Structural disorder in two-dimensional random magnets: Very thin films of rare earths and transition metals

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(Received 28 April 1992)

The low-temperature isothermal magnetization curves, $M(H)$, of $SmCo_4$ and Fe_3Tb thin films are studied according to the two-dimensional correlated spin-glass model of Chudnovsky. We have calculated the magnetization law in approach to saturation and shown that the $M(H)$ data fit well the theory at high and low fields. In our fit procedure we have used three different correlation functions. The Gaussian decay correlation function fits well the experimental data for both samples.

INTRODUCTION

Magnetic multilayers of transition metals (TM) and rare earths (RE) exhibit a large variety of magnetic properties depending on the single layer thickness and the nature of the interface formed between two consecutive layers of TM and RE. When the layers are thin enough, the magnetic multilayer can be considered as formed by an alloy. The structure of this interface alloy is due to the process of interdiffusion of different atoms. This interdiffusion process can be viewed as a diffusion driven rearrangement of atoms toward the minimum energy state. Depending on the temperature of the substrate and the evaporation rate of atoms, the structure of the interface is modified. As a consequence of both the high magnetic anisotropy, single ion in nature, of the RE atoms and the topological disorder inherent to the amorphous state, the RE TM interface amorphous alloys may behave as random magnets.[6] Furthermore, these thin films are the perfect systems to study the properties of the two-dimensional (2D) Heisenberg model and to observe the transition from two- to three-dimensional behavior when increasing the number of magnetic monolayers in the sample.[9]

The effect of an applied field in a system with random anisotropy was first studied by Chudnovsky, Saslow, and Serota[1,2] showing that the magnetic behavior depends crucially on the parameter $\Lambda_r=\lambda_r(R_a/a)^2$, λ_r being the ratio of the random magnetic anisotropy strength to exchange, R_a the length of spatial correlation of the local anisotropy axis, and a the interatomic distance.

Following the notation of Chudnovsky, Saslow, and Serota,[2,3] three characteristic fields may be defined: (i) the exchange field $H_{ex}\equiv\alpha M_0/R_a^2$, where the parameter α is proportional to Ja^2 and M_0 is the saturation value of the magnetization; (ii) the random anisotropy field $H_R\equiv\beta_r M_0$, where β_r is proportional to the average random magnetic anisotropy constant D; (iii) the coherent anisotropy field $H_c=\beta_c M_0$, where β_c is proportional to the coherent anisotropy strength D_c.

The magnetic behavior of the random anisotropy system changes drastically with the value of the dimensionless parameter $\lambda_r\sim H_R/H_{ex}$. At $\Lambda_r<1$ (weak anisotropy) the ferromagnetic correlation length R_f remains finite at $T=0$ for however small H_R. Application of a magnetic field transforms it into a partially ordered state that has been called ferromagnetic with wandering axes (FWA). The magnetization law in the 3D FWA follows: $1/\sqrt{H}$ at $H\ll H_{ex}$ and $1/H^2$ at $H\gg H_{ex}$.[2-4]

The difference between two- and three-dimensional cases is the well-known lack of ferromagnetic long-range order for $d=2$ in the isotropic system, even in the absence of random anisotropy.[8] As has been shown by Chudnovsky,[5] the random anisotropy needed in two dimensions is smaller than in the three-dimensional case, but $|\beta_r/4|\geq\beta_c^{1/4}$. Prediction of the model in two dimensions is that the $M(H)$ data follows $1/H$ at $H\ll H_{ex}$ and $1/H^2$ at $H\gg H_{ex}$. Note that the differences in the $M(H)$ data are only detectable at $H\ll H_{ex}$.

EXPERIMENT

The SmCo and FeTb thin films were prepared by using two electron beam evaporators and a high vacuum chamber. The pressure during the metal evaporation was 6.10^{-7} torr and the evaporation rate of metals was 0.5 Å/s. A very thin kapton foil was used as a substrate and before evaporating the metals we deposited 100 Å Cu or

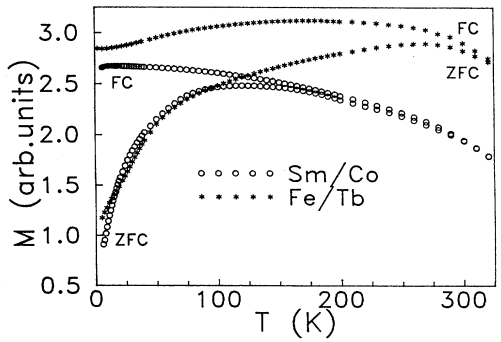

FIG. 1. Zero-field and field-cooled magnetization values for the two samples at $H=100$ Oe. The field was applied along the film plane.

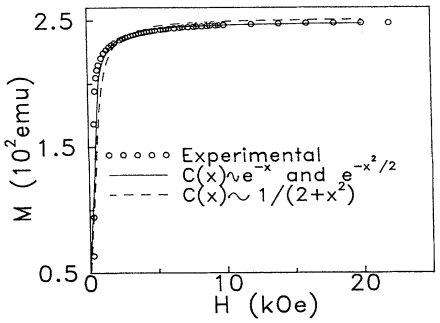

FIG. 2. Magnetization vs field dependence at $T=5$ K for the sample of $SmCo_4$. We also show in this figure the result of our fitting procedure using different forms for the correlation function.

Ag onto the kapton foil. The evaporated materials correspond to the following composition:

$$\text{Cu}(100\ \text{Å})\{[\text{Co}(4\ \text{Å})/\text{Sm}(3\ \text{Å})]_5/\text{Cu}(100\ \text{Å})\}_{x11}\ ,$$

$$\text{Ag}(100\ \text{Å})\{[\text{Fe}(3\ \text{Å})/\text{Tb}(4\ \text{Å})]_{50}/\text{Ag}(100\ \text{Å})\}\ .$$

The modulation in the composition was checked by secondary-ion-mass spectroscopy (SIMS) and low-angle x-ray-diffraction methods and the final composition of the bimetallic layers was deduced by electron microscope probe resulting Co_4Sm and Fe_3Tb, respectively. The magnetic measurements were performed by using a SHE SQUID magnetometer.

THEORY AND RESULTS

To determine the existence of irreversible phenomena the samples were cooled down to 4.2 K in zero applied field [zero-field-cooled (ZFC) process], then a field, $H=100$ Oe was applied and $M_{\text{ZFC}}(T)$ was measured up to 300 K. The temperature was then reduced gradually to 4.2 K again and $M_{\text{FC}}(T)$ was measured in the same applied field (FC process). These low-field curves for both samples are shown in Fig. 1. The onset of irreversibility, marked by the separation of the FC and ZFC curves,

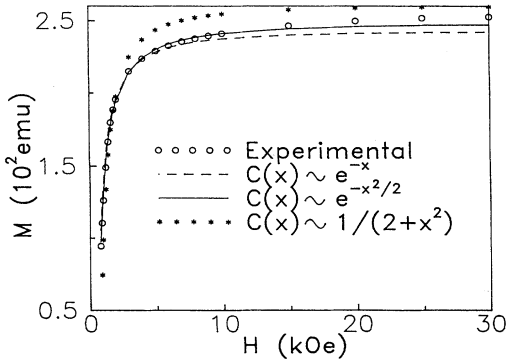

FIG. 3. Magnetization vs field dependence at $T=5$ K for the $TbFe_3$ thin film. As in Fig. 2, we also show the result of our fitting procedure.

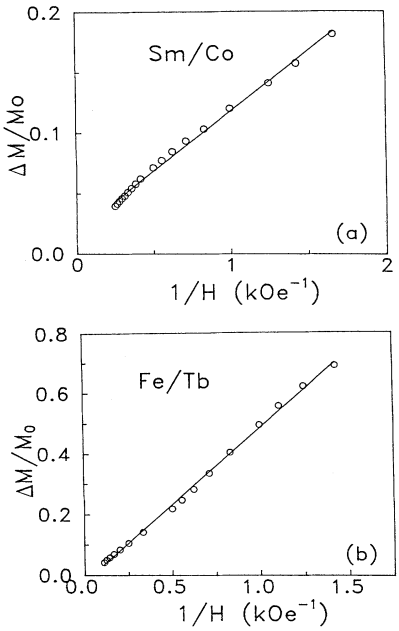

FIG. 4. Low-field regime in approaching to saturation for (a) $SmCo_4$ and (b) $TbFe_3$.

starts at a higher than that corresponding to the cusp of the peak in the ZFC, indicating that clusters of spins are involved in the freezing phenomenon. The broadening of the ZFC peak points out the existence of a broad distribution of energy barriers which may correspond to the existence of ferromagnetic clusters with different volume and different orientations of the effective anisotropy axes

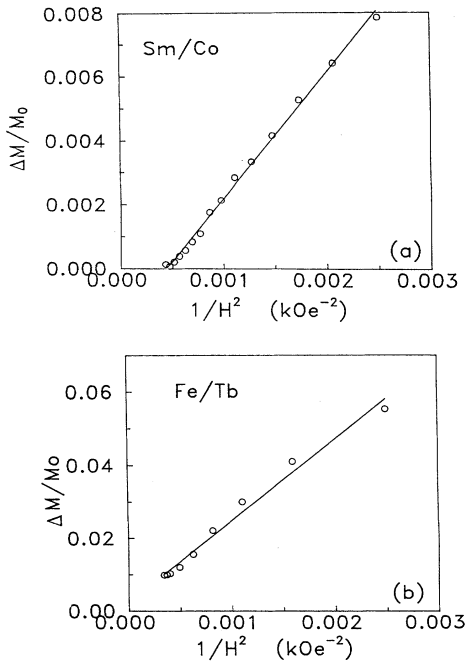

FIG. 5. High-field regime in approaching to saturation for (a) $SmCo_4$ and (b) $TbFe_3$.

TABLE I. The values of the characteristic fields H_{ex} and H_R and the values of λ for the two samples.

	S_1 (kOe)	S_2 (kOe^2)	M_0 (emu)	H_{ex} (kOe)	H_R (kOe)	λ
Sm/Co	0.1404	3.90	0.025	16.7	8.7	0.52
Fe/Tb	0.5359	20.00	0.025	22.4	19.2	0.86

ropy axes with respect to the applied field, supporting the idea that the alloy formed at the interfaces between TM and RE layers is in an amorphous state.

The isothermal, $T=5$ K variation of the magnetization for both samples as a function of the applied field after a ZFC process is shown in Figs. 2 and 3, respectively. These $M(H)$ data have been fitted by the law of approach to saturation for 2D and 3D random magnets by Chudnovsky.[1,3]

According to the theory, the distinction between the 2D and the 3D behavior relies on the different laws followed in the low-field regime, the high-field regime following the same law in both cases. Our data are well fitted by the $1/H$ law at low fields for fields up to ~ 4 kOe [Fig. 4(a)] for the SmCo sample, and up to ~ 6 kOe for FeTb [Fig. 4(b)]; and by the $1/H^2$ law from the 15 to 25 kOe for SmCo, and from 15 to 30 kOe for FeTb [Figs. 5(a) and 5(b)]. Therefore, our thin films behave as 2D random magnets, this being the first experimental observation of such systems. The in-plane magnetization inside a cluster of size R_F changes smoothly and in a random way from one cluster to another.

From these two $M(H)$ curves we can estimate the values of the characteristic fields H_{ex} and H_R because of the dependence of their slopes on H_{ex}, H_R (see below); these values as well as those of λ for the two samples are given in Table I. We can also confirm that we are in the $H_R < H_{ex}$ regime as required by the predictions of the theory and that the influence of the coherent anisotropy,[5] measured by the dimensionless parameter λ_c, is small.

For an intermediate range of fields $H \sim H_{ex}$, the magnetization law is very sensible to the specific form of the structural disorder correlation function $C(x)$ that describes the gradual rotation of the local anisotropy easy directions over the sample.

Our study of the magnetization law is based upon a generalization of a formula given by Chudnovsky for 3D (Ref. 3) that we have recalculated for the 2D case:[7]

$$\delta M/M_0 = \Lambda^2/32p \int_0^\infty dx\, x^2 C(x) K_1(px) , \quad (1)$$

where $\Lambda = KR_a^2/A = H_R H_{ex}$, K is the anisotropy constant, A the exchange constant, $p^2 \equiv h = H/H_{ex}$, and $K_1(x)$ is the modified Hankel function of first order.

The high- and low-field limits of this formula agree with those predicted by the theory of 2D amorphous ferromagnets[3] where they were obtained analyzing the equation for the extremal energy configurations of the magnetization field $M(x)$:[7]

$$\delta M/M_0 \sim (\Lambda^2\Omega/64\pi)(H_{ex}/H) \quad \text{for } H \ll H_{ex} , \quad (2)$$

$$\delta M/M_0 \sim (3\pi\Lambda^2/128\sqrt{2})(H_{ex}^2/H^2) \quad \text{for } H \gg H_{ex} , \quad (3)$$

where $\Omega \equiv \int d^2x\, C(x)$ is a factor of order unity. These two formulas give us H_{ex} and H_R from the experimental values of the slopes S_1 and S_2, respectively, as

$$H_{ex} = (4\sqrt{2}/3\pi)S_2/S_1, \quad H_R^2 = (128\sqrt{2}/3\pi)S_2 . \quad (4)$$

The random anisotropy field is obtained from measurements at high fields only, as expected, while the determination of the exchange field involves the study of both regimes.

Formula (1) has the advantage that it relates the microscopic structural distribution of easy axes $[C(x)]$ to the macroscopic magnetization law of the sample. In this way we can gain insight about the internal structure of amorphous materials just by fitting the $M(H)$ law to different forms of $C(x)$.

Our fit procedure is similar to that used by Tejada *et al.* in Ref. 5. Once we have calculated the values of the critical fields and the dimensionless parameter λ listed in Table I, we compute the numeric integral in (1) for different correlation functions, namely, exponential, Gaussian, and Lorentzian distributions. In the first two cases the magnetization law can also be given by an exact expression as[7]

$$\begin{aligned} &\delta M/M_0 = (\Lambda^2/20)[p^2(1+p)^2]_2F_1[-\tfrac{1}{2},2;\tfrac{7}{2};(1-p)/(1+p)] \text{ for } C(x)=e^{-x} , \\ &\delta M/M_0 = (\Lambda^2/16p^4)_2F_0[2,1;-2/p^2] \text{ for } C(x)=e^{-x^2/2} . \end{aligned} \quad (5)$$

The results are plotted in Figs. 2 and 3. We observe that for the FeTb system the data are well fitted using the Gaussian correlation function which means a fast decay of the ferromagnetic correlation length. For the SmCo system, we obtain similar results but in this case the fits to the exponential and Gaussian functions are almost indistinguishable. The Lorentzian decay is too slow to supress the long-range ferromagnetic correlation.

We note also that, for such complex systems, information about the structure of the amorphous interface formed is very difficult to obtain by any other experimental method. Therefore, our method can be used to get a full understanding of the different magnetic phenomena exhibited by multilayers of RE and TM with no sharp interfaces between single layers.

A. García acknowledges support from Departament d'Ensenyament de la Generalitat de Catalunya.

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