ELSEVIER

Journal of Magnetism and Magnetic Materials 156 (1996) 341–342

journal of magnetism and magnetic materials

On the Fe thickness dependence of the giant magnetoresistance in epitaxial Fe/Cr superlattices

R. Schad *,[1], P. Beliën [2], J. Barnas [3], G. Verbanck, C.D. Potter [4], G. Gladyszewski, V.V. Moshchalkov, Y. Bruynseraede

Laboratorium voor Vaste-Stoffysika en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

Abstract

We analysed the transport properties of Fe/Cr(100) superlattices as a function of the Fe thickness. We find two magnetic inactive atomic layers and interpret the magnetoresistance with the quasi-classical formalism based on the Boltzmann kinetic equation.

In the Fe/Cr system, the coupling between adjacent Fe layers was found to be ferromagnetic or antiferromagnetic depending on the thickness of the Cr interlayer [1]. This displayed itself first as a giant magnetoresistance (GMR) [2], the amplitude of which oscillated with the thickness of Cr with a period of 18 Å [3]. With improvements in the layering quality, an additional short period oscillation was seen in Fe/Cr/Fe trilayers [4].

Subsequently, oscillations of the GMR and the resistivity as a function of the Fe layer thickness (t_{Fe}) were also found [5]. In this case the Cr spacer thickness was chosen such that the coupling was not at its maximum strength, making the transport properties more sensitive to the influence of t_{Fe}.

The dependence of the amplitude of the GMR on the structural properties of the superlattices is still an open issue [6]. It is influenced by scattering in the bulk of the ferromagnetic layers as well as by interface scattering [7]. The latter is believed to be the more effective part but a separation is not always possible. Interesting insight into the transport properties can be gained by investigating the dependence of the transport parameters upon a reduction of the Fe layer thickness towards zero. We report on the evaluation of the GMR for $0 < t_{Fe} < 20$ Å in epitaxially grown Fe/Cr(100) samples.

The Fe/Cr superlattices were prepared in a Riber MBE deposition system equipped with two e-beam evaporators. The Fe and Cr layers were deposited onto a 12 Å thick Cr seed layer which covers a single crystalline MgO(100) substrate. The Fe layer thickness was varied in the range $0 < t_{Fe} < 12$ Å, the Cr layer thickness was kept constant at $t_{Cr} = 12$ Å and the number of bilayers was 10. The structure of the deposited multilayers was characterised by X-ray diffraction (XRD). The Fe(100)[001] || Cr(100)[001] epitaxial superlattice growth was found. Quantitative information about the structural parameters was obtained by interpreting θ–2θ XRD profiles using the computer programs SUPREX and IM-SL based on two different models of the superlattice structure. 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).

Fig. 1 shows the dependence of the transport parameters on t_{Fe}. The GMR decreases smoothly for $t_{Fe} \geq 4.5$ Å, but drops abruptly to almost zero for smaller thicknesses. None of the transport properties shows an indication of oscillatory behaviour.

The dependence of the transport properties on the thickness of magnetic films t_{Fe} was analysed theoretically within a single free-electron-like band model with a spin asymmetry between the two channels taken into account [7]. Within that model electron scattering by structural defects located inside the films is included into the Boltzmann kinetic equation by appropriate relaxation times, whereas scattering by interface roughness is taken into account by spin-dependent transmission coefficients. The

---

* Corresponding author. Fax: +31-24-365-2190; email: schad@sci.kun.nl.

[1] Present address: Res. Inst. for Mater., KUN, 6525 ED Nijmegen, The Netherlands.

[2] Present address: Philips Research Labs, 5656 AA Eindhoven, The Netherlands.

[3] Permanent address: Institute of Physics, UAM, 60-769 Poznan, Poland.

[4] Present address: Argonne National Lab, USA.

spin asymmetry in transmission coefficients is due to spin dependence of the interface scattering potential and of the s–d hybridisation. Although transport via d-electrons is not taken explicitly into account, the role of d-bands in the interfacial and bulk scattering is included in the phenomenological relaxation times and transmission coefficients.

Results of numerical calculations of the magnetoresistance are shown in Fig. 1 by the solid line. The high magnetoresistance is due to a large asymmetry in the interface transmission coefficients $T^+ = 1$ and $T^- = 0$. Apart from this, the shape of the GMR dependence on t_{Fe} clearly indicates the interfacial origin of the magnetoresistance. For bulk origin the appropriate curve has a different shape – with a small effect at small t_{Fe} and a significant maximum at some thickness t_{Fe}.

The magnetoresistance is reproduced rather well. The difference at very small thicknesses is due to the lack of Fe magnetism at those thicknesses, which of course has not been taken into account in the calculations. However, the model used here underestimates the role of interface scattering. In that limit a quantum description of electron transport is more accurate. In addition, the model based on a one electron band is also a simplification and the contribution from d-electrons has to be included more explicitly. Those two problems are currently under way and results will be published elsewhere.

The abrupt drop of the GMR below $t_{Fe} = 4.5$ Å $= 3$ atomic layers (AL) of Fe may be due to an absence of the magnetic order in the very thin films caused by discontinuities or due to non-active layers at the interfaces. In the former case for $t_{Fe} \geq 4.5$ Å the magnetic properties of the films should show the full contribution of all layers, whereas in the latter case the lack of about two layers of Fe should persist. An appropriate property to study this is the saturation field H_s, which should depend on t_{Fe} as $1/H_s \propto t_{Fe}$. However, the data (Fig. 2) are perfectly described by $1/H_s \propto (t_{Fe} - 2\ \text{AL})$ except for the value of H_s for $t_{Fe} = 4$ Å, which is already below the threshold of 3 AL. This clearly shows that indeed two AL of Fe are magnetically non-active also in the thickness range where the layers can be expected to be continuous.

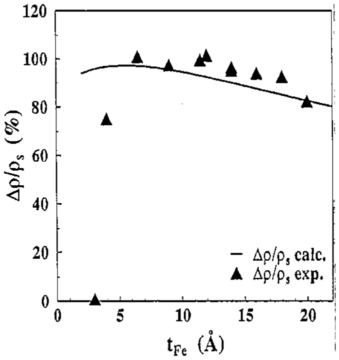

Fig. 1. Magnetoresitance $\Delta\rho/\rho_s$ as a function of t_{Fe} with experimental data (▲) and theoretical calculation (————).

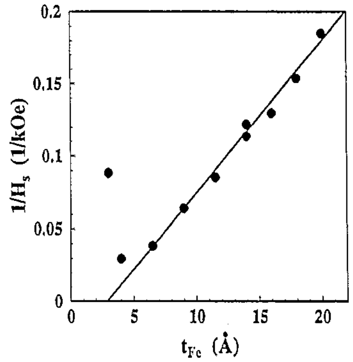

Fig. 2. Inverse saturation field H_s as a function of t_{Fe} with data (●) and a theoretical description (————) assuming two magnetically inactive atomic layers of Fe.

Acknowledgements: This work is financially supported by the Belgian Concerted Action (GOA) and Interuniversity Attraction Poles (IUAP) programs. R.S., J.B., C.D.P., G.G. and G.V. are Research Fellows supported by respectively the European Community, the Research Council of the Katholieke Universiteit Leuven and the Belgium Interuniversity Institute for Nuclear Sciences. J.B. also acknowledges support through the Research Project KBN 2 P302 213 06 of the Polish Research Committee.

References

[1] P. Grünberg, R. Schreiber, Y. Pang, M.B. Brodsky and H. Sowers, Phys. Rev. Lett. 57 (1986) 2442.
[2] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich and J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.
[3] S.S.P. Parkin, N. More and K.P. Roche, Phys. Rev. Lett. 64 (1990) 2304.
[4] J. Unguris, R.J. Celotta and D.T. Pierce, Phys. Rev. Lett. 67 (1991) 140.
[5] S.N. Okuno and K. Inomata, Phys. Rev. Lett. 72 (1994) 1553.
[6] P. Beliën, R. Schad, C.D. Potter, G. Verbanck, V.V. Moshchalkov and Y. Bruynseraede, Phys. Rev. B 50 (1994) 9957.
[7] R.Q. Hood, L.M. Falicov and D.R. Penn, Phys. Rev. B 49