

Perpendicular giant magnetoresistance of Co/Cu multilayers on grooved substrates: Systematic analysis of the temperature dependence of spin-dependent scattering

W. Oepts

*Philips Research Laboratories, Professor Holstlaan 4, 5656 AA Eindhoven, The Netherlands
and Department of Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*

M. A. M. Gijs, A. Reinders, and R. M. Jungblut

Philips Research Laboratories, Professor Holstlaan 4, 5656 AA Eindhoven, The Netherlands

R. M. J. van Gansewinkel and W. J. M. de Jonge

Department of Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

(Received 28 November 1995; revised manuscript received 12 February 1996)

The giant magnetoresistance of Co/Cu multilayers deposited at an angle onto grooved substrates is measured with the current perpendicular to the layer plane. The spin-dependent scattering parameters due to magnetic bulk and interface scattering are determined as a function of temperature, which is done by comparing our experiments with the two-channel model. We find that the decrease of the magnetoresistance from 4.2 K to room temperature is mainly due to an increase of the bulk resistivities of the Co and Cu layers, while the temperature dependence of the interface resistance and the spin-asymmetry parameters for electron scattering is small. [S0163-1829(96)03622-3]

The discovery of the giant magnetoresistance (MR) effect in magnetic multilayers,¹ has led to numerous experimental studies on this effect by many groups. Different multilayer systems as well as different experimental geometries have been investigated. Transport experiments in magnetic multilayers can be divided in two types: (i) The current flows in the plane of the layers (CIP) and (ii) the current is directed perpendicularly to the layer plane (CPP). A description of the giant magnetoresistance effect is theoretically more complex in the CIP geometry than in the CPP geometry. However, experimentally the CPP MR is much harder to access than the CIP MR due to the low perpendicular resistances involved. Several methods have been developed to measure the magnetoresistance of a multilayer in the CPP geometry. The first CPP MR measurements have been done by using superconducting contacts and ultrasensitive superconducting-quantum-interference-device- (SQUID-) based voltage measuring techniques at low temperatures.² Subsequently also microfabricated, so-called "pillar," structures have been employed.³ This method allows one the investigation of the temperature dependence of the CPP MR effect. Unfortunately, this fabrication method is rather complicated and the contact resistance to the pillars is often a problem. A third technique is the electrolytic growth of multilayers into nanopores made into insulating membranes resulting in columns with a large aspect ratio and resistances in a convenient range.⁴ Recently, we introduced an alternative and simple technique for measuring CPP MR, based on the oblique evaporation of multilayers on to grooved substrates.⁵ At the same time also perpendicular growth of thick multilayers on grooved substrates was investigated.⁶ From measurements with currents at different angles to the grooves [the so-called current at an angle to layer plane (CAP) geometry],⁵ it has been possible to derive the CPP MR of the multilayer.

In this paper we report on temperature-dependent CPP MR experiments on Co/Cu multilayers fabricated with the oblique evaporation technique. We have chosen for the Co/Cu multilayer system since this is by now a well-known system, making comparison with the literature possible. It is emphasized, however, that this technique can also be applied to other systems. We compare the experimental data with the phenomenological two-channel model introduced by Lee *et al.*⁷ We systematically analyze the relevant spin-dependent scattering parameters as a function of temperature; this has previously not been possible with the other techniques. We find that the Co/Cu interface resistance keeps its strong spin dependence at *all temperatures*. The main reason for the decrease of the MR with temperature is the increasing importance of bulk scattering with intrinsically much smaller spin dependence. We compare our low-temperature data with CPP MR experiments on Co/Cu done at Michigan State University,⁸ and find that these are similar.

The V-groove pattern in the semi-insulating InP substrates is fabricated using holographic laser interference lithography and anisotropic etching techniques. Details of this fabrication process have been recently described elsewhere.⁵ The grooves are formed by (111) planes which have an 54.7° angle to each other and have a period of typically 200 nm. The multilayer stacks are grown in a multichamber molecular beam epitaxy (MBE) system (VG Semicon V80M). The deposition takes place at room temperature, at a pressure better than 10⁻¹⁰ mbar. By evaporating at an angle perpendicular to one series of (111) planes, we naturally grow stacks of multilayers on one side of the grooves. When the individual stacks overlap, contact is made between the top and the bottom of neighboring stacks, which leads to a series connection of the stacks. A sample consists of typically 5000 to 10 000 stacks in series. To optimize a perpendicular current distribution, we start and end the growth with

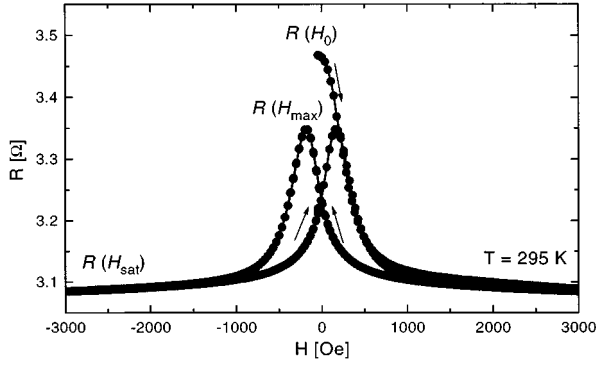


FIG. 1. Room temperature CPP magnetoresistance of a multilayer consisting of 3 nm Fe + 20 nm Cu [1.5 nm Co + 10 nm Cu] + 20 nm Cu. The initial resistance is $R(H_0)$, after a magnetic field cycle; the found maximum resistance is $R(H_{\max})$ and shows a hysteretic behavior.

a 20 nm thick Cu layer. This implies that between the connections of the multilayer stacks the current will partly flow in the plane of the film. The total thickness of the multilayer always is around 260 nm. By measuring the MR in the direction parallel to the grooves, we are able to measure the CIP MR on the same sample. We have fabricated two different sample series, one with constant Co thickness $t_F = 1.5$ nm and one with constant Cu thickness $t_N = 10$ nm. In order to have uncoupled samples, the minimum Cu thickness was chosen to be 6 nm. Room temperature magnetization measurements clearly showed that all our samples are indeed in the uncoupled regime. All samples were measured with a standard four-probe technique in a helium flow cryostat, in magnetic fields up to 1 T.

In Fig. 1 we show the CPP MR at room temperature for a multilayered [3 nm Fe + 20 nm Cu + 23(1.5 nm Co + 10 nm Cu) + 20 nm Cu] sample, with the field applied in the substrate plane in a direction parallel to the grooves and with the current perpendicular to the direction of the grooves. The thin Fe layer is grown for adhesion purposes. Due to the fact that the magnetic layers are uncoupled, a randomly oriented magnetization pattern is obtained around the resistance maximum and a hysteretic MR behavior is observed. The resistance of the as-prepared sample before exposure to a magnetic field cycle is defined as $R(H_0)$. When a field has been applied, the resistance saturates at a field H_{sat} , which for the present sample is at about 1000 Oe. When cycling the magnetic field, a maximum resistance is found at $\pm H_{\max}$, which is appreciably smaller than the first resistance maximum at H_0 . The magnetoresistance ratio $\text{MR}(H_{\max})/\text{MR}(H_0)$ varies from sample to sample. Our CPP samples show values of this ratio of 0.5 up to 0.8. The origin of this difference is not yet fully understood. It was argued⁹ that the resistance value measured at H_0 corresponds to a situation of maximum antiparallel alignment of the magnetizations in the multilayer and therefore seems to be the most reasonable choice for defining the MR to be compared to theoretical models. In the present paper we have considered the MR on the basis of both $R(H_0)$ and $R(H_{\max})$. First all $R(H_0)$ data points are determined as a function of temperature. Then the complete magnetoresistance curve is measured at 4.2 K followed by the $R(H_{\max})$ magnetoresistance curves at all temperatures.

We have tried to demagnetize the samples by spinning them in a magnetic field (of approximately 0.3 T). This enhanced the CPP MR value, but the $R(H_0)$ state could not be recovered completely. The $R(H_{\max})$ value after magnetic field cycling always turned to the same value, which shows that this state is very well reproducible. The initial CPP MR of the sample shown in Fig. 1 is 12.2% at room temperature and 35.0% at 4.2 K. The initial CIP MR value at room temperature is 4.3%.

We compared our CPP MR data to the so-called ‘‘two-channel’’ model, first used by Lee *et al.*⁷ and microscopically justified by Camblong *et al.*¹⁰ and by Valet and Fert.¹¹ In this model, the resistivity of the ferromagnetic layers in the configuration where the electron spin and the local magnetization are parallel [antiparallel] to each other is defined as $\rho_F^\uparrow = 2\rho_F/(1+\beta)$ [$\rho_F^\downarrow = 2\rho_F/(1-\beta)$]. Here, ρ_F is the bulk resistivity of Co. Similarly, also for the ferromagnet/normal metal interface, spin-dependent resistances can be defined: $R_{F/N}^\uparrow = 2R_{F/N}/(1+\gamma)$ and $R_{F/N}^\downarrow = 2R_{F/N}/(1-\gamma)$. β and γ are the important spin-asymmetry parameters of the bulk and the interface, respectively. When identifying the resistance at H_0 with a situation of antiparallel alignment of magnetizations, one obtains for the total perpendicular resistance per unit surface AR_T

$$AR_T(H_0) = M[\rho_N t_N + \rho_F^* t_F + 2AR_{F/N}^*], \quad (1)$$

with $\rho_F^* = \rho_F/(1-\beta^2)$, $R_{F/N}^* = R_{F/N}/(1-\gamma^2)$, M the number of bilayers, and A the perpendicular cross section of one multilayer stack. In our analysis we transform our measured resistance to a resistance per stack. Another useful relation for comparison to the experiment⁷ is given by

$$A\sqrt{R_T(H_0)[R_T(H_0) - R_T(H_{\text{sat}})]} = M[\beta\rho_F^* t_F + 2\gamma AR_{F/N}^*]. \quad (2)$$

It has been shown⁷ that the unknown scattering parameters of the model can be obtained from resistance measurements on a series of samples with constant total thickness L and with a varying thickness t_F or t_N . By plotting the two data series according to Eqs. (1) and (2), we obtained for both equations a linear dependence on M . The values of the slopes and intercepts of the ordinate axes of these plots were then used to determine the relevant parameters of the model. The errors of these parameters are derived from the errors in the determination of the slopes and intercepts in the plots. This is done for several temperatures between 4.2 K and room temperature. This simple two-channel model has been used for analyzing our experimental data at all temperatures. In a more complex temperature-dependent model, the most important addition is a spin-mixing contribution reducing the CPP MR.¹² This spin-mixing term is determined by temperature-dependent coherent spin-flip scattering. From earlier CPP measurements on Co/Cu pillar structures this spin-flip scattering was found to be rather small up to room temperature.¹³ Therefore, in a first-order approximation, we neglect the influence of the spin-mixing term, and apply Eqs. (1) and (2) up to room temperature.

Results of our systematic analysis are plotted in Figs. 2 and 3. In Fig. 2 the interface scattering parameters are plotted. The spin-asymmetry parameter γ is first plotted as derived from both the $R(H_0)$ and $R(H_{\max})$ data. A weak de-

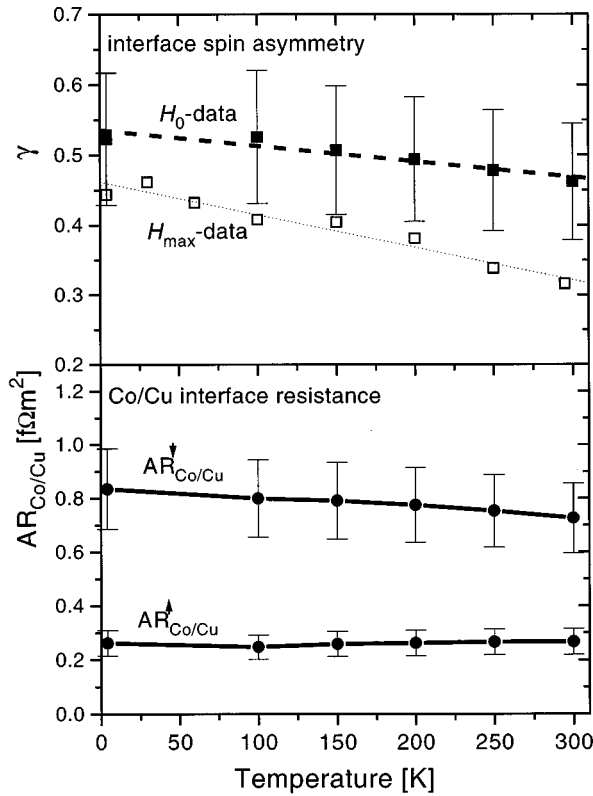


FIG. 2. The temperature dependence of the Co/Cu interface spin-asymmetry parameter γ and the interface resistance for each spin as determined by comparing the experimental data of two series of samples with the two-channel model. The error bars of the H_{\max} data have been omitted for clarity; they are of the same order as shown for the H_0 data. The dashed lines serve as a guide to the eye, to show the weak decrease of the spin-asymmetry parameters.

pendence of temperature is shown. The Co/Cu interface resistance is plotted for both spin channels in the bottom part of Fig. 2. The interface resistance is within the accuracy of our data, independent of temperature, and also the asymmetry between $AR_{\text{Co/Cu}}^{\uparrow}$ and $AR_{\text{Co/Cu}}^{\downarrow}$ has a negligible temperature dependence. In Fig. 3 we plot the model fitting parameters for the bulk resistivities. The spin-asymmetry parameter β is found to be lower than the spin-asymmetry parameter γ and is temperature independent. The resistivities for both spin channels in the Co layers and the resistivity of the Cu layer are given in the bottom part of Fig. 3. Both resistivities increase linearly with temperature. The resistivity of the Cu layer is very low; it is obvious that the contribution of the Cu layer in the total resistance is very weak. The room temperature resistivity of the Cu layer is $1.56 \mu\Omega \text{ cm}$, which is similar to the bulk resistivity of MBE-grown Cu films. The room temperature resistivity of the Co layer is $11.5 \mu\Omega \text{ cm}$. The difference in the up- and down-spin channel resistivities of Co is increasing weakly as a function of temperature. Our analysis demonstrates that the main reason for the decrease of the MR value at higher temperatures is the increase of the bulk resistivities, which have a smaller (Co) and zero (Cu) spin asymmetry with respect to the interface. The weak temperature dependence of the spin-asymmetry parameters β and γ suggests that our assumption of a low spin mixing at higher temperatures indeed is correct,

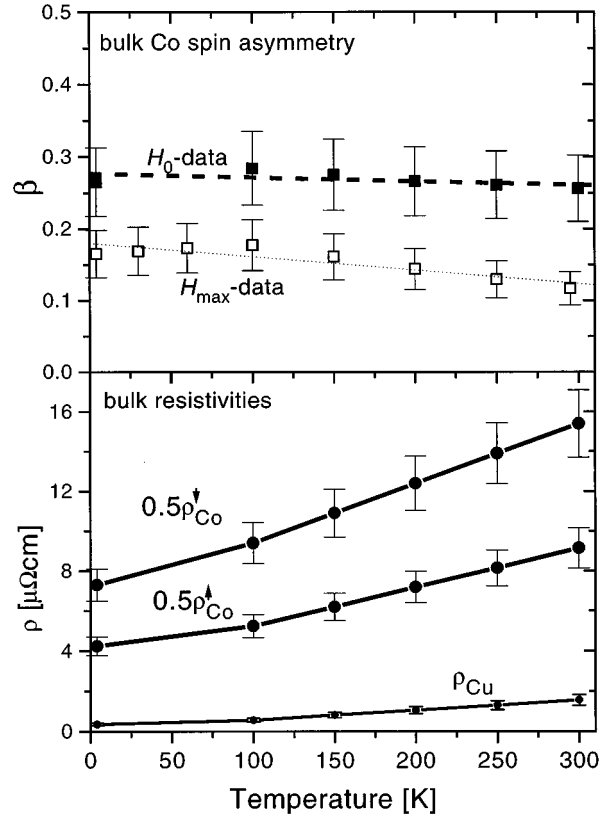


FIG. 3. Temperature dependence of the spin-asymmetry parameter β and the resistivities of the bulk Co and Cu layers. The dashed lines serve as a guide to the eye.

which seems to justify the use of the two-channel model. In Table I we give our spin-dependent parameters at 4.2 K and compare them to the Co/Cu results of the superconducting contact experiments done at the Michigan State University^{8,14} and the electrolytically grown wires by Piraux *et al.*¹⁵ The value we find for the interface resistance $AR_{\text{Co/Cu}}$ is quite similar to the value found with the superconducting contact technique. The values of β and γ in our work are lower than the values found in the other experiments. Besides the fact that our multilayers have been MBE grown, which might introduce a difference, this is due to the fact that our measuring configuration is not purely CPP at the extreme ends of the multilayer stack. An uncertainty in our analysis is the exact length of the part in the grown multilayer where the current is really flowing perpendicular to the layer planes. When we assume a shorter length, and an extra contact resistance between the stacks, we find higher values for β and the resistivities. We have estimated, using finite element calculations, that the resistance contribution of the current flowing perpendicular to the layers is more than 75% of the total resistance. Compared with the MR values with the superconducting contact technique we find that our MR values of comparable multilayers are approximately 20% lower, which is in agreement with our calculations. Although we find a somewhat reduced MR, we want to stress that choosing for this technique pays off well: We can *reproducibly* fabricate samples with many thousands of “pillars” in series, enabling a *systematic* study of all spin-dependent scattering parameters of the multilayer *as a function of temperature*.

TABLE I. Overview of the spin-dependent scattering parameters at low temperatures as derived from our measurements, compared with the superconducting contact technique (Refs. 8,14), and with the electrodeposition technique (Ref. 15). The parameters are defined and discussed in the text.

Method	$AR_{F/N}$ [$\text{f}\Omega \text{ m}^2$]	β	γ	ρ_{Co} [$\mu\Omega \text{ cm}$]	ρ_{Cu} [$\mu\Omega \text{ cm}$]
Grooved substrates H_0 data 4.2 K	0.20 ± 0.04	0.27 ± 0.05	0.52 ± 0.10	5.3 ± 0.6	0.36 ± 0.06
Grooved substrates H_{max} data 4.2 K	0.20 ± 0.04	0.17 ± 0.03	0.45 ± 0.09	4.1 ± 0.7	0.39 ± 0.07
Superconducting contacts H_0 data 4.2 K ^a	0.21 ± 0.01	0.50 ± 0.10	0.76 ± 0.05	6.45 ± 0.34	0.67 ± 0.20
Superconducting contacts H_{max} data 4.2 K ^b	0.19 ± 0.02	0.38 ± 0.06	0.71 ± 0.05	5.66 ± 0.12	1.2 ± 0.31
Electrodeposited nanowires H_{max} data 77 K ^c	0.08 ± 0.05	0.36 ± 0.04	0.85 ± 0.1	20 ± 2	3.1

^aReference 8.

^bReference 14.

^cReference 15.

In summary, we have discussed an analysis of the perpendicular CPP magnetoresistance in magnetic multilayers. Co/Cu multilayers are evaporated at an angle onto grooved substrates fabricated by holographic laser interference lithography and anisotropic etching, naturally giving rise to a CPP-like measuring geometry. Using this method we have determined systematically as a function of temperature all the important scattering parameters, by comparing our experimental data with a theoretical model. We have found that the spin-dependent scattering parameters vary weakly with temperature. An important result of our analysis is that the Co/Cu interface resistance keeps its strong spin dependence

at all temperatures. The main reason for the decrease of the MR with temperature is the increasing importance of bulk scattering with an intrinsically much smaller spin dependence. We have compared our low-temperature data with values found in multilayers grown by other techniques, and have found that our spin-asymmetry parameters are in the line of values found by other authors.

The authors would like to thank R. P. Tjburg, P. E. Huisman, and J. G. H. Stienen for the fabrication of the grooved substrates and S. K. J. Lenczowski, R. J. M. van de Veerdonk, K. M. Schep, and H. van Houten for useful discussions.

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