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Interplay between interface properties and giant magnetoresistance in epitaxial Fe/Cr superlattices

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Abstract

Epitaxial Fe/Cr superlattices with negligible intralayer scattering have been grown on MgO(100) using MBE. The careful structural analysis of such superlattices prepared under different conditions reveals the details of the interfacial origin of the giant magnetoresistance (GMR). We find the highest GMR in samples with minimum intermixing but an enhanced density of steps at the interfaces. Such Fe/Cr superlattices display GMR amplitudes up to 220%.

The discovery of the giant magnetoresistance (GMR) [1] in Fe/Cr superlattices opened a new field of possible applications for artificially tailored materials. The GMR is due to the antiferromagnetic (AF) exchange coupling of Fe layers through the nonmagnetic spacer layer.

Theoretical models [2] emphasise the importance of the electron scattering processes at the interfaces for the GMR effect. Up to now, the experimental investigations correlating the GMR to the interface quality have been on superlattices with GMR amplitudes smaller than 30% and often dominating contributions of bulk scattering [3–5]. Moreover, the results are controversial and show an increase [3,5] or a decrease [4,5] with improving interface quality. Meanwhile, much higher GMR values have been obtained [6,7], but a detailed analysis of their interface properties is still lacking.

In this paper we present a detailed study of the influence of the interface properties on the amplitude of the GMR. The following procedure was used. First, we selected a substrate on which Fe and Cr grow with a small defect density in order to ensure that the transport properties are governed only by interface scattering. Second, we varied the growth conditions systematically, in order to find the deposition parameters which provide samples with a high amplitude of the GMR effect. Third, we characterised the interfaces of these samples in detail using X-ray diffraction (XRD) and Mössbauer spectroscopy. Finally, we grew a Fe/Cr superlattice under the optimum conditions in order to produce a record high GMR.

MgO(100) substrates enable excellent epitaxial growth of Fe and Cr with a very low defect density. Applying the Fuchs–Sondheimer theory to the resistivities of single Cr and Fe films grown on MgO we found bulk resistivities of 0.35 μΩcm for Cr and < 0.1 μΩcm for Fe (at 4.2 K). These values are much lower than the resistivities of Fe/Cr superlattices grown on MgO(100) (typically 10 μΩcm), clearly indicating that the transport properties of these superlattices are governed exclusively by interface scattering.

The growth conditions were evaluated by preparing two sets of $[Fe(22\ Å)/Cr(13\ Å)]_{10}$ superlattices at different substrate temperatures ($0°C \le T_g \le 400°C$) and with or without a Cr buffer layer. The highest GMR for a Fe/Cr + Cr buffer layer was obtained for $T_g = 50°C$ (Fig. 1). Increasing T_g leads to a decrease in the difference in the GMR between the two sets of samples, while above $T_g = 300°C$ a strong reduction of the GMR amplitude is observed for both sets.

For both sets of samples the antiferromagnetic fraction, as measured with an alternating gradient magnetometer, is constant ($85 \pm 5\%$) below $T_g = 300°C$ and decreasing for $T_g > 300°C$. The deviation from 100% antiferromagnetic coupling may be due to the presence of some biquadratic coupling or caused by magnetic shortcuts at imperfections in the films. However, the observed enhancement of the GMR at $T_g = 50°C$ by using a Cr buffer can not be attributed to a change in the coupling but has to be due to differences in the interface structure.

The low-angle XRD spectra of both sets of samples

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displayed pronounced superlattice peaks except for $T_g > 300°C$. It seems therefore that the pronounced differences in the GMR amplitudes (see Fig. 1) are caused by small changes in the interface properties. At $T_g > 300°C$ Fe and Cr start to intermix at the interfaces due to the increased bulk diffusion [8], leading at $T_g > 400°C$ to a loss of the superlattice structure. At $T_g = 50°C$ the difference in the GMR of the two superlattices is due to a difference in the interface roughness in the form of atomic steps. This roughness is introduced by the Cr buffer layer which grows much rougher than Fe films, as evidenced by low-angle XRD spectra of single films. Mössbauer spectroscopy measurements confirm that this initial roughness of the Cr buffer produces an increased density of atomic steps at the interfaces of the superlattices. The vanishing difference in GMR between the two sets of superlattices at $T_g > 50°C$ is due to the increasing surface diffusion [9] causing a decrease in the step density. Consequently, in epitaxial (100)-oriented Fe/Cr superlattices a high GMR value can be obtained when a high density of atomic steps at the interface is present in the absence of interdiffusion.

This was confirmed by preparing under optimum conditions a [Fe(4.5 Å)/Cr(12 Å)]$_{50}$ superlattice, i.e. with an increased number of bilayers and a reduced thickness of the Fe layers [7]. The GMR values of this sample are 220% at 1.5 K and 42% at 300 K (see Fig. 2).

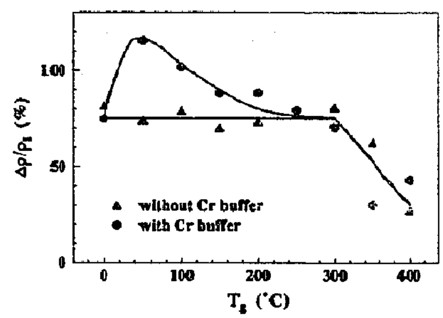

Fig. 1. Dependence of the magnetoresistance $\Delta\rho/\rho_S$ on the deposition temperature T_g for the two sets of Fe/Cr superlattices. The lines are guides for the eye.

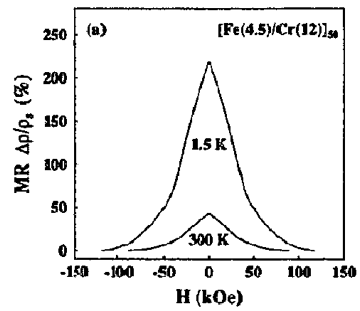

Fig. 2. Magnetoresistance $\Delta\rho/\rho_S$ of a [Fe(4.5)/Cr(12)]$_{50}$ superlattice as a function of the magnetic field applied in the film plane, showing a record value of $\Delta\rho/\rho_S = 220\%$ at 1.5 K and 42% at 300 K.

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