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The interpretation of experiments on the effect of interface intermixing on the giant magnetoresistance (GMR) effect in antiferromagnetic-coupled multilayers can be complicated by the fact that interface intermixing also changes the coupling strength; therefore, we have grown an artificially intermixed region in Co/Cu spin valves with uncoupled Co layers. The structure we used was a newly engineered spin valve composed of 100 Å Co+6 Å Ru+25 Å Co+40 Å Cu+100 Å Co. Here the Ru layer provides an antiparallel alignment of the Co layers and the Cu layer decouples the upper two Co layers. An intermixed CoCu region has been grown at the Cu/Co interface and in some cases also at the Co/Cu interface by alternately sputtering 1 Å Co and 1 Å Cu. X-ray measurements confirm the existence of an intermixed region, although no reduction of magnetic moment is observed as is reported for homogeneous sputtered $Co_{0.5}Cu_{0.5}$ alloys. This indicates the existence of Co clusters in the intermixed regions. There is no difference in GMR between an intermixed layer of thickness t at one Co/Cu interface or two intermixed layers of thickness $t/2$ at both Co/Cu interfaces. Thus, it seems that the total thickness of the intermixed regions is decisive for the magnitude of the GMR. Because G, ΔG, and $\Delta G/G_{ap}$ all show a gradual decrease when the nominal thickness of the intermixed region increases from 0 to 36 Å, this indicates that there is no strong spin-dependent scattering in this region. This is in agreement with calculations on a model bilayer Co/Cu/Co with the Camley–Barnas model. © *1995 American Institute of Physics.*

I. INTRODUCTION

It is generally accepted that the giant magnetoresistance (GMR) effect finds its origin in spin-dependent scattering, i.e., different scattering rates for spin-up and spin-down electrons; however, whether this spin-dependent scattering predominantly occurs in the bulk of the ferromagnetic layers or at the interfaces between the magnetic and nonmagnetic layers still remains a subject of investigation.

For a number of materials[1–11] experiments have been performed to elucidate this subject. The bulk and interface contributions are evaluated by comparing the magnetoresistance (MR) measurements with model calculations such as resulting from a resistor network, the semiclassical Boltzmann transport equation, or the quantum model of Levy and Zhang.

In recent years especially the Co/Cu system has drawn attention. One reason for this is that Co/Cu is a suitable candidate for verifying theoretical predictions on the period(s) of oscillations in the exchange coupling strength as a function of Cu-layer thickness. Another reason is that in Co/Cu one of the largest GMR effects so far has been observed (65% at room temperature). Nevertheless, particularly for this Co/Cu system the source of the spin-dependent scattering (interface versus bulk) is indistinct. While, for instance, for Fe/Cr layers it is agreed upon both experimentally[1–3] and theoretically[12] that by far the most important contribution to the GMR effect is due to spin-dependent scattering at the Fe/Cr interfaces, this is much less clear in the Co/Cu system.

A number of experiments both with the Current In the Plane of the layers (CIP geometry) and with the Current Perendicular to the Plane of the layers (CPP geometry) has already been performed on the Co/Cu system. In some experiments thin layers at the Co/Cu interfaces have been substituted to modify the Co/Cu interface and therefore the interface scattering leaving the bulk scattering unaltered[11] or to investigate how the magnetoresistance depends on the thickness of this interface layer.[4] Other experiments are based on changing the relative amounts of bulk to interface. Sometimes this is done by varying the thickness of the (non)magnetic layers.[5,6] In other cases the interfaces are enlarged by interdiffusion of Co and Cu due to annealing[7] or to codeposition at the interfaces.[8] However, these experiments do not give consistent conclusions.

In this respect it is extremely relevant to realize that experiments based on a modification of the interfaces of antiferromagnetic (AF) coupled Co/Cu layers will probably alter the strength of the AF coupling as well. For example, Bruno and Chappert have argued that the coupling strength depends on the flatness of the interfaces.[13] Geometrical roughness (deviations from flatness of the interface between

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two homogeneous materials) will reduce the coupling strength. Alteration of the coupling strength can lead to deviations of the perfect antiparallel alignment and can therefore affect the GMR effect. Honda and Nawate[14] have shown that after annealing of Co/Cu multilayers the MR effect and the coupling strength have decreased in the same way. Therefore, to obtain a clear interpretation of the results, these experiments should be performed on decoupled magnetic layers.[6,10] This can be realized in spin-valve structures in which the magnetization direction of one of the layers is pinned in a certain direction, for instance by AF coupling to a third magnetic layer, or exchange biasing to an antiferromagnet.

In this article we report on the effects of interface intermixing on the MR in Co/Cu spin valves with uncoupled Co layers. In these spin-valve structures the antiparallel alignment of the magnetic layers is caused by AF coupling to a third magnetic layer. The Co/Cu interfaces are intentionally intermixed by alternately depositing Co and Cu.

According to the model of Hood, Falicov, and Penn[15] effects of roughness on the magnetoresistance are important only within an interface thickness of typically 0–2 Å. Also alterations in the spin-dependent interface scattering due to intermixing are expected to occur within a few Å intermixing. For larger thicknesses the intermixed regions can be viewed as extra "bulk" layers.[16] For the sputtered samples employed in the present study an intrinsic diffuse intermixing of the order of a few Å was found. This intermixed region is intentionally increased to a nominal thickness of 36 Å. Therefore, the results of these samples rather will provide mainly information on the "bulk properties" of the intermixed regions.

II. THE SAMPLES

The samples consist of a spin-engineered structure of three magnetic layers M_1/6 Å Ru/M_2/40 Å Cu/M_3, as shown in the inset of Fig. 1. The 6 Å Ru layer provides a strong antiferromagnetic coupling between layers M_1 and M_2 which acts as a biasing. The 40 Å Cu layer decouples the magnetic layers M_2 and M_3. The three magnetic layers are composed of: M_1=75 Å Co, M_2=25 Å Co and M_3=25 or 100 Å Co. The samples are high vacuum HV-magnetron sputter deposited on SiO_2 substrates at room temperature at an Ar pressure of 7 mTorr. All samples have a base layer of 200 Å Ru and a protection layer composed of 10 Å Cu+30 Å Ru. According to x-ray measurements the samples are grown in the (111) direction; however, broad rocking curves (full width at half-maximum≈13°) indicate a rather poor texture. In these samples the Co/Cu interface with layer M_3 (and in some cases also layer M_2) are artificially intermixed by alternately depositing 1 Å Co and 1 Å Cu. The total nominal thickness of the intermixed region varies from 0 to 36 Å. When there is an intermixed region the thicknesses of the layers M_3, Cu (and M_2) are reduced such that the total thickness of Co, Cu, and CoCu mixed regions together is kept constant.

A. "Clean" samples

We first consider the clean (i.e., no intentional intermixing) samples. As layer M_3 is not coupled to the other magnetic layers, the magnetization direction of this layer will always be along the field direction. Layers M_1 and M_2 are coupled antiferromagnetically. Therefore, at small applied fields the magnetization directions of these layers will be antiparallel, with the magnetization of the thinner layer (M_2) pointing opposite to the field direction. When the applied field is enlarged, the magnetization direction of layer M_2 will reverse to the field direction. A typical $M(H)$ curve is shown in Fig. 1. Between $H=0$ and H_1 there is a clear plateau in the magnetization where layer M_2 is aligned antiparallel with layers M_1 and M_3. The measured magnetic moment corresponding to this plateau agrees well with what one would expect for the antiparallel configuration. Between H_1 and H_2 the magnetization direction of layer M_2 reverses along the field direction. Since the layers are grown in the (111) direction and the field is applied in the plane of the layers no magnetic anisotropy is involved here and the magnetization reversal will be a rotation process as can be seen in Fig. 1. For fields larger than H_2 the magnetization direction of all layers point in the field direction.

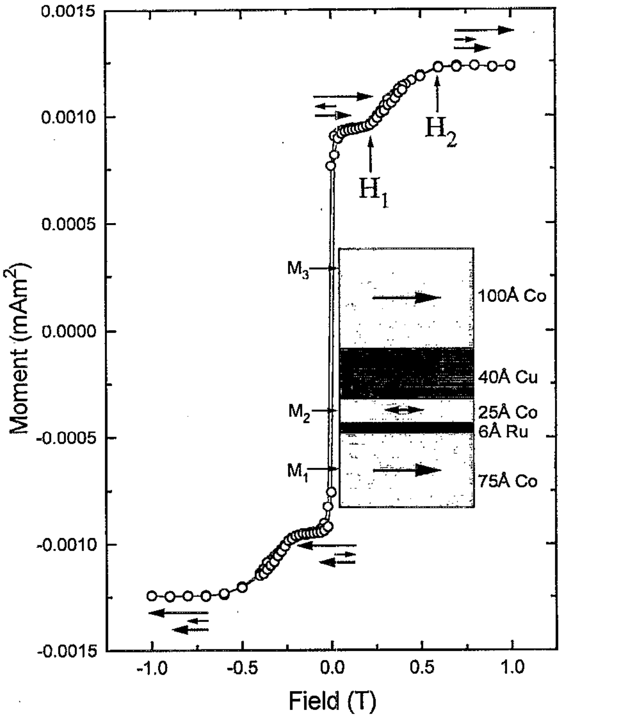

FIG. 1. Typical $M(H)$ loop. The arrows indicate the magnetization directions of the Co layers.

The most essential feature of the magnetization is the possibility to create a parallel and an antiparallel alignment of the magnetization directions of layers M_2 and M_3 through the application of a magnetic field although they are not coupled to each other. Therefore, in this type of spin-valve structure it is possible to investigate the influence of intermixing at the Co/Cu interfaces without complicating effects due to AF coupling between the constituents of the valve.

At this point we would like to emphasize that this spin valve consists of three magnetic layers and the bottom layer M_1 in principle may contribute to the MR effect also. How-

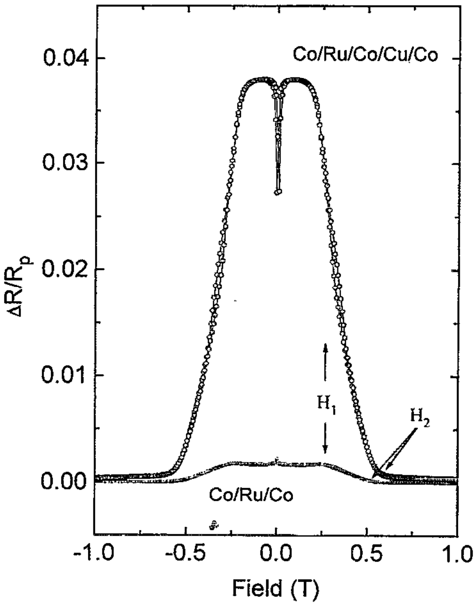

FIG. 2. Magnitude of the magnetoresistance of the underlying Co/Ru/Co system compared to the magnetoresistance of the clean sample Co/Ru/Co/Cu/Co. The MR values are measured in the transverse configuration ($H \perp I$) at $T=300$ K.

ever, the MR of a Co/Ru spin valve is typically an order of magnitude smaller than that of the Co/Cu system. Dieny[6] reports even no measurable MR in Co/Ru/NiFe/FeMn exchange-biased spin valves. Although it is difficult to compare $\Delta R/R$ values with literature because this quantity is influenced also by the choice of, for example, base and cap layers, a small $\Delta R/R$ ($\approx 0.03\%$) is reported by Bloemen for Co/Ru multilayers.[17] A MR effect of the same order of magnitude has been reported by Arbaoui, Dinia, and Panissod[18] for Co/Ru epitaxial superlattices. The highest value for $\Delta R/R$ is obtained by Parkin in dc magnetron-sputtered Co/Ru superlattices. At a Ru thickness of 6 Å Ru a value of $\approx 4\%$ is reached.[19]

To elucidate the effect of the underlying Co/Ru system we have measured the MR effect of the system 200 Å Ru/75 Å Co/6 Å Ru/25 Å Co/150 Å Cu/30 Å Ru where the free Co layer is substituted by Cu. The $\Delta R/R$ of this system is shown in Fig. 2. For fields larger than H_2 all magnetization directions are aligned parallel and the resistance is relatively low. Between H_2 and H_1 the magnetization direction of layer M_2 reverses and the resistance increases. Between H_1 and $H=0$ the magnetizations are aligned antiparallel and the resistance is high. The peak in $\Delta R/R$ around $H=0$, where both layers reverse their magnetization direction, might be due to the changing angles between the magnetization directions and the current (anisotropic magnetoresistance effect).

Also in Fig. 2 the $\Delta R/R$ of the total (clean) sample is shown. In general the MR effect displays the same features as the underlying Co/Ru system. Around $H=0$, however, there is now a dip in the MR effect. This is caused by the reversal of the magnetization directions of all layers resulting in a nonperfect antiparallel alignment which is apparently a much larger effect than the effect due to the anisotropic magnetoresistance. The most important conclusion from Fig. 2 is that the MR effect of the Co/Ru system is negligible compared with the MR effect of Co/Cu. The magnitude of $\sim 4\%$ at room temperature of the MR of Co/Cu is comparable with the results of Speriosu[20] for exchange-biased spin valves on a base layer of 8(20 Å Ru+12 Å Cu). It is, however, smaller than the MR effect reported by Dieny *et al.*[6] and Parkin[4] (≈ 9.5 and $\approx 7\%$, respectively) probably because of the 75 Å Co layer necessary for the antiparallel alignment which acts as a shunt.

B. Intermixed samples

In the intermixed samples, the interfaces are intermixed by alternately sputtering 1 Å Co and 1 Å Cu. In all samples the Cu/Co interface is intermixed as is in some samples also the Co/Cu interface. The total thickness of the mixed region has been varied between 0 and 36 Å. When there is an intermixed region the thickness of the Co and Cu layers are decreased such that the total amount of Co and Cu is kept constant.

According to the bulk phase diagram of Co_xCu_{1-x},[21] no thermodynamically stable solid solutions exist at any temperature in the composition range $0.05 \leqslant x \leqslant 0.88$ due to the immisibility of the two components. However, it has been established that it is possible to produce a metastable Co_xCu_{1-x} alloy over the whole concentration range by coevaporation[22] and cosputtering.[23] Since the amount of 1 Å Co and 1 Å Cu that is alternately sputtered in the samples of the present study is smaller than the distance between the (111) planes of fcc Co and Cu (2.0467 and 2.088 Å, respectively) we may expect that due to this intentionally intermixing an alloylike region at the interface will form.

Childress and Chien[23] and Kneller[22] both have reported a reduction of magnetic moment of Co atoms when intermixed with Cu. For a metastable alloy of 50% Co and 50% Cu cosputtered at 77 K on glass or mica, Childress reports a saturation magnetization of ≈ 125 emu/g_{Co} compared with 175 emu/g_{Co} for bulk fcc Co. Also for bulk Ni it is known[24] that the addition of 35% Cu produces paramagnetic alloys with zero magnetic moment at room temperature. Therefore, it is not surprising that similar effects have been observed in NiFe/Cu spin valves.[10] At the NiFe/Cu interfaces there is an intermixed region part of which, depending on the Cu concentration, is nonferromagnetic. The thickness of this nonferromagnetic layer increases upon annealing due to the increasing intermixing. The effect is ascribed to a compositional gradient across the interfaces.

In our samples, however, we did not measure any reduction of magnetic moment as a function of intermixed region thickness. Even in an extra series of samples (not spin valves) in which a much larger part of the Co (up to 92%) was intermixed with Cu we did not observe any loss of magnetic moment. This indicates the existence of Co clusters in the intermixed regions. This might be due to the fact that our samples were sputtered at room temperature, which causes a higher mobility of the atoms reaching the substrate.

To investigate the intermixing in our samples, glancing incidence x-ray measurements have been performed. In these measurements a highly collimated x-ray beam (Cu $K\alpha$ radia-

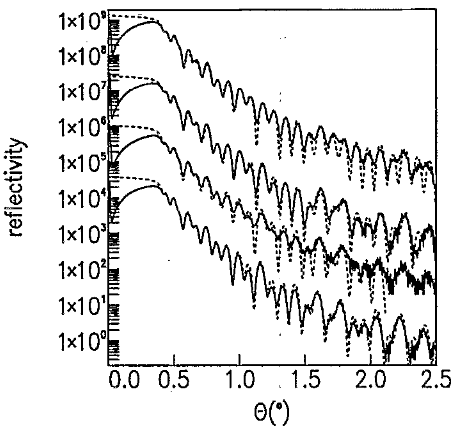

FIG. 3. X-ray reflectivity curves (solid lines) and fits (dashed lines) for the samples of Table I. From top to bottom: sample 1, sample 2, sample 3, and sample 4. For clarity the curves of samples 1, 2, and 4 have been shifted.

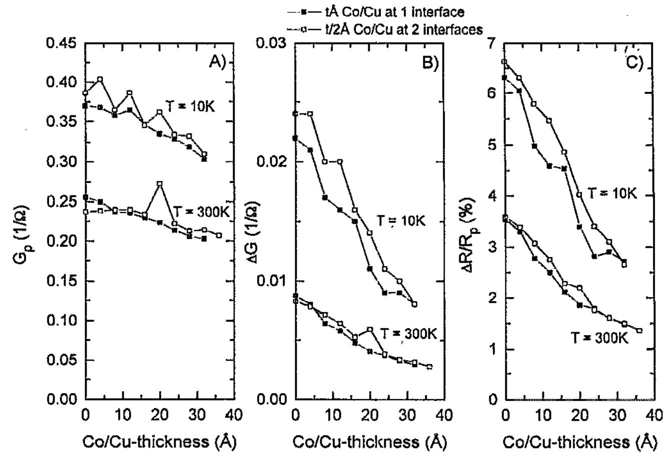

FIG. 4. (a) G_p, (b) ΔG, and (c) $\Delta G/G_{ap}$ as a function of the total intermixed region thickness.

tion) impinges on a flat sample at a small angle θ. In most cases the specular reflectivity at an angle 2θ is recorded. Often these measurements are combined with x-ray fluorescence measurements. While the fluorescence yields information on the chemical composition of the material, the $\theta-2\theta$ scans contain information on the density and the thickness of each layer, as well as on the lateral average interface widths of the layers.[25]

To extract the desired parameters such as layer thicknesses, densities, and interface width from the experiment, the measurements are to be compared with calculations. In these calculations the shape of both reflectivity and fluorescence can be described using a Fresnel-based formalism. To describe the intentionally introduced interface intermixing in our samples in an appropriate way, we assumed in our calculations an extra layer between Co and Cu. This layer consists of a CoCu alloy which has a density averaged from that of Co and Cu. Furthermore, at each interface an error-function-shaped profile with a certain interface width was assumed.

In Fig. 3 the experimental x-ray reflectivity curves including calculations are shown for some samples with a nominal thickness of the intermixed region (from top to bottom) of 0, 8, 20 and 32 Å. In Table I the experimentally determined thickness d_{expt} of the intermixed region, as resulting from our calculations, is given for the same samples shown in Fig. 3. The thickness denoted by d_{nom} is the nominal thickness of the intermixed regions. The thickness d_{expt} in Table I is the total thickness of the intermixed region including its interface width. In this respect it is important to realize that in general the interface width contains a contribution from geometrical roughness (deviations from the flatness on a lateral length scale of several μm of the interface between two homogeneous materials) which is not important for the GMR effect and compositional roughness (interdiffusion). With x-ray measurements we cannot discern between both kinds of roughness because they are incorporated in the calculations by the same effective Debye–Waller-like factors.

TABLE I. Nominal and experimental (determined by glancing incidence x-ray reflectivity measurements) layer thicknesses (Å).

Sample	d_{nom} (Å)	d_{expt} (Å)
1	0	9
2	8	17
3	20	20
4	32	34

It clearly follows from the x-ray analysis that the thickness of the CoCu layer we have to assume in our calculations to fit the measurements increases with the thickness of the alternately sputtered region. As the layers are grown by sputtering, there will be some intermixing between all layers even without alternately sputtering. The thickness of 9 Å CoCu for the clean sample denotes an upper limit for the sum of this "initial" intermixing and the geometrical roughness. In related systems recently a geometrical roughness of about 8 Å has been observed by atomic force microscopy measurements,[26] which would indicate that a small initial diffuse intermixing of the order of a few Å may be present in our samples.

The intermixing at the interfaces also results in a decrease in the electrical conductivity of the samples. This is shown in Fig. 4, where the conductivity G_p is shown as a function of nominal thickness of the mixed region. We return to this point in the following section.

III. RESULTS AND DISCUSSION

In Fig. 4 the measured variation of G_p, ΔG, and MR ($=\Delta R/R_p$) with the nominal thickness of the total intermixed region(s) is shown for two different temperatures: $T=10$ K and $T=300$ K. Naturally for the higher temperature the conductivity G is smaller due to additional scattering processes (phonons, magnons, etc.). Also ΔG and MR are lower at 300 K. The reduction with a factor of ≈ 1.85 for the MR of the clean samples when the temperature is increased from 10 to 300 K is comparable to the factor of 1.7 measured by Mosca *et al.*[27] for Co/Cu multilayers. Such a reduction can be explained within the Camley–Barnas (CB) model when including[28]

(1) temperature-dependent phonon and magnon resistivity terms for the Co and Cu layers that are determined from bulk materials and
(2) a temperature-dependent resistance term resulting from the interfaces.

When the thickness of the intermixed region is increased, clearly no dramatic changes in G, ΔG, and MR are observed. They rather show a gradual decrease even when the intermixed thickness grows larger than the Cu spacer. Of course in this case it is difficult to speak of interface intermixing since the "interface" between Co and Cu has now become a layer of its own.

These results are in marked contrast with Suzuki and Taga[8] who have reported a sharp decrease in MR from 27% to 4% when only cosputtering 1.5 Å Co and Cu at the interfaces of AF-coupled Co/Cu multilayers. This difference could be explained either by a coupling effect in the samples of Suzuki and Taga, or to a different state of initial intermixing (see foregoing paragraphs). Measurements on molecular-beam-epitaxy-grown samples with smaller intermixed regions are currently in progress.

The MR effect of the Fe/Cr system is often, by analogy with bulk alloys,[29] ascribed to spin-dependent scattering from Cr atoms dissolved in the Fe layers. As a consequence one would expect that the MR increases as a function of intermixed region thickness. In our samples, however, the MR decreases as a function of the thickness of the intermixed region. A decrease of MR in spin valves with uncoupled layers is also reported by Parkin:[4] For NiFe/Cu spin valves with thin Co layers inserted at the interfaces and Co/Cu spin valves with thin NiFe layers inserted at the interfaces the MR decreases upon annealing at elevated temperatures which increases the intermixing.

From Fig. 4 we can see that there seems to be no significant difference between an intermixed region of thickness t at the interface between the Cu layer and the free Co layer or intermixed regions of thickness $t/2$ at both Co/Cu interfaces. Both cases result in the same slope of G_p, ΔG, and MR as a function of intermixed thickness. The small difference in magnitude is already present in samples of the same composition (e.g., the clean samples without intermixing 75 Å Co/6 Å Ru/25 Å Co/40 Å Cu/100 Å Co) and is therefore ascribed to nonperfect reproducibility. The same experimental observation has also been reported for the Fe/Cr system by Baumgart *et al.*,[2] when ultrathin layers (0–4 Å) of V, Mn, Al, Ir, and Ge are inserted at the Fe/Cr interfaces. It makes no difference whether a thickness t of these layers is inserted at alternate interfaces or a thickness $t/2$ at every Fe/Cr interface. What seems to be more important than the number of interfaces is the overall number of additional (spin-dependent?) scatterers per multilayer period. This result, combined with the fact that the MR decreases with increasing intermixing, indicates that in the intermixed regions, at least for the thicknesses we have investigated here, the spin-independent scattering is dominant above the spin-dependent scattering.

At this point we would like to substantiate these provisional conclusions with model calculations and find some quantitative parameters that confirm that the scattering asymmetry for spin-up and spin-down electrons is small in the CoCu-mixed regions. Moreover, we might obtain information on the scattering asymmetry in the Co layers and at each interface.

Since the present study uses sputtered layers we cannot investigate the effects of interfacial roughness (geometrical or interdiffusion) in the limit of atomical sharpness. Thus, we cannot prove experimentally for instance the results of the Falicov–Hood–Penn (FHP) model that the most important changes in MR due to increasing roughness occur within a rough interface of thickness ≤ 2 Å. Therefore, we try to interpret our results with the common CB model,[30] which is an extension of the semiclassical Fuchs–Sondheimer model for the conduction in thin films. The input parameters of this CB model are with σ the spin direction;

(1) The Fuchs specularity factor p^σ at the outer surfaces. When $p^\sigma=0$ (rough surface approximation) the electrons will scatter completely diffuse at the outer surfaces, when $p^\sigma=1$ the scattering will be completely specular;
(2) probabilities of coherent transmission, specular reflection and diffusive scattering (T^σ, R^σ, and D^σ, respectively) at each interface;
(3) λ^σ the (spin-dependent) mean free path of the conduction electrons in each layer; the ratio $\lambda^\uparrow/\lambda^\downarrow$ is called α, which is a measure for the spin dependence of the scattering.

With the help of the CB model it is possible to simulate bulk spin-dependent scattering by choosing different $\lambda^\uparrow$ and $\lambda^\downarrow$ in the magnetic layers. Interface spin-dependent scattering will be the result of the asymmetry in T^σ and R^σ for different σ. In the model each layer is considered to have a perfectly flat interface. Therefore, to simulate some geometrical or chemical (intermixing) roughness at the interface one can change the parameters T^σ and R^σ or, following the approach of Johnson and Camley[16] to describe intermixing in the Fe/Cr system, assume some extra layer at the interface with a "bulk mean free path" of its own. Since in our samples the intermixed regions become quite large, we have chosen for the latter approach which of course will also provide an extra interface.

An example of a fit to the low-temperature data with the CB model is shown in Fig. 5 which shows that it is possible to fit the data when assuming small or no scattering asymmetry in the intermixed regions; however, because of the large number of fit parameters it was possible to describe the data with different sets of parameters. Especially the scattering asymmetry in the Co layers and the interface parameters T^σ depend strongly on each other. Therefore, we restrict ourselves to more transparent calculations on a model system to gain insight in the role of the scattering processes as a function of intermixed region thickness.

As a model system we take a simple trilayer: 50 Å Co/40 Å Cu/50 Å Co. We represent the intermixed regions as extra

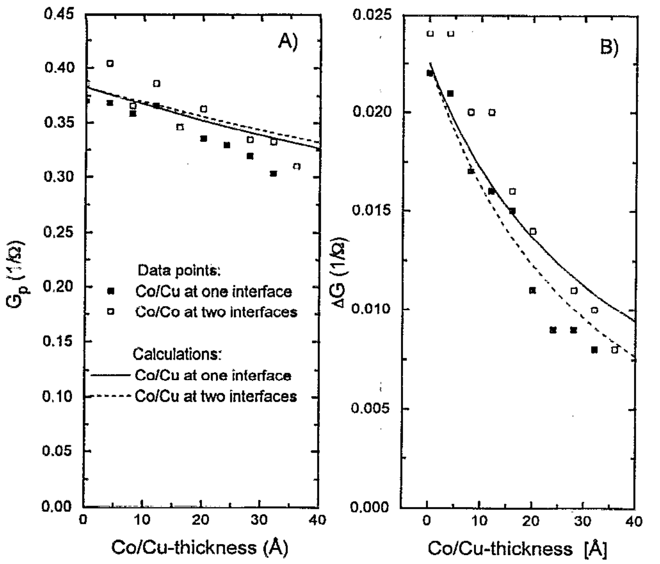

FIG. 5. Example of a fit of the low-temperature data according to the *CB* model. The fit parameters are: $\lambda^{\uparrow}_{Co}=140$ Å; $\lambda^{\downarrow}_{Co}=10$ Å; $\lambda^{\uparrow}_{Cu}=\lambda^{\downarrow}_{Cu}=795$ Å; $\lambda^{\uparrow}_{CoCu}=\lambda^{\downarrow}_{CoCu}=78.9$ Å; $\lambda^{\uparrow}_{Ru}=\lambda^{\downarrow}_{Ru}=10$ Å, $T^{\uparrow}_{Co/Ru}=T^{\downarrow}_{Co/Ru}=0.75$; $T^{\uparrow}_{Co/Cu}/T^{\downarrow}_{Co/Cu}=1/0.2$; $T^{\uparrow}_{CoCu/Cu}/T^{\downarrow}_{CoCu/Cu}=1/1$; and $T^{\uparrow}_{CoCu/Co}/T^{\downarrow}_{CoCu/Co}=1/0.2$.

layers with bulk parameters $\lambda^{\uparrow}_{CoCu}$ and $\lambda^{\downarrow}_{CoCu}$ and interfaces of their own. In fact this is the same system that we have investigated experimentally, however, we have omitted here the Co/Ru part of our samples since this part does not contribute to the magnitude of the magnetoresistance. The total thickness of the structure is always kept constant at 140 Å. The interfaces are described by an interface parameter T which may be spin dependent. We assume that electrons that are not transmitted are diffusively scattered such that there is no reflection ($R=0$). At the outer boundaries we assume completely diffusive scattering ($p^{\sigma}=0$). Further input parameters that we use are: $\lambda^{\uparrow}_{Co}+\lambda^{\downarrow}_{Co}=100$ Å and $\lambda^{\uparrow}_{Cu}=\lambda^{\downarrow}_{Cu}=200$ Å which are known from literature to be reasonable values.[6,31] As the conductivity decreases when the intermixed thickness increases, we take a smaller mean free path in the mixed layer: $\lambda^{\uparrow}_{CoCu}+\lambda^{\downarrow}_{CoCu}=50$ Å. In the following we consider the effect of interface intermixing on the MR effect in two different cases where no interface spin-dependent scattering (SDS) or no bulk SDS is assumed.

A. No interface SDS

In the case of no interface spin-dependent scattering the interface parameter T is set at $T=1$ at all interfaces. It is assumed that there is an asymmetry in the mean free paths of Co: $\lambda^{\uparrow}_{Co}/\lambda^{\downarrow}_{Co}=90$ Å/10 Å. In view of our results two different alternatives are compared. In the first case we take the scattering in the intermixed regions to be spin independent ($\lambda^{\uparrow}_{CoCu}=\lambda^{\downarrow}_{CoCu}=25$ Å), in the other case we assume in the intermixed layers the same asymmetry in the scattering as in the Co layers ($\lambda^{\uparrow}_{CoCu}/\lambda^{\downarrow}_{CoCu}=45$ Å/5 Å).

The results for G_p, ΔG, and MR ($=\Delta G/G_{ap}$) are shown in Fig. 6. In both cases the conductivity decreases because the resistivity of the intermixed layers is larger than that of Co and Cu. In the case of spin-independent scattering in the intermixed layers [Fig. 6(A)] ΔG and MR decrease monotonously. This can be understood because the intermixed layers in this case can be viewed as part of the spacer layer. Thus, intermixing in this case leads to an increase in spacer layer thickness and a decrease in Co-layer thickness. Both effects will result in a decrease of ΔG and MR.

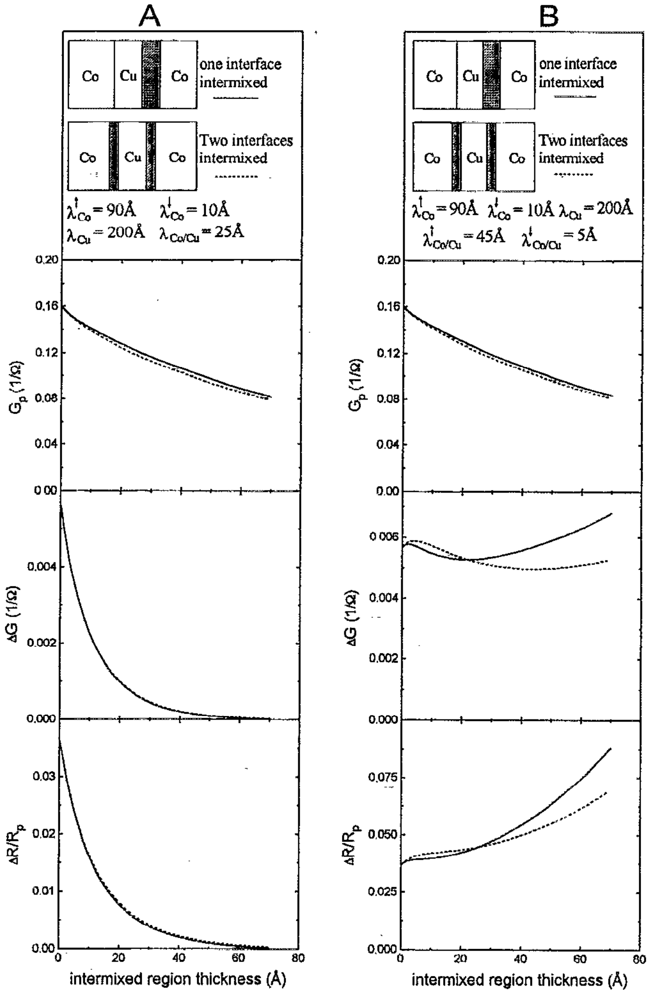

FIG. 6. Calculation of G, ΔG, and $\Delta R/R_p$ with the CB model for a model system Co/Cu/Co with intermixing at one interface (solid line) and intermixing at two interfaces (dashed line) in the case where no interface SDS is assumed ($T^{\uparrow}=T^{\downarrow}=1$ at each interface). The input parameters are drawn in the top panel of the figure.

In the case of spin-dependent scattering in the intermixed layers [Fig. 6(B)] the behavior of ΔG is more complicated. First, when the intermixed layers are very thin, a small part of the Cu spacer has been substituted by CoCu that displays spin-dependent scattering. This results in an increase of ΔG. Then, when the intermixed layers grow thicker, another effect becomes dominant. Since the conductivity of the intermixed layers is smaller than the conductivity of Co, these layers will prevent part of the electrons from the Co layers from crossing the Cu spacer and contribute to ΔG. This effect will lead to a decrease of ΔG until the intermixed layers have reached a thickness such that they will completely mask the Co layers and we have effectively a CoCu/Cu/CoCu spin-valve system. In this regime a further increase of thickness of the intermixed layers will decrease the Cu-spacer thickness which yields an increase in ΔG again. The behavior of MR simply follows from the ratio of ΔG and G_{ap}.

B. No bulk SDS

In the case of no bulk spin-dependent scattering in each material $\lambda^{\uparrow}=\lambda^{\downarrow}$. We use $\lambda^{\uparrow}_{Co}=\lambda^{\downarrow}_{Co}=50$ Å, $\lambda^{\uparrow}_{CoCu}=\lambda^{\downarrow}_{CoCu}=25$ Å and $\lambda^{\uparrow}_{Cu}=\lambda^{\downarrow}_{Cu}=200$ Å. At the interfaces between Co and Cu we assume a spin-dependent interface scattering: $T^{\uparrow}/T^{\downarrow}=1/0.2$. When there is an intermixed region we again consider two cases. In the first case we assume spin-dependent scattering at the interfaces between the Co layers and the intermixed layers ($T^{\uparrow}/T^{\downarrow}=1/0.2$) but no spin-dependent scattering at the interfaces between the Cu layers and the intermixed layers ($T^{\uparrow}/T^{\downarrow}=1/1$). In the other case we will assume spin-dependent scattering at the interfaces between the Cu layer and the intermixed layers ($T^{\uparrow}/T^{\downarrow}=1/0.2$), but no spin-dependent scattering at the interfaces between the Co layers and the intermixed layers ($T^{\uparrow}/T^{\downarrow}=1/1$). The interfaces where we assume spin-dependent scattering are shown in the top panels of Fig. 7.

The results for G_p, ΔG, and MR are shown in Fig. 7. In the case of spin-dependent scattering at the Co interfaces as well as in the case of spin-dependent scattering at the Cu interfaces the conductivity of the system decreases as the intermixing increases due to the high resistivity of the intermixed CoCu layer(s).

In case of spin-dependent scattering at the Co interfaces [Fig. 7(A)] ΔG decreases monotonously as one would expect as intermixing in this case leads to an increase of spacer layer thickness and an increase of spacer resistivity.

Assuming spin-dependent scattering at the Cu interfaces [Fig. 7(B)] leads to a minimum in ΔG. This minimum occurs when the thickness of the intermixed layer(s) equals 25 Å which is the mean free path in the intermixed layers. We can understand this result in the following way. For small thickness of the intermixed layers ΔG decreases because the mean free paths in the intermixed layers are smaller than those in the Co layers. Therefore, the flow of electrons that crosses both Cu interfaces without scattering diminishes. This effect will stop when the thickness of the intermixed layers is such that they shield the Co layers completely, i.e., when the thickness of the intermixed layers equals the mean free path in the intermixed layers. Effectively we have now a CoCu/Cu/CoCu spin valve in which the Co layers merely act as shunt layers. Increasing the intermixing even further will result in a smaller distance between the Cu interfaces and therefore to an increase of ΔG.

From comparison of the experimental data and the model calculations one may conclude that the best description is obtained when no spin-dependent scattering in the CoCu-mixed region is assumed in the case of no interface spin-dependent scattering [Fig. 6(A)] or when assuming spin-dependent scattering at the Co/CoCu interfaces in the case of no bulk spin-dependent scattering [Fig. 7(A)]. In both cases a monotonous decrease of G, ΔG, and MR is observed and there is almost no difference between intermixing at one interface or divided over two interfaces. Note that these model calculations seem to be in agreement with our provisional conclusion, based on the measurements, that in the intermixed regions the spin-independent scattering dominates.

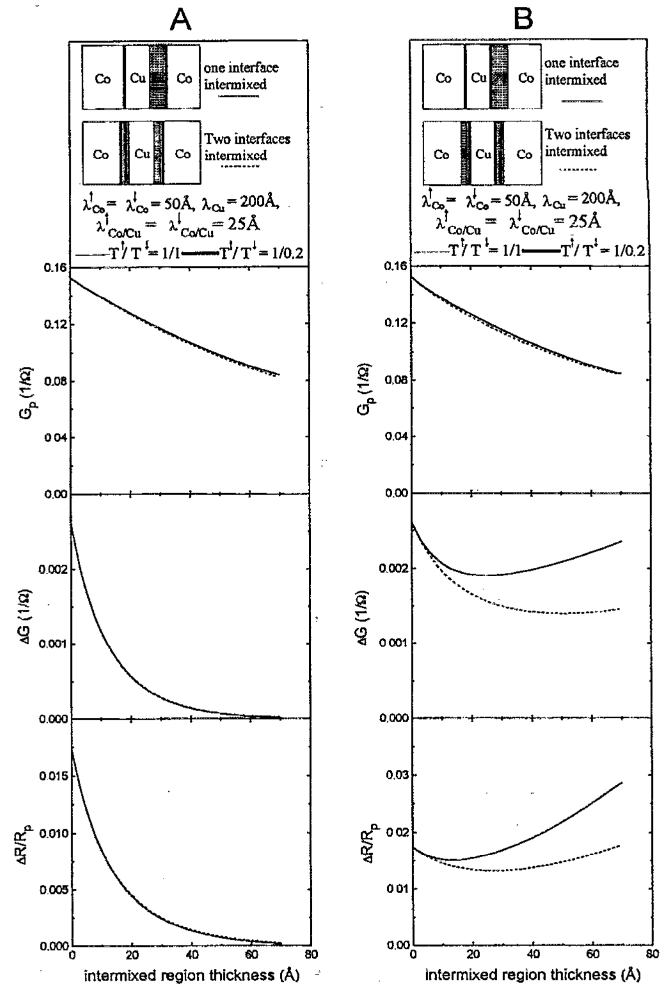

FIG. 7. Calculation of G, ΔG, and $\Delta R/R_p$ with the CB model for a model system Co/Cu/Co with intermixing at one interface (solid line) and intermixing at two interfaces (dashed line) in the case where no bulk SDS is assumed ($\lambda^{\uparrow}=\lambda^{\downarrow}$ in each layer). The input parameters are drawn in the top panel of the figure.

It should be noted however that, although we described the intermixed regions as extra layers, these intermixed regions are not uniform in composition. Tentatively we can distinguish between three areas each with a different Co concentration. In the middle of the CoCu region there will be an equal amount of Co and Cu. According to the magnetic moment measurements there might be Co clusters in this region. At the interfaces with the Co and Cu layers there will be compositional gradients. As these gradients are from Co to CoCu at one side and from Cu to CoCu at the other side of the CoCu region, there will be a larger area that has a surplus Co and a larger area that has a surplus Cu than when there is a compositional gradient directly between Co and Cu. All three areas can have a different spin dependence, which we cannot discern from our experiment. When the scattering in one of the areas is spin independent, this can already decrease the magnetoresistance. It might therefore be worthwhile to investigate other compositions of artificial intermixing (e.g., $Co_{0.75}Cu_{0.25}$ instead of $Co_{0.5}Cu_{0.5}$) also.

IV. CONCLUSIONS

We have measured the effect of interface intermixing in Co/Cu spin valves with uncoupled Co layers. The intermixing is induced by alternately sputtering of 1 Å Co and 1 Å Cu. The intermixing does not affect the magnetic moment of the Co atoms. A gradual, monotone decrease of G, ΔG, and MR at low temperature as well as at room temperature is observed when the nominal thickness of the intermixed region is increased from 0 to 36 Å. There is no significant difference between an intermixed region of thickness t Å at one Co/Cu interface or intermixed regions of thickness $t/2$ Å at both Co/Cu interfaces. These results indicate that spin-independent scattering dominates in the intermixed CoCu regions. Calculations on a model system according to the CB model yield the same qualitative behavior when assuming no interface scattering spin-dependent scattering and spin-independent scattering in the intermixed regions or assuming no bulk spin-dependent scattering and spin-independent scattering at the CoCu/Cu interfaces.

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