# Analysis of scattering lengths in Co/Cu/Co and Co/Cu/Co/Cu spin-valves using a Ru barrier

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We use uncoupled Co/Cu/Co and Co/Cu/Co/Cu spin-valve structures with a Ru barrier shifted through the top Co and Cu layer, respectively, to measure the longest of the electron mean free paths in Co and Cu as originally suggested by Parkin. From semiclassical transport calculations and careful analysis of the magnetoresistance data we conclude that the exponential behavior of $\Delta G$ is uniquely related to the longest of the Co and Cu mean free paths under the condition of effective spin-dependent filtering at the interfaces or in the bulk of the Co. In this regime we have compared $\lambda^{\text{long}}$ in Co and Cu with bulk conductivities ($\propto\lambda^{\text{short}}+\lambda^{\text{long}}$), yielding no strong evidence for bulk spin-dependent scattering in Co. [S0163-1829(96)02037-1]

## I. INTRODUCTION

It is quite generally accepted that the giant magnetoresistance (GMR) effect in spin-valves and multilayers 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 occurs predominantly at the interface or in the bulk of ferromagnetic layers, is one of the most prominent fundamental issues in studies on GMR.[1,2]

In particular for Co/Cu systems it is not clear whether spin-dependent scattering occurs mainly in the bulk, or at the interfaces of the magnetic layers. Several experimental approaches have been followed to shed a light on this issue. In one type of experiments the interfaces are changed by adding thin layers at the Co/Cu interfaces[3] or by intentionally enlarging the diffusion at the Co/Cu interfaces by annealing[4,5] or during deposition.[6,7] In most of these studies the importance of the Co/Cu interfaces for the giant magnetoresistance effect is emphasized. In other experimental studies the GMR is studied as a function of the thickness of magnetic and nonmagnetic layers,[8,9] leaving the Co/Cu interfaces unchanged. However, experimental verification of the scattering asymmetry for spin-up and spin-down electrons is usually indirect via fits with models such as the resistor network model,[10] models based on the semiclassical Boltzmann transport equation[11] and the quantum model of Zhang, Levy, and Fert.[12] Due to the large number of input parameters the conclusions obtained are often questionable.

Recently,[13] Parkin proposed a more straightforward method to determine if bulk spin-dependent scattering, represented by an asymmetry in the mean free paths $\lambda^{\text{long}}$ and $\lambda^{\text{short}}$ for spin-up and spin-down electrons, plays an important role in ferromagnetic materials such as Co. It was suggested that in a spin-valve, with a thin highly resistive Ru barrier layer shifted through one of the magnetic constituents, the GMR ratio is proportional to $1-\exp(-t/\xi)$, with $t$ the position of the Ru layer and $\xi$ a characteristic length. Since the position of the Ru layer determines how far electrons may propagate into the ferromagnetic layer, $\xi$ is suggested to represent the longest of the mean free paths, $\lambda^{\text{long}}$. Subsequently, the comparison of $\lambda^{\text{long}}$ in various magnetic and nonmagnetic systems such as Co, $Ni_{81}Fe_{19}$, $Cu_{80}Au_{20}$ with their bulk conductivity ($\propto\lambda^{\text{short}}+\lambda^{\text{long}}$) provided no evidence for a substantial bulk spin-dependent scattering at room temperature.

In this paper we will try to provide a more theoretical basis for this method by analyzing the transport properties of spin valves with a shifting Ru barrier through the uncoupled ferromagnetic layer with the Boltzmann transport equation. In particular we will investigate with model calculations what parameters determine the characteristic length scale $\xi$ observed in experimental data. It will be concluded that $\xi$ indeed can be used as a fingerprint for $\lambda^{\text{long}}$, however not by a simple equality as suggested by Parkin. Experimentally, Parkin applied the method to a number of alloys and Co only at room temperature, whereas we have concentrated on elementary spin-valves consisting of Cu and Co, in which we first verified the efficiency of the diffusive scattering at an embedded thin Ru layer. Thereafter, the temperature dependence of the evaluated Co and Cu scattering lengths and conductivity are used to address the role of bulk spin-dependent scattering.

## II. EXPERIMENTAL

All samples were grown at Philips Research Laboratories by dc magnetron sputtering. The samples were prepared at room temperature on $SiO_2$ substrates in an Ar plasma atmosphere. Resistivity measurements were made in standard four-point contact geometry with the current in the plane of the sample. A superconducting quantum interference device magnetometer is used for magnetic characterization of the samples. X-ray-diffraction measurements showed [111] texture of the Co and the Cu layers.

Several series of spin-valves were grown. A first series of spin-valves was grown to test the effectiveness of the Ru barrier layer. This series has the composition: Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Ru($d_{\text{Ru}}$ Å)/Cu(30 Å)/Ru($d_{\text{Ru}}$ Å)/Co(100 Å)/Cu(10 Å)/Ru(30 Å), with $d_{\text{Ru}}$ in the range 0–6 Å. A second series was designed to probe the longest of the mean free paths in Co with the following composition: Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Cu(30 Å)/Co(250 Å)/Ru(30 Å). A 2 Å Ru layer was incorporated at various positions in the Co(250 Å) layer. The Ru barrier was chosen 2 Å thick because a thicker Ru layer, which might be a more effective barrier, resulted in antiferromagnetic coupling between the two parts of the Co(250 Å) layer separated by Ru.

 

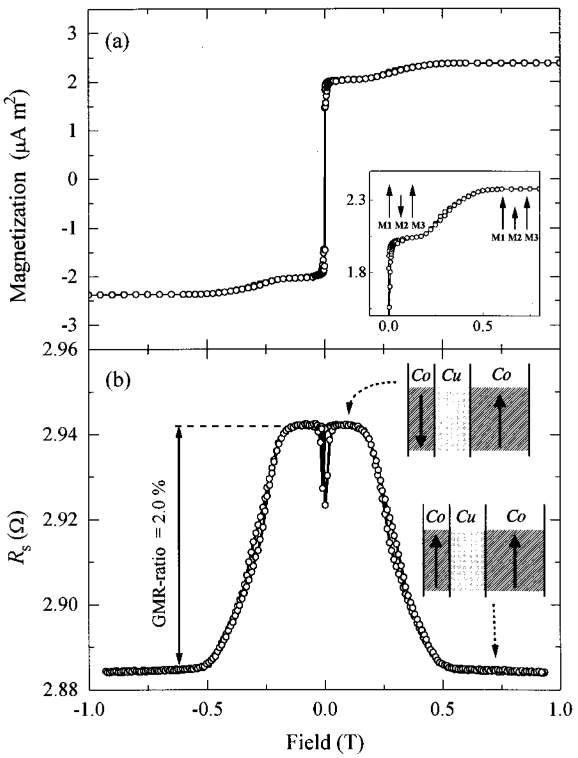


FIG. 1. (a) Magnetization curve of the sample with the composition Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Cu(30 Å)/Co(250 Å)/Ru(30 Å), with a Ru barrier layer incorporated at position $t=40$ Å in the Co(250 Å) layer. The inset shows a magnification in which the arrows indicate the relative orientation of the magnetic moments of the Co layers. (b) Corresponding sheet resistance ($R_s$) versus field curve. The giant magnetoresistance ratio is defined as GMR ratio$=(R_{ap}-R_p)/R_p=(G_p-G_{ap})/G_{ap}$.

A third series, designed to probe the scattering lengths in Cu, has the composition: Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Cu(30 Å)/Co(25 Å)/Cu(300 Å)/Ru(30 Å), with a 5 Å Ru layer at various positions in the Cu(300 Å) layer. Single Co and Cu layers were grown with the composition: Ru(200 Å)/Co($d_{Co}$ Å)/Ru(30 Å) and Ru(200 Å)/Cu($d_{Cu}$ Å)/Ru(30 Å), with $d_{Co}$=250, 500, 1000, and 2000 Å, and $d_{Cu}$=2000, 4000, 8000, and 10 000 Å. The Ru(200 Å) base layer ensures equal texture as for the spin-valves. The Ru(30 Å) top layer prevents oxidation of the Co and Cu layers.

## III. RESULTS

To understand the magnetic behavior of the samples we consider the basic composition of the series of spin-valves: $M1$/Ru(6 Å)/$M2$/Cu(30 Å)/$M3$, with $M1$=Co(75 Å), $M2$ =Co(25 Å), and $M3$=Co(100 Å), Co(25 Å) or Co(250 Å), which is the spin-valve designed by Willekens *et al.*[6] Figure 1(a) shows a typical magnetization curve at room temperature. In low fields $M1$ and $M3$ will align parallel to the applied field, and because of the antiferromagnetic coupling with layer $M1$, layer $M2$ will align antiparallel to the applied field, essentially without coupling with $M3$ across Cu. This is one of the key elements of our spin-valves, as a shift of a Ru barrier through layer $M3$ will not affect the degree of antiparallel alignment of layer $M2$ and $M3$. At higher fields $M2$ will rotate towards the field direction, which ends in a parallel state of all magnetic moments for fields higher than approximately 0.5 T. As can be seen in Fig. 1(b), the antiparallel alignment of layer $M2$ and $M3$ leads to an increase in resistivity which amounts to 2% in this specific example.

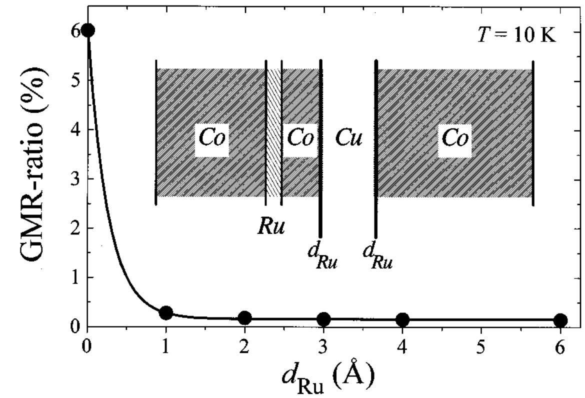


FIG. 2. GMR ratio at $T=10$ K of the spin-valves with the composition Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Ru($d_{Ru}$ Å)/Cu(30 Å)/Ru($d_{Ru}$ Å)/Co(100 Å)/Cu(10 Å)/Ru(30 Å) as a function of Ru layer thickness $d_{Ru}$.

The essential feature of the second and third series of spin-valves, used for the determination of $\lambda^{long}$, is the shifting Ru barrier layer. We define a barrier as a layer which diffusely scatters electrons and transmits no electrons. To be sure that we have fulfilled this condition we have checked the properties of the barrier layer by adding thin layers of Ru at the interfaces of the Co/Cu/Co spin-valves. Figure 2 shows the GMR ratio for the first series of spin-valves with the basic composition Co(25 Å)/Ru($d_{Ru}$ Å)/Cu(30 Å)/Ru($d_{Ru}$ Å)/Co(100 Å) as a function of the thickness of the Ru layers $d_{Ru}$. By adding only a 2 Å thick Ru layer at the Co/Cu interfaces of the spin-valve, the GMR ratio decreases by more than a factor 20 from about 6 to 0.25 % and then saturates at about 0.15% for thicker Ru layers. This clearly demonstrates that Ru is very effective in blocking electrons and that Ru is an excellent candidate for a barrier layer. At this point we would like to note that the bottom part of our stack of layers, Co(75 Å)/Ru(6 Å)/Co(25 Å), also forms a spin-valve, and this produces the small saturation GMR ratio of 0.15%. This background contribution will be neglected in the following (see also Ref. 6).

Subsequently, we have measured the transport properties of the Co/Cu/Co(/Cu) structures as a function of the position of the Ru barrier layer (second and third series of spin-valves). In the left panel of Fig. 3 a typical result of the sheet conductivity $G$, the differential conductivity $\Delta G$, and the GMR ratio are plotted for the second series of spin-valves, composed of Co/Cu/Co with a 2 Å Ru barrier shifted through Co. The sheet conductivity $G$ in antiparallel alignment of the magnetic moments in the spin-valve ($G_{ap}$) and parallel alignment ($G_p$) first decreases and then increases as a function of $t$, which might seem somewhat confusing as the total thickness of the stack of layers is constant. However for the layer thickness regime discussed here, mean free paths are restricted by the boundaries of the layers and hence also by diffusive scattering introduced by the Ru barrier layer, which leads to the observed minimum in $G$ when the barrier is roughly in the middle of the spin-valve. More important for

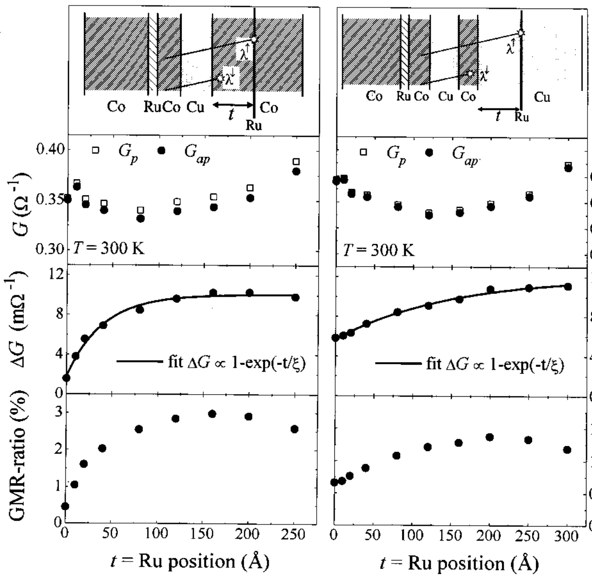


FIG. 3. Experimental results at $T = 300$ K of the conductivity $G$, the differential conductivity $\Delta G$ and the GMR ratio as a function of the Ru barrier layer position $t$ for the spin-valves Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Cu(30 Å)/Co($t$ Å)/Ru(2 Å)/Co(250$-t$Å)/Ru(30 Å) (left panel) and the spin-valves Ru(200 Å)/Co(75 Å)/Ru(6 Å)/Co(25 Å)/Cu(30 Å)/Co(25 Å)/Cu($t$ Å)/Ru(5 Å)/Cu(300$-t$ Å)/Ru(30 Å) (right panel). The solid line indicates an exponential fit $\propto 1-\exp(-t/\xi)$.

the determination of the mean free paths in Co and Cu is the behavior of $\Delta G$. Upon an increase of $t$ the differential conductivity $\Delta G$ increases and finally saturates. We have illustrated this in Fig. 3 by schematically drawing the imaginary trajectories of electrons. Due to spin-dependent scattering (represented by a star) the mean free path is smaller for spin-down than for spin-up electrons. However, the spin-up electrons will be scattered by the Ru barrier which is most effective when the barrier is located near the Co/Cu interface. At higher $t$, however, spin-up electrons may experience their full bulk mean free path and then the difference in spin-up and spin-down conductivity and hence $\Delta G$ is maximal. The increase shows exponential behavior as is demonstrated with the fit of $\Delta G$ (solid line). Finally, because $G_p$ and $G_{\mathrm{ap}}$ are roughly constant, the GMR ratio shows similar behavior as $\Delta G$. At higher $t$, however, the GMR ratio decreases because of the small but noticeable increase of $G_{\mathrm{ap}}$. In the following we therefore fit $\Delta G$ and not the GMR ratio with an exponential expression.

In Fig. 4(a) $\Delta G$ is presented as a function of the position of the Ru barrier layer at several temperatures between 10 and 300 K. For each temperature the figure is supplemented with a solid line which is a fit $\propto 1-\exp(-t/\xi)$, yielding the characteristic length $\xi$ as a function of temperature which will be analyzed later on.

In the right panel of Fig. 3 we present room temperature measurements of $G$, $\Delta G$, and GMR ratio for the third series of spin-valves, composed of Co/Cu/Co/Cu, as a function of the position $t$ of the shifting 5 Å Ru barrier through Cu. We will refer to the top Co layer as the *filter* layer and to the Cu layer as the *back* layer, a concept originally introduced by Gurney *et al.*[14] First, the sheet conductivity shows similar

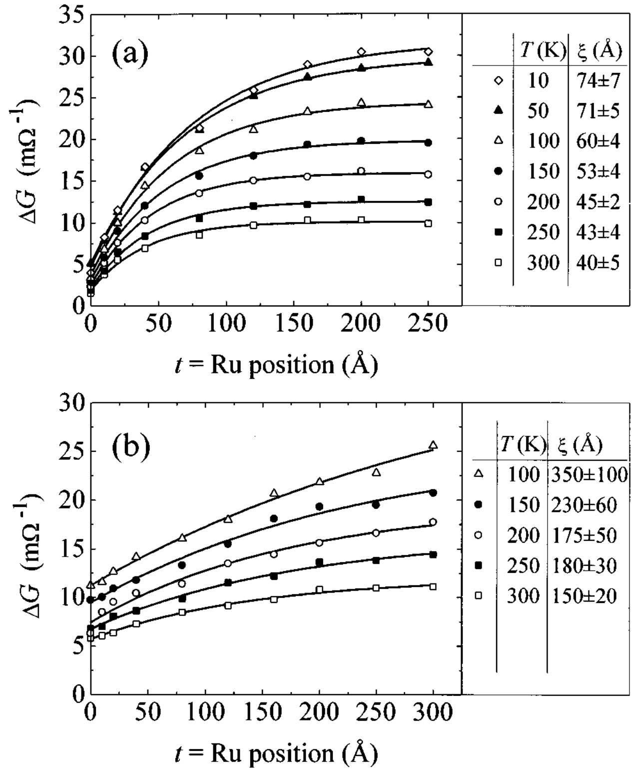


FIG. 4. $\Delta G$ as a function of the Ru barrier layer in (a) Co/Cu/Co and (b) Co/Cu/Co/Cu spin-valves for different temperatures. In each figure the characteristic lengths $\xi$ as derived from exponential fits (solid lines) are shown.

behavior as for the Co/Cu/Co spin-valves, with a minimum in the conductivity for intermediate values of $t$. Next, $\Delta G$ increases as a function of $t$, and although $\Delta G$ does not saturate completely we can identify an exponential behavior demonstrated by the exponential fit of $\Delta G$ (solid line). For $t = 0$ Å it is observed that the differential conductivity $\Delta G$ has an offset, which we attribute to the Co/Cu/Co part of the sample. The GMR ratio clearly decreases at larger $t$ due to the increase in $G_{\mathrm{ap}}$.

In Fig. 4(b) we have plotted $\Delta G$ as a function of the position of the Ru barrier layer for $T = 100$–$300$ K. Unfortunately, the exponential fits, denoted with the solid lines in Fig. 4(b) resulted in a characteristic lengths $\xi$ with a large error (larger than 13% to almost 30% for $T = 100$ K, in comparison to an error of approximately 10% for the Co/Cu/Co spin-valves). Therefore, we restrict ourselves to the experimental data for $T = 250$ and 300 K, for which the error is acceptable. We think that part of the error is caused by the fact that $\Delta G$ is not completely saturated at maximal $t$, which explains why the error decreases with increasing temperature, as the high temperature $\Delta G$ seems almost saturated in contrast to the low temperature $\Delta G$.

The last part of the experimental results deals with the conductivity of the single Co layers for temperatures between 10 and 300 K and the single Cu layers for the temperatures 250 and 300 K. In Fig. 5 the sheet conductivity of the single Co and Cu layers is plotted as a function of thickness. The macroscopic conductivity is determined from the slope of the sheet conductivity as a function of thickness. For the Cu single layers, which varied in thickness between 2000

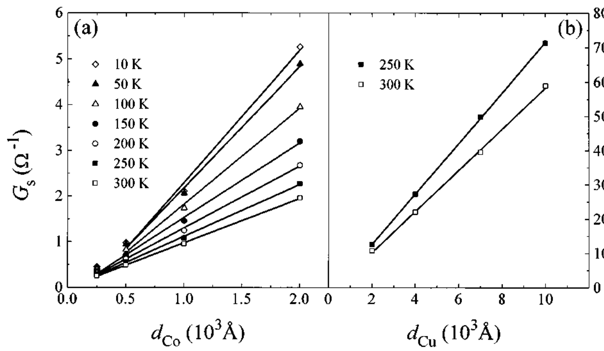


FIG. 5. Sheet conductivity $G_s$ as a function of layer thickness of (a) single Co layers and (b) single Cu layers. The slope of the sheet conductivity as a function of layer thickness, as indicated with the dashed lines, is the macroscopic conductivity.

and 10 000 Å, a fit of the sheet conductivity with a linear equation, indicated by the solid lines in Fig. 5, resulted in conductivities $\sigma_{Cu}=0.71$ $(\mu\Omega\,\mathrm{cm})^{-1}$ for $T=250$ K and $\sigma_{Cu}=0.58$ $(\mu\Omega\,\mathrm{cm})^{-1}$ for $T=300$ K. For the single Co layers however, which varied in thickness between 250 and 2000 Å, the slope of the sheet conductivity as a function of thickness is not constant. This is probably caused by boundary effects for smaller thickness as the mean free path for Co is in the range of the thickness of the layers. We have therefore fitted only the larger thicknesses, indicated by the solid lines, where the slope of the sheet conductivity as a function of the Co thickness becomes nearly constant. As a typical result we have found $\sigma_{Co}=0.096$ $(\mu\Omega\,\mathrm{cm})^{-1}$ for $T=300$ K.

## IV. MODEL CALCULATIONS

In this paper we use a semiclassical calculation based on the Fuchs-Sondheimer extension of the Boltzmann equation,[15] that was applied initially by Camley and Barnas[11] to calculate the conduction and the GMR ratio in spin-valves and multilayers. We will refer to this model as the CB model. In subsequent studies[1,16,18] it was shown that, although the CB model is not designed to predict *ab initio* the magnitude of the GMR ratio, the experimental behavior of $\Delta G$ and GMR ratio on ferromagnetic and nonmagnetic layer thicknesses can be described qualitatively very well. In view of this, we will apply the CB model to investigate under what conditions the *qualitative* experimental behavior of the differential conductivity $\Delta G$ can be used to extract the longest of the mean free paths in Co and Cu.

The input parameters in this model are (a) the mean free paths of the different metals in the spin-valves $\lambda_{Co}$, $\lambda_{Cu}$, and $\lambda_{Ru}$, (b) probabilities of coherent transmission, specular reflection and diffusive scattering $T$, $R$, and $D$ at each interface, and (c) the Fuchs specularity factor $p$ at the outer surfaces. Bulk spin-dependent scattering in the Co layers is modeled via spin-dependent mean free paths $\lambda_{Co}^{\uparrow}=\lambda^{\mathrm{long}}$ and $\lambda_{Co}^{\downarrow}=\lambda^{\mathrm{short}}$. Interface spin-dependent scattering at the Co/Cu interfaces is modeled by spin-dependent transmission coefficients $T_{Co/Cu}^{\uparrow}$ and $T_{Co/Cu}^{\downarrow}$. At the barrier and at the outer boundaries we will assume that there is no reflection ($R=0$, $p=0$), which are both reasonable assumptions as we have shown that Ru is a good diffusive barrier.

To make interpretations with the CB model more transparent we have performed model calculations on two spin-valves in which we ignore Ru base and cap layers and the Co/Ru bias layers. The first has the composition Co(25 Å)/Cu(30 Å)/Co($t$ Å)/Ru(2 Å)/Co($250-t$ Å), with $0\leqslant t\leqslant 250$ Å, and the second is composed of Co(25 Å)/Cu(30 Å)/Co(25 Å)/Cu($t$ Å)/Ru(5 Å)/Cu($300-t$ Å), with $0\leqslant t\leqslant 300$ Å. In the following we will refer to the first model spin-valves as Co/Cu/Co and to the second as Co/Cu/Co/Cu spin-valves. As a starting point we will adopt parameters which are known from literature to be reasonable values.[17] For the Cu mean free path $\lambda_{Cu}=200$ Å is taken and a spin-dependent Co mean free path ratio $\lambda_{Co}^{\uparrow}/\lambda_{Co}^{\downarrow}=10$. Spin-dependent scattering at the Co/Cu interfaces will be modeled with spin-dependent transmission coefficients $T_{Co/Cu}^{\uparrow}=1$ and $T_{Co/Cu}^{\downarrow}=0.2$. For Ru we adopt a mean free path $\lambda_{Ru}=0$, representing the fact that Ru is a barrier layer for electrons.

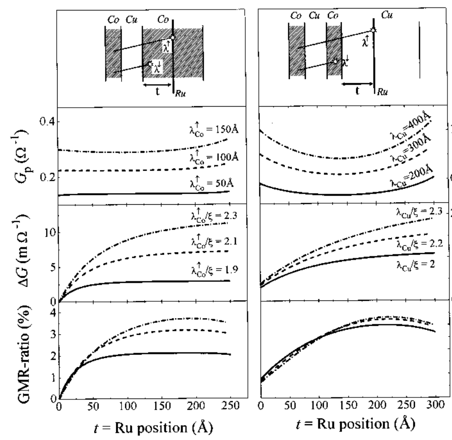


FIG. 6. The left panel shows Camley-Barnas calculations of $G_p$, $\Delta G$, and GMR ratio for the model spin-valve Co(25 Å)/Cu(30 Å)/Co($t$ Å)/Ru(2 Å)/Co($250-t$ Å), with $0\leqslant t\leqslant 250$ Å for $\lambda_{Co}^{\uparrow}=50$, 100, and 150 Å. The input parameters in the model are $\lambda_{Cu}=200$ Å, $\lambda_{Co}^{\uparrow}/\lambda_{Co}^{\downarrow}=10$, $T_{Co/Cu}^{\uparrow}=1$, $T_{Co/Cu}^{\downarrow}=0.2$. The right panel represents Camley-Barnas calculations of $G_p$, $\Delta G$, and GMR ratio for the model spin-valve Co(25 Å)/Cu(30 Å)/Co(25 Å)/Cu($t$ Å)/Ru(5 Å)/Cu($300-t$ Å), with $0\leqslant t\leqslant 300$ Å for $\lambda_{Cu}=200$, 300, and 400 Å. The input parameters in the model are $\lambda_{Co}^{\uparrow}=100$ Å, $\lambda_{Co}^{\downarrow}=10$ Å, $T_{Co/Cu}^{\uparrow}=1$, $T_{Co/Cu}^{\downarrow}=0.2$.

### A. Co/Cu/Co

The left panel of Fig. 6 shows the calculations of the parallel sheet conductivity $G_p$, the differential conductivity $\Delta G=G_p-G_{\mathrm{ap}}$, and the GMR ratio $\Delta G/G_{\mathrm{ap}}$ as a function of the position of the Ru barrier layer $t$ for the first model spin-valve. As this spin-valve was designed to probe the longest of the Co mean free paths, $\lambda_{Co}^{\uparrow}$ was varied from 50 to 150 Å, which is in the typical range of mean free paths for Co as reported in the literature.[9] The Cu mean free path was kept at a constant value $\lambda_{Cu}=200$ Å. The calculated conductivity $G_p$, the differential conductivity $\Delta G$, and the GMR ratio are in perfect *qualitative* agreement with the experimental results of the Co/Cu/Co spin-valves presented in the left panel of Fig. 3. As anticipated, $\Delta G$ increases exponentially with a characteristic length $\xi$ and the plot is supplemented with the quotient of $\lambda_{Co}^{\uparrow}$ and $\xi$. We find that $\lambda_{Co}^{\uparrow}$ is typically about a factor of 2 higher than $\xi$.

We can understand the exponential behavior of $\Delta G$ in a more direct way from the analytical expression for the differential conductivity

$$\Delta G \propto \sum_{\sigma=\uparrow\downarrow} \int \nu_x d^3\nu \int [g_p^\sigma(\nu_z,z) - g_{\rm ap}^\sigma(\nu_z,z)]dz, \quad (1)$$

which shows that there is a linear relationship between the macroscopic measurable quantity $\Delta G$ and the distribution function $g$. Because the Boltzmann transport equation is a first degree differential equation, $g$ is exponential, and consequently $\Delta G$ will also show exponential-like behavior. If we neglect the various angles of incidences of the electrons with respect to the normal to the plane of the layers, then one can easily derive that $\Delta G \propto 1-\exp(-t/\lambda_{\rm Co}^{\uparrow})$ for the case that $\lambda_{\rm Co}^{\downarrow}$ is much smaller than $\lambda_{\rm Co}^{\uparrow}$. If we include the integration over position $z$ and velocity $\nu$, $\Delta G$ behaves roughly as $1-\exp(-t/\xi)$ with $\lambda_{\rm Co}^{\uparrow}/\xi \approx 2$ as seen in Fig. 6, which can be understood from geometrical arguments; the effective thickness seen by the conduction electrons in the $z$ direction is about a factor of 2 smaller than their mean free path because of the various angles of incidences.

One of the main goals of this paper is to test to what extent bulk spin-dependent scattering in Co plays an important role in the GMR effect, and therefore our interpretation of $\xi$ being a measure for $\lambda_{\rm Co}^{\uparrow}$ must be independent of the degree of bulk or interface spin-dependent scattering present in our samples. Therefore we will calculate the influence of nonperfect filtering of spin-down electrons at the Co/Cu interfaces and the influence of the degree of bulk scattering on the quotient $\alpha = \lambda_{\rm Co}^{\uparrow}/\xi$. We also consider the influence on a variation of the magnitude of $\lambda_{\rm Cu}$, as a variation with temperature of the mean free path of the Cu spacer layer might affect the penetration depth of electrons in Co and consequently $\xi$.

In Fig. 7(a), first the dependence of $\alpha$ on the variation of the Cu mean free path $\lambda_{\rm Cu}$ is shown. Upon an increase of $\lambda_{\rm Cu}$ from 200 to 600 Å, the ratio $\alpha$ only slightly increases. Intuitively, we suggest that when electrons are not much disturbed in crossing the relative thin spacer layer, because of the long scattering lengths of electrons in Cu, a variation of $\lambda_{\rm Cu}$ does not influence our interpretation of $\xi$. We are confident that this is the case for our spin-valves as our Cu spacer layer is only 30 Å thick.

Figure 7(b) shows the variation of $\alpha$ as a function of the ratio $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}$, which in fact represents the amount of bulk spin-dependent scattering present in Co. The ratio $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}$ also represents to what extent spin-down electrons are filtered in Co. First we consider the case (solid circles) of significant amount of spin-dependent scattering at the Co/Cu interfaces described by the transmission coefficients $T_{\rm Co/Cu}^{\uparrow}=1$ and $T_{\rm Co/Cu}^{\downarrow}=0$. Starting from our initial value of $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}=0$, we see that an increase of $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}$ from 0 to 1 has almost no influence on the ratio $\alpha$. At an intermediate scattering asymmetry, $T_{\rm Co/Cu}^{\uparrow}=1$ and $T_{\rm Co/Cu}^{\downarrow}=0.5$ (open triangles), $\xi$ still appears to be a good measure for $\lambda_{\rm Co}^{\uparrow}$. Only in the situation of no spin-dependent scattering at the Co/Cu interfaces (solid squares), $\alpha$ significantly decreases from about 2 to approximate 1.2 upon an increase of $\lambda_{\rm Co}^{\downarrow}$ towards $\lambda_{\rm Co}^{\uparrow}$, and in this regime $\xi$ is no longer a valid measure for the longest mean free path.

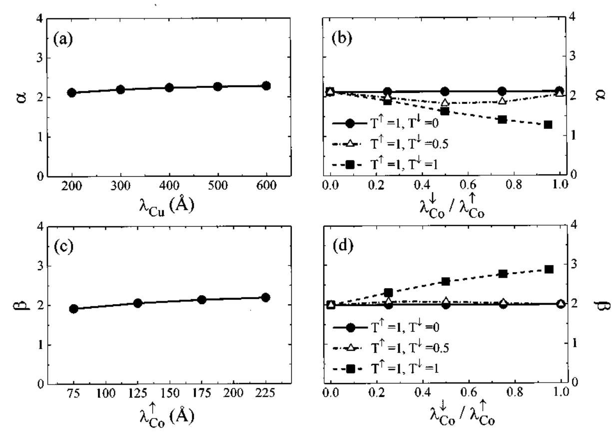


FIG. 7. Variation of several parameters in the CB model calculations on the ratio $\alpha = \lambda_{\rm Co}^{\uparrow}/\xi$ and $\beta = \lambda_{\rm Cu}/\xi$. As a starting point we have adopted the following mean free paths and transmission coefficients: $\lambda_{\rm Cu}=200$ Å, $\lambda_{\rm Co}^{\uparrow}=100$ Å, $\lambda_{\rm Co}^{\downarrow}=0$ Å, $T_{\rm Co/Cu}^{\uparrow}=1$, $T_{\rm Co/Cu}^{\downarrow}=0$. (a) Impact of a variation of $\lambda_{\rm Cu}$ on $\alpha$ for the Co/Cu/Co model spin-valves. (b) Relationship between $\alpha$ and the bulk scattering ratio $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}$ for the Co/Cu/Co spin-valves in case of significant interface spin-dependent scattering (solid circles), intermediate (open triangles), and no interface spin-dependent scattering at Co/Cu interfaces (solid squares). (c) Impact of a variation of $\lambda_{\rm Co}^{\uparrow}$ on $\beta$ for the Co/Cu/Co/Cu model spin-valves. (d) Relationship between $\beta$ and the bulk scattering ratio $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}$ for the Co/Cu/Co/Cu spin-valves in case of significant interface spin-dependent scattering (solid circles), intermediate (open triangles) and no interface spin-dependent scattering at Co/Cu interfaces (solid squares).

From Fig. 7 we conclude that, when there is a significant amount of spin-dependent scattering either at the Co/Cu interfaces or in the Co bulk, $\xi$ is a constant measure for the longest of the mean free paths in Co, independent of the Cu mean free path and the Co mean free path for spin-down electrons.

### B. Co/Cu/Co/Cu

For the Co/Cu/Co/Cu model spin-valve we also have calculated $G_p$, $\Delta G$, and the GMR ratio as a function of the position of the Ru barrier layer $t$ (right panel of Fig. 6). As this spin-valve was designed to probe the mean free path of Cu, we have varied $\lambda_{\rm Cu}$ between 200 and 400 Å. In general we conclude that the calculated conductivity $G_p$, the differential conductivity $\Delta G$ and the GMR ratio are in perfect *qualitative* agreement with the experimental results of the Co/Cu/Co/Cu spin-valves presented in the right panel of Fig. 3. We find that $\lambda_{\rm Cu}$ is typically about a factor of 2 higher than $\xi$ for similar reasons as discussed in the foregoing paragraphs. Again we have calculated the influence of various parameters in the CB model on the quotient $\beta = \lambda_{\rm Cu}/\xi$.

In Fig. 7(c) the dependence of $\beta = \lambda_{\rm Cu}/\xi$ is shown as a function of the longest of the mean free paths in Co. As the longest of the mean free paths in Co becomes larger compared to the thickness of the back layer, $\beta$ increases slightly. Figure 7(d) shows the dependence of $\beta$ on the ratio $\lambda_{\rm Co}^{\downarrow}/\lambda_{\rm Co}^{\uparrow}$, which represent as mentioned before the amount of bulk spin-dependent scattering. We have discriminated three cases; the first (solid circles) with significant amount of Co/Cu interface spin-dependent scattering, represented by

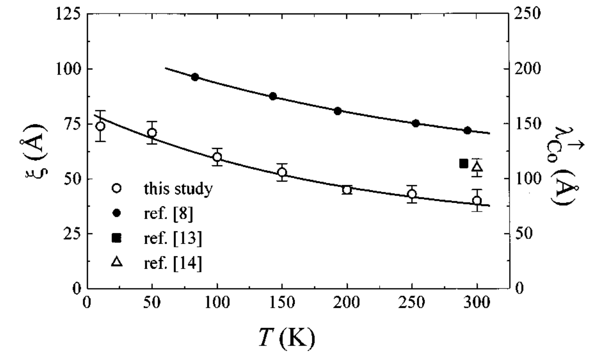


FIG. 8. Characteristic length $\xi$ as measured in our structures as a function of temperature (open circles) and comparison with literature results from Dieny (Ref. 8) (solid circles), Parkin (Ref. 13) (solid square), and Gurney (Ref. 14) (open triangle). The scale at right represents $\lambda^{\uparrow}_{Co}$ obtained by multiplication with a factor of 2 to take into account the angle dependence of the electron trajectories as discussed in the text.

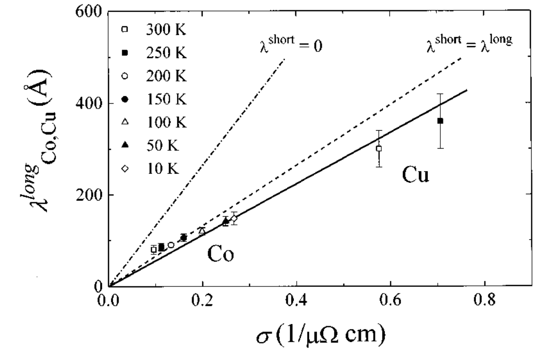


FIG. 9. The longest of the mean free paths for Co and Cu as a function of the conductivity $\sigma$, with the solid line representing a linear fit of the data points of both Co and Cu. The dashed and dashed-dotted lines are based on the Drude model; the dashed line represents maximal spin asymmetry ($\lambda^{short}=0$), whereas the dashed-dotted line represents the absence of bulk spin-dependent scattering ($\lambda^{short}=\lambda^{long}$).

$T^{\uparrow}_{Co/Cu}=1$, $T^{\downarrow}_{Co/Cu}=0$, the second (open triangles) with intermediate ($T^{\uparrow}_{Co/Cu}=1$, $T^{\downarrow}_{Co/Cu}=0.5$), and the third (solid squares) with no Co/Cu interface spin-dependent scattering. From Fig. 7(b) it is clear that in case of large interface spin-dependent scattering or bulk spin-dependent scattering $\xi$ is a perfect measure for $\lambda_{Cu}$.

## V. DISCUSSION

From the calculations with the CB model it followed that there exists a proportionality of approximately a factor of 2 between $\xi$ and $\lambda^{\uparrow}_{Co}$ or $\lambda_{Cu}$, provided that one of the current channels is sufficiently filtered due to a considerable spin-dependent scattering in the bulk of the ferromagnetic layer or at the interface. If this condition is not satisfied, the characteristic length $\xi$ also contains, at least partially, the shortest of the mean free paths. However, from several studies[17–19] it has become clear that there exists a large bulk and/or interface scattering asymmetry, especially in Co/Cu based systems. Therefore we feel confident that we may interpret $\xi$ as being uniquely related to the longest of the mean free paths as suggested in Ref. 13, although our data on Co and Cu do not contain straightforward quantitative evidence for sufficient spin-dependent filtering of the electrons. In Fig. 8 the longest of the Co mean free paths is estimated via $\lambda^{\uparrow}_{Co}=2\xi$ (open circles) and is shown to decrease with increasing temperature, in agreement with a lower conductivity due to increasing phonon scattering at higher temperatures. The figure is supplemented with data obtained by Parkin,[13] Dieny and co-workers,[2,8] and Gurney *et al.*[14] who have determined in a similar way a characteristic length from magnetoresistance measurements on related structures. We think that the observed discrepancies are a consequence of the growth conditions of the samples, which may have obviously a considerable impact on scattering lengths.

We will now concentrate on the role of bulk spin-dependent scattering which does not depend on the magnitude of the derived mean free paths but rather on the proportionality between $\lambda^{long}$ and the macroscopic conductivity, as argued by Parkin. The conductivity in the relaxation time approximation is proportional to the sum of $\lambda^{short}$ and $\lambda^{long}$, when we assume a free-electron-like conduction band for Co and Cu. This is well known for Cu, and although Co possesses a more complicated band structure, transport in Co is dominated by free-electron-like behavior as well.[20,21] We may expect that a large asymmetry in the bulk scattering lengths of Co ($\lambda^{short}\ll\lambda^{long}$) would be manifested in a different proportionality or slope when Co is compared to Cu ($\lambda^{short}=\lambda^{long}$). Figure 9 presents the measured $\lambda^{\uparrow}_{Co}$ and $\lambda_{Cu}$ ($\lambda^{long}_{Co,Cu}$) versus the macroscopic conductivity as determined (see Fig. 5) from the separate single layers. It is clear that the data for Co and Cu nearly coincide on one single line (solid line in Fig. 9) and from this we conclude that within our experimental accuracy, which is rather limited for Cu, we find no evidence for significant bulk spin-dependent scattering in Co for the covered temperature regime. We can substantiate this by the fact that the slope of the data is rather close to Drude's formula $\lambda=ne^2/\sigma m v_f$ (dashed line in Fig. 9), when $\lambda^{short}=\lambda^{long}$. We ascribe the deviations from this theoretical line to the use of electron density $n_{Cu}=8.45\times10^{22}$ cm$^{-3}$ and Fermi velocity $v_f=1.57\times10^8$ cm/s of bulk Cu, which may be different for thin films. We also have plotted in Fig. 9 Drude's equation in the limiting case of large bulk spin-dependent scattering $\lambda^{short}=0$ Å (dashed-dotted line in Fig. 9). Parkin[13] has found similar results from the study of Ru barriers in exchange biased spin-valves. He observed that the proportionality constant between $\lambda^{long}$ and the conductivity in nonmagnetic alloys like $Cu_{80}Au_{20}$ and $Cu_{10}Au_{90}$ is essentially the same as that found in the structures with ferromagnetic Co and alloys such as $Ni_{81}Fe_{19}$ and $Ni_{12}Co_{88}$, which leads to the conclusion that for all of these materials $\lambda^{short}\approx\lambda^{long}$, although this refers to room temperature only. The absence of a considerable bulk spin-dependent scattering is in striking contrast with Gurney *et al.*[14] who reported a $\lambda^{\downarrow}_{Co}\leqslant6$ Å from analysis of $\Delta G$ as a function of $d_{Co}$ in backed spin-valves of the basic composition Co($d_{Co}$ Å)/NiFe(20 Å)/Cu(23 Å)/NiFe(50 Å)/FeMn(80 Å). However, meaningful and quantitative comparison with these results is difficult, because in their analysis the impact of averaging over all electron angles was not recognized, which leads to a too crude simplification $\Delta G\propto1-\exp(-t/\lambda^{long})$.

Although the CB model is only applicable to low temperatures, the proposed analysis of our data at higher temperatures and the room-temperature data in Ref. 13 may still be valid provided that the additional scattering processes do not mix up the spin-up and spin-down current channels. The Boltzmann equation should then be supplemented with a term containing a spin-mixing relaxation time $\tau_{\uparrow\downarrow}$, which complicates a straightforward interpretation of $\xi$ as a measure for $\lambda^{\rm long}$. However, in Co/Cu no evidence was found for substantial spin-flip scattering,[19,22] and therefore the determination of $\lambda_{\rm Co}^{\uparrow}$ and $\lambda_{\rm Cu}$ via the analysis presented in the foregoing paragraphs can be safely extended to higher temperatures. For other ferromagnetic materials the role of spin-flip scattering should be separately considered in view of the analysis of the mean free paths.

At this point we focus again on the proportionality factor 2 between $\xi$ and $\lambda_{\rm Co,Cu}^{\rm long}$. As argued before, the magnitude of $\lambda^{\rm long}$ is not crucial in the comparison of the longest of the mean free paths in Co and Cu with bulk conductivities, provided that the proportionality factor is the same for both the Co/Cu/Co and the Co/Cu/Co/Cu structures. We have seen in Fig. 7 that deviations from $\xi=2\lambda^{\rm long}$ occur when electrons are not completely filtered at the interface of the Co layers. However, this would result in an overestimation of the longest of the Co mean free paths and an underestimation of the Cu mean free paths, and consequently our result of $\lambda^{\rm short}\approx\lambda^{\rm long}$ (within experimental accuracy) represents an upper limit for the bulk scattering asymmetry. Also the determination of $\lambda^{\rm short}+\lambda^{\rm long}$ via the bulk conductivity may be subject to errors in the interpretation. In order to exclude boundary effects, we have determined the bulk conductivity of Co and Cu from single *thick* layers of Co and Cu. An extrapolation of this bulk conductivity to thin layer conductivity is not correct if layer quality or grain sizes[23] change drastically with layer thicknesses. However, in Fig. 5 we see that the conductivity scales linearly with thickness, at least for large thicknesses where boundary effects play no role, which demonstrates a constant layer quality although we did not check this separately, for instance by visualization of the grains.

## VI. CONCLUSIONS

In conclusion, we have investigated the giant magnetoresistance behavior of uncoupled Co/Cu/Co and Co/Cu/Co/Cu spin-valves with shifting Ru barrier through the top Co and Cu layer, respectively. With the help of the semiclassical model of Camley and Barnas we showed that the exponential behavior of the differential conductivity $\Delta G$ as a function of the Ru barrier layer is uniquely related to the longest of the mean free paths in Co and Cu, provided there exists significant filtering of spin-down electrons in the bulk or at the interface of Co.

Under this assumption we have determined the longest of the mean free paths in Co and Cu at various temperatures. Comparison of $\lambda^{\rm long}$ with bulk conductivities obtained from separately grown films of Co and Cu, yields no evidence for significant bulk spin-dependent scattering in the ferromagnetic Co layer.

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