Interface Magnetoresistance of Fe/Ag Multilayers

J. Balogh[1]) (a), I. Vincze (a), D. Kaptás (a), T. Kemény (a), T. Pusztai (a), L. F. Kiss (a), E. Szilágyi (b), Z. Zolnai (c), I. Kézsmárki (d), A. Halbritter (d), and G. Mihály (d)

(a) Research Institute for Solid State Physics and Optics, 1525 Budapest, P.O.B. 49, Hungary

(b) Research Institute for Particle and Nuclear Physics, 1525 Budapest, P.O.B. 49, Hungary

(c) Research Institute for Technical Physics and Materials Science, 1525 Budapest, P.O.B. 49, Hungary

(d) Budapest University of Technology and Economics, 1111 Budapest, Budafoki ut. 8, Hungary

Magnetoresistance and magnetic behaviour of a vacuum evaporated multilayer consisting of 1.4 nm Fe and 2 nm Ag layers were studied. The magnetisation of the multilayer shows normal ferromagnetic behaviour while the resistance decreases both in parallel and transversal geometry up to 12 T magnetic field and can be well described by squared Langevin functions. The giant magnetoresistance (GMR) is attributed to a small amount of Fe clusters and/or single impurities in the Ag matrix. This explanation is supported by similar results on a 8 nm Ag/25 nm Fe/8 nm Ag trilayer. The concentration distribution due to interface mixing was studied by Rutherford backscattering spectrometry (RBS) measurements.

Introduction Oscillatory behaviour of interlayer coupling in Fe/Ag multilayers has been predicted theoretically and found experimentally. Few works studied, however, the magnetoresistance [1–3], and the role of antiferromagnetic coupling in the observed giant magnetoresistance (GMR) is ambiguous. In this work we study a multilayer structure with 2 nm Ag spacer, which is close to the value where the second maximum and the largest magnetoresistance in the spacer thickness dependence was reported for sputtered samples [2].

Experiment The $[Ag(2\,nm)/Fe(1.4\,nm)]_{60}$ multilayer covered with 2 nm Ag was prepared by vacuum evaporation with two electron guns in a base pressure of 10^{-7} Pa. The deposition was made at a rate of about 0.2 nm/s on Si single crystal substrate at room temperature. The layer thickness was controlled by a quartz oscillator during sample deposition. The X-ray reflectivity and the grazing incidence diffraction pattern measured by Cu-K_α radiation are shown in Fig. 1. The well resolved first peak and the smeared second peak of the reflectivity signify a periodicity (3.9 nm) 10% larger than the nominal value. The diffraction pattern shows more peaks than a simple mixture of bcc Fe and fcc Ag. Both superlattice reflections and non-equilibrium phases can contribute to the diffraction pattern.

The magnetoresistance measured at 4.2 K with the current in the sample plane and the magnetic field aligned parallel or transversal to it is shown in Fig. 2. It does not

[1]) Corresponding author; Phone: +36-1-3922636; Fax: +36-1-3922215; e-mail: baloghj@szfki.hu

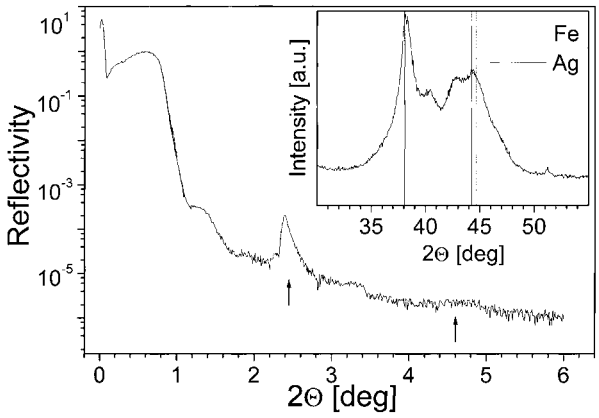

Fig. 1. X-ray reflectivity. The insert shows the diffraction pattern

saturate up to 12 T magnetic field and, except a small anisotropy at very low fields, the two curves coincide as it is expected for GMR. The magnitude of the effect is similar to that observed for sputtered samples [3] of similar Fe and Ag layer thickness. The magnetoresistance curves could be well fitted by the equation

$$(R(H) - R(12\ \mathrm{T}))/R(12\ \mathrm{T}) = -(A_1 \mathrm{L}\ (m_1 H/kT) - A_2 \mathrm{L}\ (m_2 H/kT))^2 - A_3 H^2 + B, \qquad (1)$$

where $\mathrm{L}(x) = \mathrm{cth}(x) - 1/x$ is the Langevin function. It contains six parameters: the cluster moments m_1 and m_2, three intensities (A_1, A_2, and A_3), and an additive constant B. Equation (1) contains terms generally used to describe the magnetoresistance of granular materials [4] and canonical spin glasses [5]. It gives a much better description of the magnetoresistance curve than the single linear Langevin function used in Ref. [2].

The magnetoresistance curve cannot be related by any simple scaling to the total magnetisation of the sample. A magnetisation measurement performed in a SQUID up to 5 T applied magnetic field at 4.2 K is presented in Fig. 3. It shows normal ferromagnetic behaviour with a coercivity around 20 Oe. The hysteretic behaviour can also be observed in the small field magnetoresistance as a slight effect. The continuous variation of the magnetoresistance at large fields is in clear contrast to the saturation of the magnetisation. The GMR certainly arises from scattering at such a small amount of magnetic moments, which is close to the sensitivity of the SQUID measurement

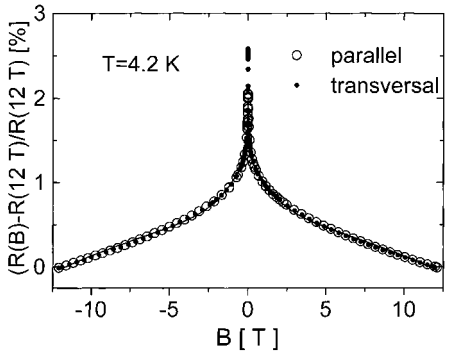

Fig. 2. Parallel and transversal magnetoresistance of the $[\mathrm{Ag}(2\ \mathrm{nm})/\mathrm{Fe}(1.4\ \mathrm{nm})]_{60}$ multilayer measured at 4.2 K and the curve fitted by Eq. (1) with $m_1 = 6.4\,\mu_B$, $m_2 = 382\,\mu_B$, $A_1 = 0.042$, $A_2 = 0.086$, $A_3 = 3 \times 10^{-5}\ \mathrm{T}^{-2}$, and $B = 2 \times 10^{-2}$

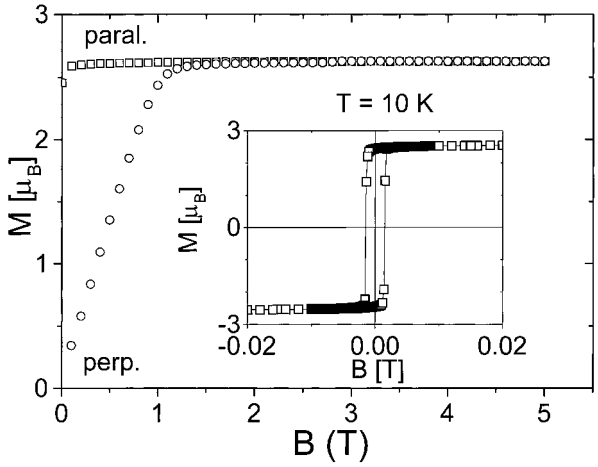

Fig. 3. Magnetization measured by external field parallel and perpendicular to the sample plane. The insert shows the low field hysteresis on a magnified scale

($\sim 10^{-3}\,\mu_B$). This observation suggests the presence of Fe impurity atoms and clusters in the Ag layers.

In order to check the range of interface mixing and the resultant magnetoresistance, a trilayer sample, 8 nm Ag/25 nm Fe/8 nm Ag, was prepared under conditions identical to the multilayer preparation. The composition and the impurity content of the sample were determined by RBS and elastic recoil detection (ERD) techniques. ERD was carried out at recoil and tilt angles of 20° and 80°, while RBS was performed at a scattering angle of 165° and at tilt angles of 70° and 80°. The RBS and ERD spectra were simulated with the same layer structure using the RBX code [6]. The ERD shows hydrogen content layers at the surface of the substrate and the sample, but no significant hydrogen was found in the Fe and Ag layers. In the RBS spectrum shown in Fig. 4, the trilayer structure can be observed, but due to chemical mixing and interface roughness the supposition of several sublayers (shown in the insert) gives the best agreement between the measured and simulated spectra. Significant oxygen contamination, mainly close to the surface, is found, but oxygen contamination is also present in heat treated samples with normal (Kohler type) magnetoresistance.

Magnetoresistance curves of the 8 nm Ag/25 nm Fe/8 nm Ag trilayer sample are shown in Fig. 5. It can be well fitted to Eq. (1) and its magnitude can be related to that

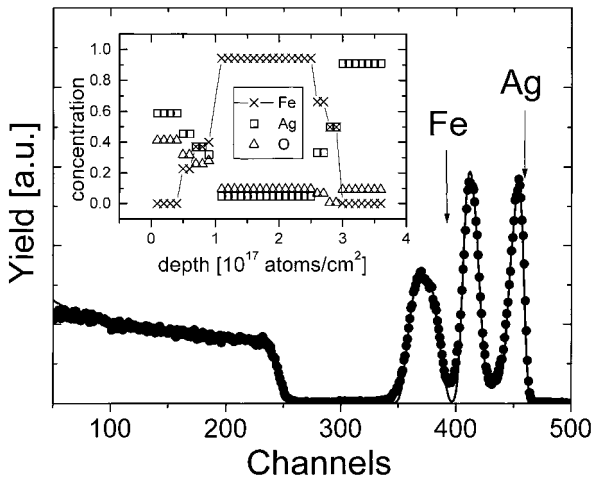

Fig. 4. Measured and calculated RBS spectrum taken by a 1610 keV He beam on the 8 nm Ag/25 nm Fe/8 nm Ag trilayer sample at tilt angle 70° and scattering angle of $\theta = 165°$. The surface positions of Fe and Ag are indicated by arrows. The insert shows the element distribution used to calculate the simulated curve

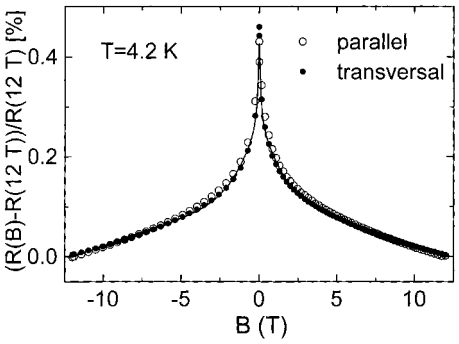

Fig. 5. Parallel and transversal magnetoresistance of the 8 nm Ag/25 nm Fe/8 nm Ag trilayer and the curve fitted by Eq. (1) with $m_1 = 6.6\,\mu_B$, $m_2 = 188\,\mu_B$, $A_1 = 0.019$, $A_2 = 0.043$, $A_3 = 4.3 \times 10^{-6}\ T^{-2}$, and $B = 4 \times 10^{-3}$

of the multilayer in a parallel resistor network model, supposing that the interface conductivity is negligible in zero field. The high field resistance of a single interface is around 7.7 and 5.4 kΩ in the trilayer and the multilayer, respectively. The order of magnitude agreement in this simplified model and the field dependence according to Eq. (1) suggest that the magnetoresistance of Fe–Ag multilayers mainly arises from the interface mixing.

Conclusion The GMR effect, which does not saturate up to 12 T and can be well described in the framework of granular magnetism, is observed for a ferromagnetic $[Ag(2\ nm)/Fe(1.4\ nm)]_{60}$ multilayer sample. It is explained by the formation of small clusters and/or impurity atoms due to interface mixing. GMR originating purely from interface scattering was shown to exist on a 8 nm Ag/25 nm Fe/8 nm Ag trilayer.

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