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Effect of annealing on the roughness and GMR of Fe/Cr multilayers

H. Laidler [a], B.J. Hickey [a,*], T.P.A. Hase [b], B.K. Tanner [b], R. Schad [c,1], Y. Bruynseraede [c]

[a] *Department of Physics, University of Leeds, Leeds, LS2 9JT, UK*
[b] *Department of Physics, University of Durham, Durham, UK*
[c] *Laboratium voor Vaste-Stoffysika en Magnetisme, K.U. Leuven, Leuven, Belgium*

Abstract

The giant magnetoresistance (GMR) of a Fe/Cr multilayer decreased on annealing and was accompanied by a reduction in anti-ferromagnetic (AF) coupling. The underlying structural changes were studied using grazing incidence X-ray scattering. Specular and diffuse measurements were used to characterize the interface roughness which has been found to be mostly uncorrelated and increased upon annealing.

There is still controversy over the role of interface roughness in Fe/Cr multilayers. Recent growth studies on Fe/Cr multilayers [1–3] have found that the GMR was highest in structurally more perfect samples. In fact, Schad et al. [3] found that samples with GMR of over 80% had very smooth interfaces but a high density of atomic steps. Previous annealing studies on Fe/Cr multilayers have concentrated on samples of lower GMR and have relied on specular X-ray measurements to infer changes in interface roughness. Petroff et al. [4] reported that annealing MBE-grown Fe/Cr multilayers roughened the interfaces but caused an enhancement of the GMR. Rensing and Clemens [5] found however that annealing sputtered Fe/Cr multilayers caused both a rise and fall in GMR but that any structural effects were too subtle to be deduced from low angle specular X-ray data.

We present careful diffuse X-ray measurements, which are a more reliable measure of interface roughness and are able to distinguish between correlated and uncorrelated roughness. By exploiting the tunability of synchrotron radiation, we have used anomalous dispersion to enhance the scattering from the Fe interfaces. In this paper we report that anneals of up to the growth temperature had no effect but above this the GMR suddenly decreased accompanied by a dramatic loss of coupling.

* Corresponding author. Fax: +44-113-233-3846; email: b.j.hickey@leeds.ac.uk.
[1] Present address: Exp. Vaste Stoffysika II, Toernooiveld 1, Nijmegen, The Netherlands.

The $[Fe(22\ Å)Cr(13.5\ Å)]_{10}$ (100) multilayer was grown by MBE onto a MgO(100) substrate held at 400°C. It was cut into five identical pieces and each annealed in oxygen-free nitrogen at a different temperature. Detailed grazing incidence X-ray scattering measurements were made using synchrotron radiation. Further experimental details have been reported elsewhere [6].

The magnetotransport and magnetization measurements are summarized in Table 1. The longitudinal MOKE curve of the unannealed sample is characteristic of a high degree of AF coupling. There is no detectable change in the magnetization until the 425°C anneal, when the saturation field drops from 15 to 5 kOe and the remanence more than doubles, indicating a dramatic loss in both strength and volume fraction of AF coupled regions. There is little change in the GMR, saturation field resistivity, ρ_s, or the

Table 1
Resistivity measurements taken at 4.2 K and room-temperature longitudinal MOKE measurements

Annealing temperature	ρ_s ($\mu\Omega$cm)	$\Delta\rho$ ($\mu\Omega$cm)	GMR (%)	M_r/M_s	H_{sat} (kOe)
Unannealed	17.5	13.7	79	0.3	15
200–400°C (in 100° steps)	19.4	13.6	70	0.3	15
410°C	18.3	13.8	75	0.3	15
425°C	23.1	5.8	25	0.7	5
500°C	34.0	1.2	4	0.7	5

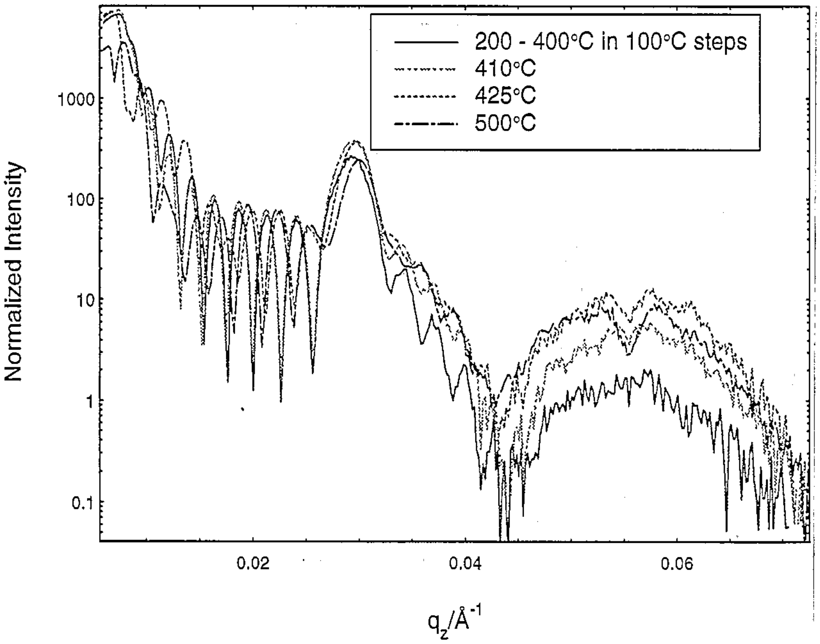

Fig. 1. Specular X-ray reflectivity data of the Fe/Cr multilayer annealed at different temperatures. The wavlength was set at 1.742 Å.

difference in resistivity between zero and saturation field $\Delta\rho$ for anneals of 410°C and below.

A dramatic change occurs at an annealing temperature of 425°C when the GMR drops to 25%. This is due to both an increase in ρ_s but mainly to a larger decrease in $\Delta\rho$. This can be explained by the loss of coupling. An annealing temperature of 500°C caused a disappearance of the GMR effect, although no further change in magnetization was evident, except that the coercive field doubled. Fig. 1 shows the specular X-ray scatter taken at a wavelength of 1.742 Å. The broad modulation around $q_z = 0.06$ Å^{-1} increases upon annealing indicating the growth of an increasingly thick chromium oxide layer.

Fig. 2 shows the diffuse scans taken through the Bragg

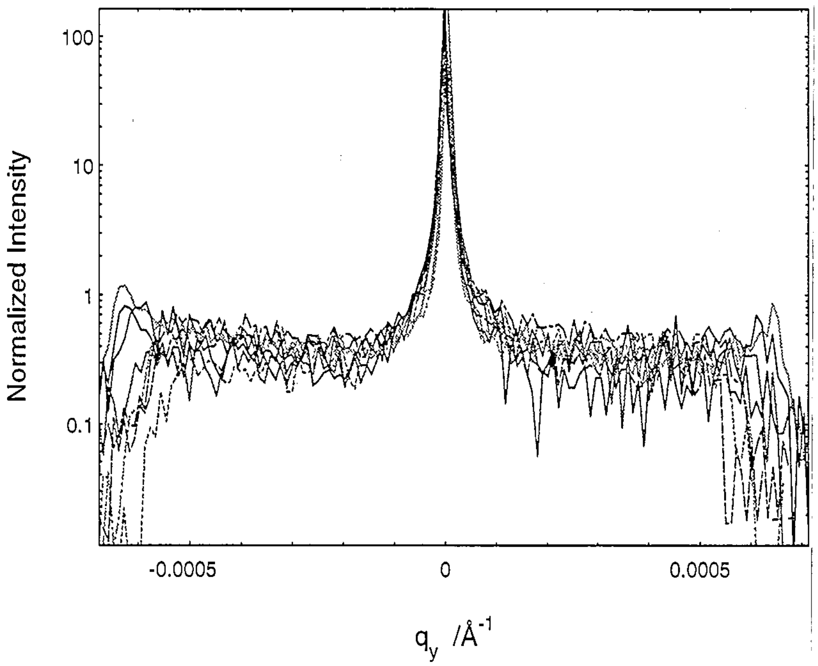

Fig. 2. Transverse scans through the specular Bragg peak at $\lambda = 1.9$ and 1.742 Å.

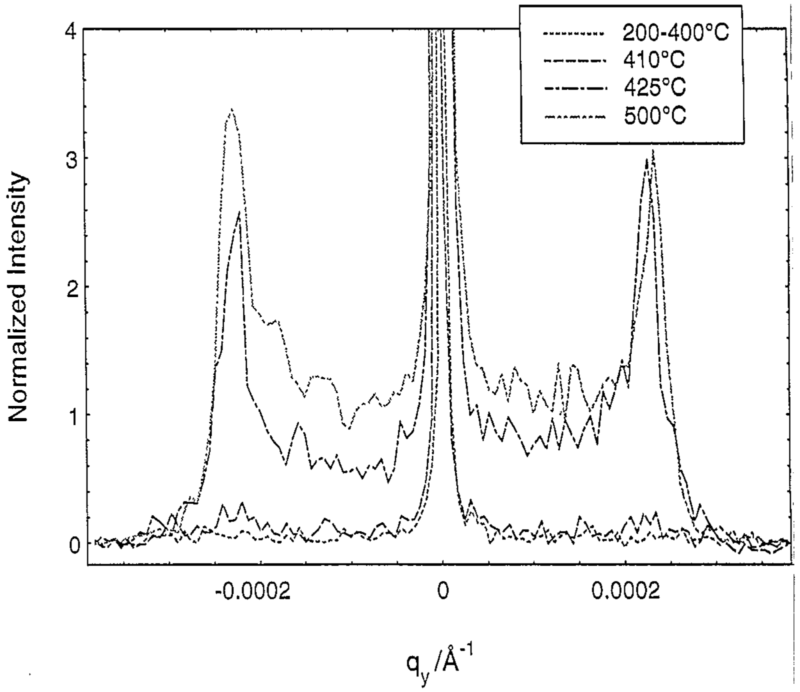

Fig. 3. Transverse scan taken at a detector angle away from the Bragg peak at $q_z = 0.02$ Å^{-1}. The wavelength was set at 1.9 Å.

peak, at and away from the Fe absorption edge (1.742 and 1.9 Å, respectively). There is no change upon annealing or upon changing the wavelength, indicating that the correlated roughness has remained constant. The diffuse scatter taken away from the Bragg peak using $\lambda = 1.9$ Å is shown in Fig. 3. The diffuse scatter for anneals of 410°C and below is constant and much less than the scatter for the samples annealed at 425 and 500°C. This indicates that annealing above 410°C caused a sharp increase in the uncorrelated roughness. Surprisingly as the wavelength is tuned to the Fe edge, the scatter away from the Bragg peak drops for both the 425 and 500°C samples. This is difficult to explain as the scatter from Fe is enhanced without affecting the scatter from Cr. A rise or no change in scatter is therefore expected upon tuning to the Fe edge.

In conclusion, the Fe/Cr multilayer was structurally stable up to 410°C. The rise in resistivity on annealing can be explained by the formation of an oxide layer on the top layer of Cr. After annealing at 425°C and above, the GMR fell due to a reduction in antiferromagnetic coupling. Analysis of the X-ray measurements has shown that most of the roughness in this multilayer is uncorrelated, and it rises upon annealing. This Fe/Cr multilayer has been found to be much rougher than previously measured MBE-grown Co/Cu (111) multilayers with typically a 35% GMR [6].

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