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Influence of different kinds of interface roughness on the giant magnetoresistance in Fe/Cr superlattices

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Abstract

We present a detailed study of the influence of the interface properties on the amplitude of the GMR in Fe/Cr superlattices, including changes of the coupling, a synchrotron X-ray diffraction analysis and a theoretical interpretation within the quasi-classical formalism. With increasing amplitude of the interface roughness we observe a reduction of the GMR.

The discovery of the giant magnetoresistance (GMR) [1] in Fe/Cr superlattices opened a new field of possible applications for artificially tailored materials. Theoretical models emphasise the importance of the electron scattering processes at the interfaces for the GMR effect. However, the experimental investigation of the correlation between interface properties and the GMR is a complicated matter [2], because also spin-dependent scattering processes inside the ferromagnetic layers can produce a GMR effect. Further, a change of the interface properties, like for instance interdiffusion leading to pinhole formation, can easily change the coupling by reducing the fraction of the sample which is antiferromagnetically ordered (AFF). This, of course, reduces the GMR amplitude but has nothing to do with a change in the effectiveness of the spin-dependent scattering. Therefore, it is necessary to estimate the AFF from magnetisation measurements.

Even more complicated is an exact characterisation of the interface structure. A single parameter ('roughness') description is far from being sufficient. The following ingredients are necessary for a complete characterisation of the interface properties: the width of the interface η, the lateral correlation length $\xi_{\|}$, the fractal dimension h describing the decay of the height–height correlation function, and $\xi_{\perp}$ being the cross-correlation between different interfaces, i.e. the degree to which neighbouring interfaces replicate each other. Of course, each of these parameters may have an influence on the spin-dependent electron scattering and all of these influences may be different. Having this in mind, the contradictory results reported so far are not surprising.

In this contribution we present a detailed study of the influence of the interface properties on the amplitude of the GMR in polycrystalline Fe/Cr superlattices. Part of these results has already been reported earlier [3] but now we quantified also the AFF in order to correct the observed changes in the transport data for changes in the coupling. Furthermore, a detailed X-ray diffraction (XRD) study using synchrotron radiation allows a full statistical description of the interface properties.

The Fe/Cr superlattices were deposited in a Riber MBE deposition system onto Y-stabilised ZrO_2 at different growth temperatures (T_G) with or without a 20 Å Cr buffer layer. The Fe and Cr layer thicknesses were kept constant at $t_{Fe} = 22$ Å and $t_{Cr} = 12$ Å and the number of bilayers was 10. The GMR is defined as $\Delta\rho/\rho_s = (\rho_0 - \rho_s)/\rho_s$, with ρ_0 and ρ_s being respectively the resistivities at zero applied field and at saturation field (H_s).

As a function of T_G we found the best layering quality and also the highest GMR amplitudes around $T_G = 200°C$ [3]. However, the magnetisation measurements reveal that the reduction of the GMR towards higher temperatures is

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only caused by a decrease of the AFF. Therefore, we concentrate the analysis of the data on the samples grown at lower T_G. Low angle XRD rocking curves show that the lateral coherence length is about 150 Å in the range $0 < T_G < 200°C$. The structural parameter that is varying in this temperature range is the roughness amplitude η, which is estimated from fits to the symmetrical θ–2θ XRD scans. The figure shows the dependence of the spin-independent resistivity ρ_s and spin-dependent part $\Delta\rho$. First, the increase of ρ_s with increasing η indicates that in these samples the transport properties are dominated by interface scattering. However, the magnetoresistance $\Delta\rho$, being corrected for the AFF, is decreasing with increasing η.

The dependence of the magnetoresistance on the interface roughness was analysed theoretically within a single free-electron-like band model with a band mismatch at the interfaces between the magnetic and spacer materials [4]. The spin asymmetry in bulk scattering processes is taken into account by appropriate spin-dependent relaxation times. Spin-dependent scattering at the interfaces is included via spin-dependent factors S^σ, which are defined in such a way that specular transmission across the interface is $S^\sigma T$ and specular reflection is $S^\sigma R$, where T and R are specular transmission and reflection coefficients for s-like wave functions (plane waves) from geometrically rough interface. The coefficients S^σ take into account s–d hybridisation at the interfaces and immediate relaxation in the d-bands. The coefficients T and R are determined by the potential step at the interface and the amplitude η of the vertical roughness.

Numerical analysis shows that small interface roughness can increase the magnetoresistance if there is a significant difference between S^+ and S^-. The magnetoresistance reaches maximum at some amplitude of the vertical roughness and then decreases with a further increase of the roughness. The position of the maximum depends on the relative role of interface scattering, spin asymmetry in the coefficients S^σ and spin asymmetry in relaxation times. If spin asymmetry for interface scattering is opposite to that for bulk scattering, a small roughness considerably reduces the magnetoresistance.

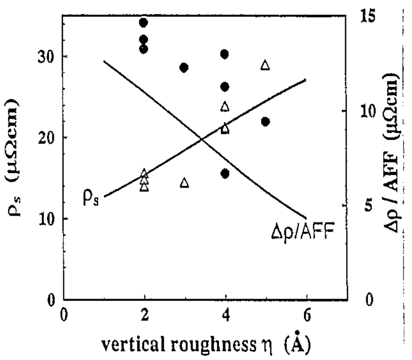

Fig. 1. Magnetoresistance $\Delta\rho$ (●) and resistivity ρ_s (△) as a function of the interface roughness amplitude η. ρ_s increases with increasing η, whereas $\Delta\rho$ decreases.

In Fig. 1 the numerical data are presented for the resistivity ρ_s and the resistivity change $\Delta\rho$ versus the amplitude of the interface roughness together with the experimental data points. The results were obtained for $S^+ = 1$, $S^- = 0$ and the potential step of 0.5 eV. The theory describes the experimental values rather well, only the magnetoresistance $\Delta\rho$ is underestimated.

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