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Magnetoresistance study of Fe/Cr magnetic multilayers: Interpretation with the quantum model of giant magnetoresistance

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We measured the magnetoresistance of Fe/Cr magnetic multilayers grown by sputtering techniques as a function of temperature and Cr thickness. Our experimental results are well described by the quantum model of giant magnetoresistance of Levy, Zhang, and Fert. The influence of the various electron-scattering processes is discussed.

I. INTRODUCTION

Since the discovery of giant magnetoresistance (MR) in Fe/Cr magnetic multilayers,[1] several other multilayer systems, e.g., Co/Au,[2] Co/Ru,[3] and Co/Cu,[4] have shown similar effects. The giant MR effect stands for the fact that the resistivity is high when the magnetizations of neighboring magnetic layers are antiparallel, and much smaller when these are switched to the parallel state by a magnetic field. It is based on the large spin dependence of electron-scattering processes. Whether this spin-dependent scattering predominantly takes place at interfaces or in the bulk of the magnetic material depends on the system and is still a point of discussion. Camley and Barnas[5] developed a semiclassical MR model which is based on the spin-dependent Boltzmann equation. Originally a numerical solution was obtained; recently Barthélémy and Fert[6] presented simple analytical expressions for the MR which made the model very attractive and easy to handle. However, quantitative agreement with experiments is hard to obtain mainly because of the underestimate of the interface contribution to the resistivity and the MR by the semiclassical approach. In a recent paper[7] this problem was solved by treating the interface scattering as bulk scattering in the mixing region, a few atomic layers thick, near an interface. A totally different approach was introduced by Levy, Zhang, and Fert[8] with a full quantum-mechanical model of MR in which bulk and interface scattering are considered on equal footing and which is capable of describing experimental results in a quantitative way. However, the general solution of this model can only be obtained numerically, requiring considerable computational effort.

In this paper we report on MR measurements on antiferromagnetically coupled Fe/Cr multilayers grown by sputtering techniques. We determined the giant MR effect as a function of temperature and for different Cr thicknesses t_{Cr}. The quantum model of MR is briefly outlined and systematically compared with experimental data. The various electron-scattering lengths are treated as fitting parameters and we discuss their influence on the t_{Cr} dependence of the MR. We find that the spin-dependent scattering at Fe/Cr interfaces is more important than spin-dependent scattering in bulk Fe.

II. EXPERIMENTAL RESULTS

The multilayer samples were prepared by dc sputtering of the Fe and rf sputtering of the Cr layers. The last sputtering method was chosen to avoid mechanical stress in the Cr layers. The system pressure prior to deposition was 3×10^{-7} Torr and the Ar pressure during sputtering was 3×10^{-3} Torr. The polycrystalline multilayers were deposited at a rate of 0.2 nm/s onto $\mathrm{SiO_2}$ substrates held at room temperature, giving rise to a predominantly (110) growth, as determined by x-ray diffraction (XRD). The relatively high degree of disorder of the layers is evident from the observance of only two multilayer peaks at low angles in the XRD spectrum and from the rocking curves of the (110) peak with a full width at half maximum of 12°–18°. The samples were mounted in a ^{4}He flow cryostat and the resistance was measured in the 4–430 K temperature region using conventional ac techniques. In Fig. 1(a) we show a MR curve at 4 K for a multilayer with layer thicknesses of 3-nm Fe and 1-nm Cr. The dashed curve represents the measurement where the magnetic field is swept from left to right and the full curve is measured during a field sweep from right to left. A very small hysteresis is characteristic for a strong antiferromagnetic coupling between neighboring Fe layers. We define the magnetoresistance ratio as $(R_0-R_S)/R_0$, where R_0 is the maximum resistance around zero field and R_S the value at saturation. The magnitude of the MR (20.5%) is close to the result for the dc sputtered layers of Parkin, More, and Roche[3] and somewhat higher than the (extrapolated) value found by Obi *et al.*[9] for Fe/Cr multilayers, where both Fe and Cr were deposited using rf sputtering. For comparison, the MR values of these sputtered layers are in the same range as found for Fe/Cr multilayers grown by molecular beam epitaxy (MBE). Here one typically finds a MR ranging from 33% (relatively rough Fe/Cr interfaces) to 14% (relatively sharp Fe/Cr interfaces).[10] The saturation field B_S is defined by the crossing point of the low field resistance decrease with the horizontal line of constant resistance at higher fields. For Fig. 1(a) we find that $B_S=0.51$ T. As we can neglect the small in-plane magnetic anisotropy in polycrystalline multilayers, the saturation field

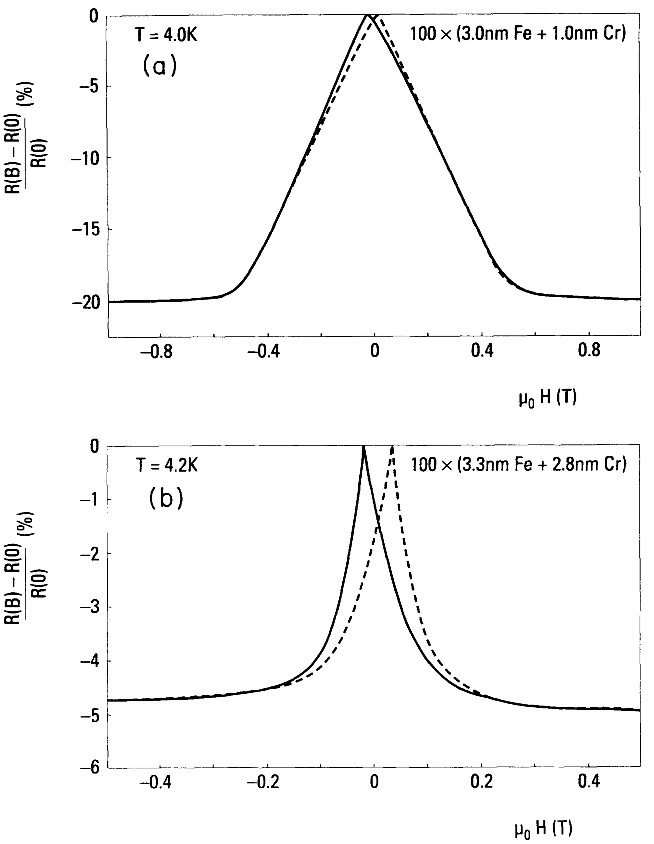

FIG. 1. Magnetoresistance curves at $T=4$ K for Fe/Cr multilayers with a Fe thickness of 3 nm and a Cr thickness of (a) 1.0 nm and (b) 2.8 nm.

$$B_S(T) \equiv \mu_0 H_S(T) \simeq [2|A_{12}(T)|/t_{\mathrm{Fe}} M_S] ,$$

where $A_{12}(T)$ is the interlayer exchange coupling per unit area, t_{Fe} the Fe thickness and M_S the saturation magnetization of Fe.[2] For $t_{\mathrm{Cr}}=1.0$ nm we obtain $|A_{12}(4\ \mathrm{K})|=1.30\ \mathrm{mJ/m^2}$. In Fig. 1(b) we show the MR curve at 4.2 K for a multilayer with $t_{\mathrm{Cr}}=2.8$ nm. The decreased coupling between layers is immediately clear from the lower value for $B_S=0.090$ T and the hysteretic behavior around zero field. Also the MR is considerably lower.

In Fig. 2 the MR effect is presented as a function of temperature for multilayer samples with different Cr thicknesses. The MR strongly decreases with temperature; this is in contrast with the weaker temperature dependence of the MR of, e.g., Co/Cu multilayers.[4] This may be related to the large magnon scattering for Fe, which is a weak ferromagnet [spin-up ($d\uparrow$) not completely filled], resulting in an increased spin mixing at higher temperatures. More specifically, local spin excitations at the roughened Fe/Cr interfaces seem to be responsible for the strong temperature dependence of the MR.[11]

The dependence of the MR on t_{Cr} at $T=4.2$ K is shown in Fig. 3. Measured points are indicated by full dots and the connecting dashed line is a guide to the eye. The full curve is calculated using the quantum model and will be discussed in the next section. The MR strongly decreases between 1 and 2 nm and shows the typical oscillation with a second maximum around 2.8 nm. This value is somewhat higher than that found by Parkin, More, and Roche,[3] but agrees well with the result of Obi *et al.*[9] for rf sputtered Fe/Cr multilayers. The magni-

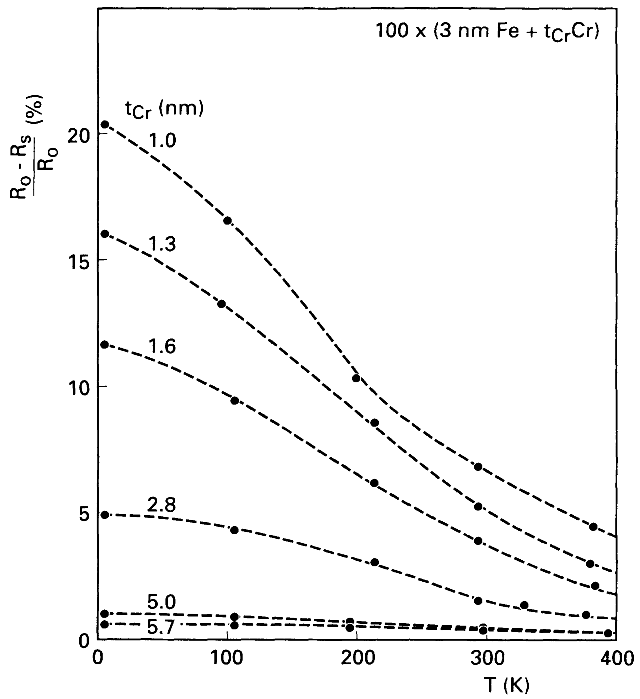

FIG. 2. Temperature dependence of the magnetoresistance for Fe/Cr multilayers with different Cr thickness (R_0 is the maximum resistance around zero field and R_S the value at saturation).

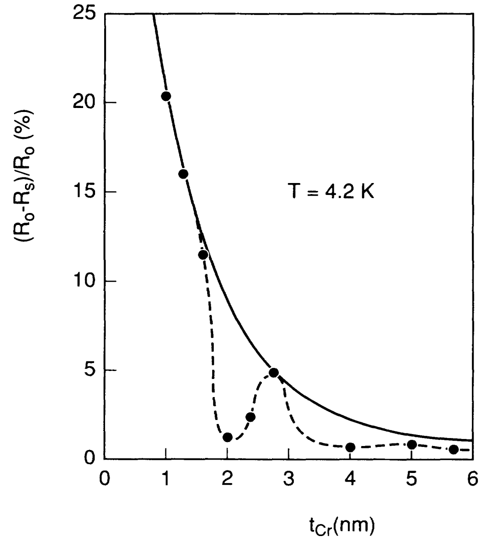

FIG. 3. Dependence of the magnetoresistance on the Cr thickness at $T=4.2$ K. The full curve is calculated using the quantum model of giant MR of Levy, Zhang, and Fert; the dashed curve is a guide to the eye.

tude of the MR is smaller than in Ref. 3, which may be due to an increased interface interdiffusion and disorder originating from the rf sputtering process.

III. DISCUSSION

As said before, the full curve in Fig. 3 represents our best fit to the full quantum theory of Levy, Zhang, and Fert.[8] In this approach a local in-plane conductivity σ is depending on the coordinate z perpendicular to the multilayer planes. An essential difference with the semiclassical model is the representation of the electron by a wave packet having (spin-dependent) scattering probabilities at Fe/Cr interfaces or bulk lattice planes. For clarity, we reformulate the theoretical expressions, exactly as they have been used in our extensive calculations. It is important to note that Eq. (1) is only valid when the magnetizations of the magnetic layers are (anti)parallel (i.e., the ferromagnetic or antiferromagnetic coupling case).

$$\sigma(z)=\frac{ne^2}{2m}\sum_{\sigma}\frac{\hbar}{E^{\sigma}(z)} \tag{1a}$$

with

$$E^{\sigma}(z)=\frac{\hbar^2 k_F}{m\lambda^{\sigma}}\left\{\sum_i \mathrm{Re}\Delta_i^{\sigma} e^{-|z-z_i|/\lambda^{\sigma}} + \sum_l \mathrm{Re}\Delta_l^{\sigma} e^{-|z-z_l|/\lambda^{\sigma}}\right\} \tag{1b}$$

with

$$\lambda^{\sigma}=T\left\{\sum_{i\in T}\mathrm{Re}\Delta_i^{\sigma}+\sum_{l\in T}\mathrm{Re}\Delta_l^{\sigma}\right\}^{-1} , \tag{2}$$

$$\mathrm{Re}\Delta_i^{\sigma}=\frac{1}{\lambda'}\langle\sigma|(1+p_i\boldsymbol{\sigma}\cdot\mathbf{M}_i)^2|\sigma\rangle , \tag{3a}$$

and

$$\mathrm{Re}\Delta_l^{\sigma}=\frac{a_0}{\lambda_l}\langle\sigma|(1+p_l\boldsymbol{\sigma}\cdot\mathbf{M}_l)^2|\sigma\rangle , \tag{3b}$$

where n is the free electron density, m the electron mass, k_F the Fermi wave number, and T one period of the superlattice. The summation in Eq. (1a) is over the two spin directions; z_i and z_l in Eq. (1b) represent the position of a Fe/Cr interface and a lattice plane, respectively. $\mathbf{M}_i$ and $\mathbf{M}_l$ denote the magnetization at an interface and a lattice plane, respectively. p_i and p_l are fitting parameters representing the ratio of spin-dependent to spin-independent scattering at an interface or a lattice plane; these should not be mixed up with the ratios of spin-up over spin-down scattering, but they are of course related. λ' and λ_l are fitting parameters determining the magnitude of the scattering length due to interface and bulk scattering, respectively. We assume λ_l to be the same for Fe and Cr, due to the similar resistivities of these two metals in the multilayer. a_0 is the distance between two lattice planes. The summations of Eq. (2) are over interfaces and lattice planes within one superlattice period $[T=2(t_{\mathrm{Cr}}+t_{\mathrm{Fe}})]$. Equations (3a) and (3b) are scattering matrix elements at the Fe/Cr interface and in the bulk, respectively. In Eq. (1) it is assumed that the two spin directions contribute to independent conduction channels. This is a good assumption at low temperatures, but may not be correct at room temperature where magnon scattering and spin mixing are important. A high-temperature extension of the quantum model has been formulated,[11] but for a quantitative comparison one has to discriminate between the MR component due to interface roughness and the MR of a multilayer with perfectly flat interfaces. Also one additional fitting parameter is introduced. In this paper we will focus on our low-temperature experiments and compare them with the low-temperature quantum model. To calculate the MR we average Eq. (1) over the z coordinate for the ferromagnetic (F) and antiferromagnetic (AF) alignment situations. The MR is then defined as $(R_0-R_S)/R_0=(\sigma_{\mathrm{F}}-\sigma_{\mathrm{AF}})/\sigma_{\mathrm{F}}$. For the prefactor $ne^2/\hbar k_{\mathrm{F}}$ in Eq. (1) we used 2×10^{15} $(\Omega\,\mathrm{m}^2)^{-1}$, which is the mean value of Fe and Cr in the free-electron model. As an illustration of the model we show in Fig. 4 the z-dependent conductivity [i.e., Eq. (1)] for a unit cell of the superlattice with $t_{\mathrm{Fe}}=3$ nm and $t_{\mathrm{Cr}}=0.9$ nm. The upper curve is calculated for the ferromagnetic alignment of the Fe layers and the lowerone for the antiferromagnetic alignment. In the last case we assumed a perfect antiferromagnetic coupling of the Fe magnetizations. The model parameters were $p_i=0.55$, $p_l^{\mathrm{Fe}}=0.30$, $p_l^{\mathrm{Cr}}=0$ (as Cr is a nonferromagnetic metal), $\lambda_l=1.3$ nm and $\lambda'=1.0$. From Fig. 4 it is clear that, with this choice of parameters, the conductivity shows a dip at an interface, due to the locally combined bulk and interface scattering processes.

In Fig. 3 we show our best fit to the experimental MR values, which was obtained with the fitting parameters used in Fig. 4. It is an "envelope" function which de-

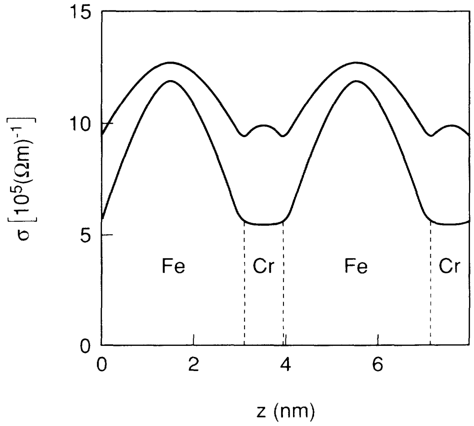

FIG. 4. Calculation of the conductivity as a function of the z coordinate perpendicular to the multilayer plane for a multilayer with $t_{\mathrm{Cr}}=0.9$ nm and $t_{\mathrm{Fe}}=3$ nm. The upper curve is calculated for a ferromagnetic alignment of the magnetizations of the Fe layers and the lower one for an antiferromagnetic alignment. Fitting parameters were $p_i=0.55$, $p_l^{\mathrm{Fe}}=0.30$, $p_l^{\mathrm{Cr}}=0$, $\lambda_l=1.3$ nm, and $\lambda'=1.0$.

scribes the t_{Cr} dependence of the MR in the AF coupling case and hence does not reproduce the oscillatory behavior. Using Eq. (2) we obtain, e.g., for a multilayer with $t_{\mathrm{Fe}}=3$ nm and $t_{\mathrm{Cr}}=6$ nm for the spin-up (↑) and spin-down (↓) electrons that $\lambda_{\mathrm{F}}^{\uparrow}=0.68$ nm, $\lambda_{\mathrm{F}}^{\downarrow}=1.46$ nm, and $\lambda_{\mathrm{AF}}^{\uparrow}=\lambda_{\mathrm{AF}}^{\downarrow}=0.92$ nm. For the conductivities we find $\sigma_{\mathrm{F}}^{\uparrow}=3.9\times10^{5}\ (\Omega\,\mathrm{m})^{-1}$, $\sigma_{\mathrm{F}}^{\downarrow}=7.4\times10^{5}\ (\Omega\,\mathrm{m})^{-1}$, and $\sigma_{\mathrm{AF}}^{\uparrow}=\sigma_{\mathrm{AF}}^{\downarrow}=5.6\times10^{5}\,(\Omega\,\mathrm{m})^{-1}$. The zero-field resistivity $\rho_0=89\ \mu\Omega\,\mathrm{cm}$ is of the order of the experimental values.

We now want to discuss the significance of the values of each of the four basic fitting parameters (p_i,p_l^{Fe},λ_l, and λ'). We systematically varied these parameters while taking care of keeping a reasonable fit with the experimental data. Our main results are as follows: (1) p_i can only be varied in the 0.50–0.55 range. This value strongly determines the MR behavior for $t_{\mathrm{Cr}}<2$ nm and hence can be determined very accurately. The result for p_i agrees very well with the result obtained for MBE grown Fe/Cr multilayers[1,8] and thus seems to be characteristic for the Fe/Cr interface. (2) This high sensitivity of the fit to the precise value of p_i is achieved at the cost of a low sensitivity to the parameter p_l^{Fe}. This parameter could be varied in the 0.05–0.30 range; hence we cannot obtain very quantitative information on the spin dependence of the bulk scattering in Fe. Still p_l^{Fe} is relatively small and we may thus conclude from the quantum model that interface scattering is essential for a giant MR in Fe/Cr multilayers and that the role of spin-dependent bulk scattering is less important. (3) The length λ_l can again be determined more accurately. This parameter is responsible for the strong decrease of the theoretical curve at $t_{\mathrm{Cr}}>2$ nm and measures the spin-independent scattering in the bulk; it needs to be in the 1.4–1.7 nm range to give a reasonable fit. (4) The fourth parameter, λ', determining the scattering length of both spin-dependent and spin-independent interface scattering, can vary between 0.6 and 1.0. λ_l^{Fe} and λ' are parameters which, in contrast to the parameter p_i, seem to be more strongly related to the specific microstructure and deposition method of the samples.

IV. CONCLUSIONS

We have fabricated Fe/Cr magnetic multilayers where Fe was deposited using dc sputtering and Cr using rf sputtering. The giant MR effect was determined as a function of temperature and as a function of Cr thickness. The latter experimental data, obtained at 4.2 K, are well described by the quantum model of MR of Levy, Zhang, and Fert.[8] We have systematically studied the sensitivity of the MR to the different fitting parameters of the model. An interesting result is that the parameter reflecting the ratio of spin-dependent to spin-independent interface scattering was found to be $p_i=0.55$, in agreement with Fe/Cr multilayer samples prepared in another way.[1] Hence this parameter seems to be an intrinsic property of the Fe/Cr interface. From the model we have evidence that the major part of the spin-dependent scattering takes place at the Fe/Cr interface and not in the bulk of the Fe layer.

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