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Magnetization temperature dependence in Fe/Cr superlattices

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Abstract

We report the temperature dependence of the saturation magnetization, $M_s(T)$, of Fe(t)/Cr(40 Å) superlattices grown on MgO(1 0 0) and MgO(1 1 0) and its variation with Fe-layer thickness (5 Å $< t <$ 80 Å). The structure was characterized by X-ray diffraction. $M_s(t)$ vs. T, as measured by DC magnetization and ferromagnetic resonance, show a large interface effect. The origins of this effect are discussed. © 2002 Published by Elsevier Science B.V.

Keywords: Fe/Cr superlattices; Shape anisotropy

Since the discovery of the GMR effects in Fe/Cr superlattices (SL) [1], there has been a large effort in understanding and exploiting the novel properties of these artificial materials. In this area Fe/Cr SL have been one of the most extensively studied, yet an understanding of the observed anisotropies and their temperature (T) dependence is not complete. One of these properties, the appearance of an uniaxial anisotropy when Fe/Cr SL are grown on MgO(1 1 0), has allowed the study of exchange bias due to the coupling of a ferromagnetic film with an uniaxial antiferromagnetic SL [2]. Such structures avoid the limitations imposed by most antiferromagnets where the surface termination and roughness are crucial in understanding the exchange bias. Other basic research achievements using these SL include the first experimental demonstration of the surface spin-flop in antiferromagnets [3].

One of the simplest SL applications is to study very thin layers with symmetric boundary conditions. Along this line we have recently shown [4] that ferromagnetic resonance (FMR) can clearly distinguish the uniaxial and cubic anisotropies present in [Fe(t)/Cr]/MgO(1 1 0) (SL110) and [Fe(t)/Cr)]/MgO(1 0 0) (SL100). The Cr spacing, nominally 38 Å, was chosen so as to have a negligible coupling between the layers. FMR in fact shows that the spectra can be described as characteristic of independent layers.

Recently [5], saturation magnetization, $M_s(T)$, studies in Fe/Cu SL showed that surface M_s decays 17 times faster than bulk. This was interpreted as due to a large reduction of the Fe–Fe exchange near the interface. In this paper we report an X-ray characterization of the SL110 and SL100 series [4], and $M_s(T)$ obtained from magnetization and FMR measurements. This work aims to study the $M_s(T, t)$ evolution and identify the 3D–2D crossover on different substrate orientations.

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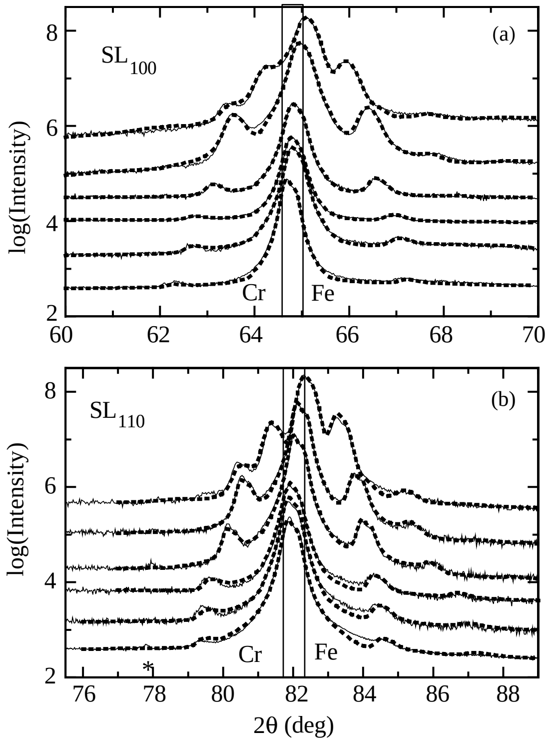

Fig. 1. X-ray $\theta-2\theta$ scans of the Fe/Cr SL (a) grown on MgO(1 0 0) and (b) on MgO(1 1 0). The dotted line is a fit using the model of Ref. [7]. The vertical lines indicate bulk values.

The samples were grown by DC magnetron sputtering as previously described [6], with a total thickness of ~1100 Å X-ray diffraction scans were carried out in a Phillips PW1170 diffractometer using CuK$_\alpha$ radiation in a $\theta-2\theta$ geometry at high angles.

Fig. 1 shows the high-angle X-ray diffraction. These scans were fitted using the model of Ref. [7] (dotted lines) which allows to estimate the layer's thickness, the disorder and the strains for each of the components. For the Fe layer we found: $t(\mathrm{Fe}) = 5 \pm 3$, 10 ± 3, 14 ± 3, 25 ± 5, 35 ± 5, and 80 ± 7 Å going from bottom to top of Fig. 1, and $t(\mathrm{Cr}) = 40 \pm 5$ Å for both series. The large uncertainties are due to the correlation between t and the layers' lattice parameters.

Fig. 2 shows the room temperature M_s values as measured in a SQUID magnetometer. The sample volume was calculated from t and the area. The absolute errors are estimated to be 20% of the quoted values and come mainly from the volume uncertainty. The $M_s(t)$ behavior can be approximately described by $M_s(1/t) = M_s(0)(1 - 2t_0/t)$. Fit of this functional form for the $t > 5$ Å layers led to: $M_s(0) = 1740 \pm 20$ emu/cm^3 (1710 ± 100 emu/cm^3), and $t_0 = 0.83 \pm 0.09$ Å (1.7 ± 0.5 Å), for the SL100 (SL110) series. $M_s(0)$ values are close to the bulk value. The t-dependence indicates a significant lowering of the saturation magnetization with decreasing t. If the magnetization would be reduced through the interface (i.e. due to interdiffusion, surface roughness or simply fewer neighbors) we could write $M_s(1/t) = M_s(0)(1 - 2at_0/t)$, where t_0 is the interface thickness and $a \leqslant 1$, which would explain qualitatively our results. Fig. 2 also shows the FMR results for the $4\pi M_{\mathrm{eff}} = 4\pi M_s - H_a$, where H_a is a perpendicular anisotropy field. Comparison with M_s indicates that H_a is positive and also increases with decreasing t. The lines in Fig. 2 correspond to a linear fit to the functional form $4\pi M_{\mathrm{eff}}(1/t) = 4\pi M_{\mathrm{eff}}(0)(1-2t_0'/t)$, for which we obtain: $4\pi M_{\mathrm{eff}}(0) = 21.1 \pm 0.3$ kG (20.9 ± 0.3 kG) and $t_0' = 1.26 \pm 0.07$ Å (2.2 ± 0.2 Å) for SL100 (SL110) series.

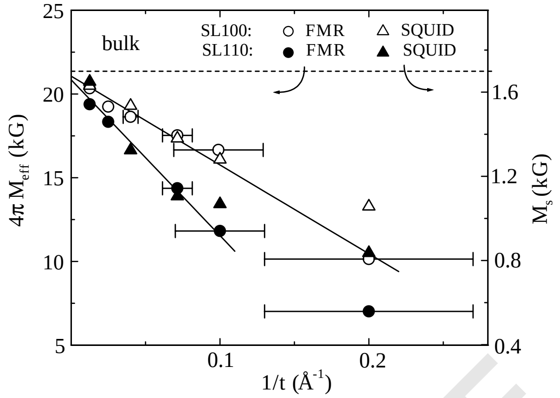

Fig. 2. Room temperature effective demagnetization anisotropy field as observed by FMR in the SL100 and SL110 samples and DC magnetization measurements.

In Fig. 3 we show $M_s(T)/M_s(0)$ as measured with the SQUID. The full circles indicate the FMR results for one of the samples: $M_{\mathrm{eff}}(T)/M_{\mathrm{eff}}(0)$ which follows the same T-dependence as $M_s(T)/M_s(0)$ within experimental uncertainty.

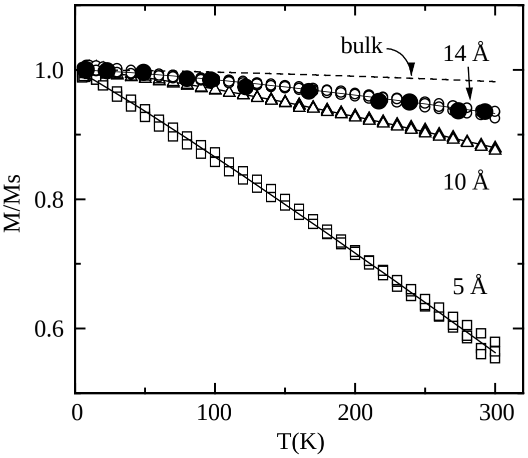

Fig. 3. $M_s(T)$ for some of the SL110 samples. The solid circles correspond to FMR data.

This T-dependence was fitted to a law $M(T) = M(0) - B(t)(T/300\,\mathrm{K})^x$. The results of these fits are shown in Fig. 4. Theoretical predictions [8] have shown that the effective exponent x can be lower than $\frac{3}{2}$ if fitted over a large T-interval, yet experimental results [5] have shown that the interface effect is to increase B, keeping $x = \frac{3}{2}$.

Recently, interface roughness has been shown to produce a large decrease in $M_s(T)$ [9]. Fig. 4 seems to indicate that x decreases from 1.5 for small t while $B(t)$ increases. We note that both series behave similarly, except for the SL110 $t = 5\,\text{Å}$ point. This could be due to partially discontinuous layers. For this sample a weak reflection at $2\theta = 77.8^\circ$ appears (star in Fig. 1), which could be associated to a *double* period reflection. Such a reflection would be allowed if a portion of the sample has discontinuous Fe layers; in such a way the SL period would be double in these regions. This reflection would then correspond to the third satellite of this "double period" portion (the first satellite falls on the tail of the main reflection). Yet, our structural characterization of large-t SL110 are best modeled by less disorder than the equivalent SL100.

In summary, $M(T,t)$ is reported in these two Fe/Cr SL series. A systematic variation of $M_s(t)$ and the magnon decay is observed. The magnon T-exponent seems to slightly decrease from 1.5 to a value closer to 1 for very thin layers.

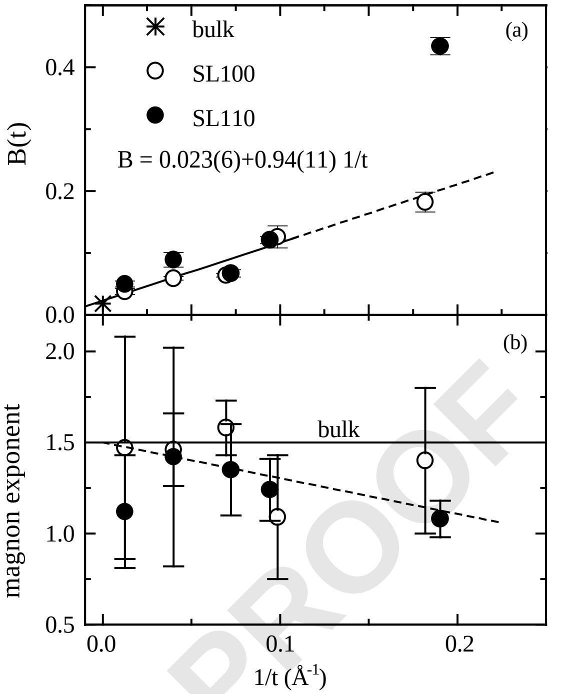

Fig. 4. Values of $B(t)$ and x obtained from the $M_s(T,t)$ data (see text).

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