated with the existence

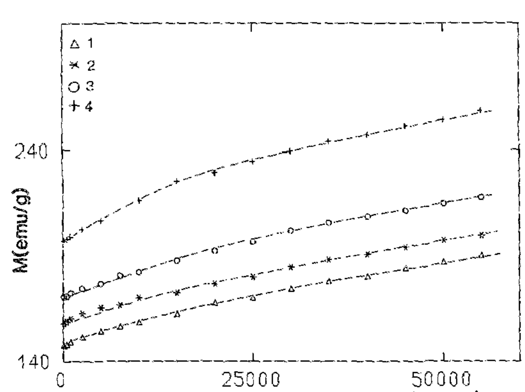

FIG. 1. $M_{\parallel}$ dependence on the external applied field at constant $T=4.2$ K for the different samples.

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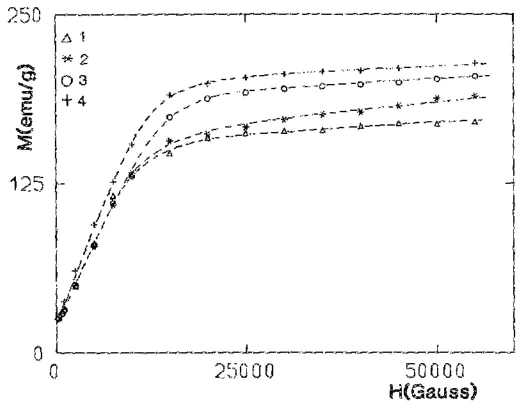

FIG. 2. M_1 dependence on the external applied field at constant $T = 4.2$ K for the different samples.

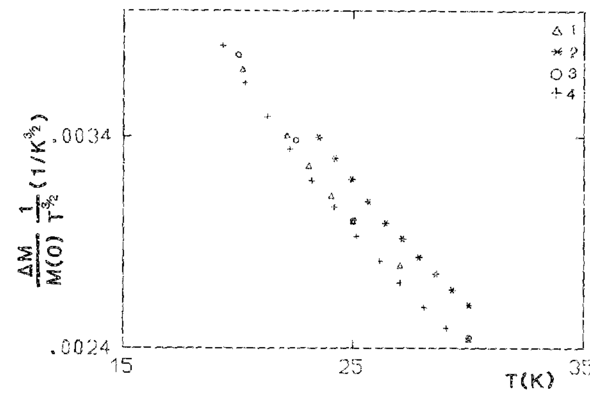

FIG. 4. $[\Delta M/M(0)]T^{3/2}$ vs T for the different samples differing in the λ values.

of paramagnetic iron clusters as has been deduced by means of conversion electron Mössbauer spectroscopy.[6] The magnetization values at each H, increase as the characteristic modulation length, λ.[6] In fact the $M(\lambda)$ dependence reflects the increase of both the exchange interaction and the Curie temperatures when λ increases.

We have also measured the $M(T)$ dependence, in the easy direction of magnetization, for all the samples in the low-temperature regime. In this case we measured the magnetization applying an external field of 5.5 T when the samples were at $T = 1.8$ K. Then we changed the temperature maintaining constant the applied magnetic field. Our data are shown in Fig. 3. These data can be well fitted by using Eq. (1), or equivalently

$$\frac{\Delta M}{M(0)} \equiv \frac{M(0) - M(T)}{M(0)} = BT^{3/2} + CT^{5/2}. \tag{2}$$

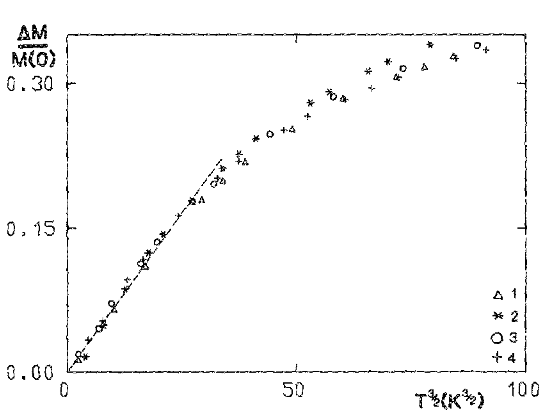

FIG. 3. Fractional change of magnetization vs $T^{3/2}$ for the different samples.

$M(0)$ is the extrapolated value of $M(T)$ as $T = 0$ K. The values of B and C can be determined by plotting$[M/M(0)]/T^{3/2}$ vs T (Fig. 4) since Eq. (2) can be rewritten as

$$[M/M(0)]/T^{3/2} = B + CT. \tag{3}$$

The B and C values obtained from our fit procedure are tabulated in Table II.

Our experimental findings can be briefly summarized as follows: (i) The leading $T^{3/2}$ term dominates in the temperature range $0 \leqslant T \leqslant 12$ K. (ii) The value of both B and C are anomalously large implying a much higher density of states at low E in the superlattice. (iii) The spin-wave stiffness constant $D \sim (1/B^{2/3})$ decreases when λ increases.

Because of the existence of a zone of interfacial iron atoms with an extension of about 6 Å as has been demonstrated by means of electron conversion Mössbauer spectroscopy,[6] our superlattice for the samples 3 and 4 can be represented by a set of two magnetic films corresponding to the bulk and interfacial iron atoms, respectively, separated by a nonmagnetic space (Fig. 5). For samples 1 and 2 we can consider that all the magnetic layer is interface because of the interlayer diffusion.

The spin-wave spectra of the different samples should depend on the distances d_1, d_2, and d_3 as well as on the number of layers. The experimental fact that the highest tem-

TABLE II. Coefficients B and C for the different samples.

Sample	B (10^{-3} K$^{-3/2}$)	c (10^{-4} K$^{-5/2}$)
1	6.23(1)	−1.27(1)
2	6.24(1)	−1.22(1)
3	6.39(1)	−1.32(1)
4	6.41(1)	−1.37(1)

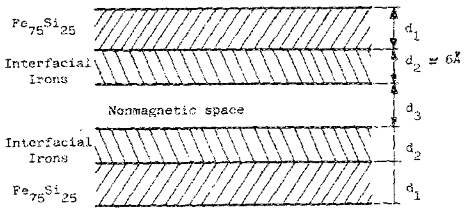

FIG. 5. Sample geometry. One has a stack of two different magnetic films of thickness d_1 and d_2 separated by a nonmagnetic film of thickness d_3.

perature at which the $T^{3/2}$ dependence on $M(T)$ does not hold any more is the same for all the samples may suggest: (1) that the frequency of the mode is independent of the ratio $(d_1 + d_2)/d_3$ which can be interpreted in terms of surface spin waves corresponding to the semi-infinite magnetic material.[2] (2) That the spin-wave spectra are not sensitive enough to the small variation occurring in the magnetic moments of the interface irons. However, new experimental evidence should be presented before concluding that no bulk superlattice waves are present in our thin films.

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