Giant magnetoresistance of magnetically soft sandwiches: Dependence on temperature and on layer thicknesses

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We present comprehensive results on the magnetoresistive properties of spin-valve sandwiches comprising glass/$M(1)$/Cu/$Ni_{80}Fe_{20}$/$Fe_{50}Mn_{50}$/Cu, where $M(1)$ is a ferromagnetic transition metal or alloy (Co,Ni,$Ni_{80}Fe_{20}$). We discuss the thermal variation of the magnetoresistance ($\Delta R/R$) and its dependence on the thicknesses of the layers constituting the active part of the spin-value sandwich [i.e., $M(1)$/Cu/NiFe]. An almost linear decrease of $\Delta R/R$ is observed between 77 and 320 K. For a given ferromagnetic material, $\Delta R/R$ extrapolates to zero at a temperature T_{0SV} significantly lower than the Curie temperature, and independent of the ferromagnetic layer thickness. We have identified spin-↑ and spin-↓ intermixing by spin-wave scattering as responsible for the thermal decrease of the magnetoresistance. We show that the magnetoresistance arises within the "active" parts of the ferromagnetic layers of thickness of about 90 Å located next to the M/Cu interfaces. We give a phenomenological expression relating $\Delta R/R$ to the longer of the two spin-dependent mean free paths, and to current shunting in the inactive part of the sandwich. The thickness of the active region is independent of temperature.

INTRODUCTION

In the past three years, very large values of magnetoresistance (MR) have been observed in an increasing number of multilayered structures and sandwiches: Fe/Cr,[1-6] Co/Ru,[3] NiFe/Cu,[7-9] Ni/Cu,[7-9] Fe/Ag,[8] Co/Ag/Fe,[8] Co/Cu,[9-11] Co/Au,[2,12] NiFe/Cu/Co/Cu.[13] This effect occurs when the relative orientation of the magnetizations of adjacent ferromagnetic layers is varied from parallel to antiparallel using either an intrinsic antiferromagnetic coupling through the nonferromagnetic spacer (as in Fe/Cr or Co/Ru) or an asymmetric pinning of the magnetizations.[2,7-9,12,13] Several models have been put forth to explain this MR, all based on the existence of spin-dependent scattering at the interfaces or in the bulk of the ferromagnetic layers.[14-16] Considerable activity has been devoted to the discovery of additional giant MR systems, but only a few quantitative studies have been carried out of the MR dependence on the thickness of the magnetic and nonmagnetic layers or on temperature.[9,17,18] However, from the thickness variation of the MR, one gains access to the various mean free paths and can thereby assess the relative importance of interfacial versus bulk scattering. From such studies one can also determine the role of the nonmagnetic spacer layer, in particular whether it merely decouples the ferromagnetic layers while allowing good transmission of conduction electrons between the ferromagnetic layers, or whether it also gives rise to some additional electronic effects induced, for instance, by a change in the density of states.[19] The thermal variation of the MR can bring valuable insight into the role of the various electron scattering mechanisms within each layer (phonons, impurities, structural defects, spin waves, spin-orbit interactions, etc.)

In a previous paper[20] we have discussed the thermal variation of the MR in spin-valve structures comprising glass/$M(1)/N/M(2)$/antiferromagnet/N, where $M(1)$ and $M(2)$ are ferromagnetic transition metals (Co, Ni, $Ni_{80}Fe_{20}$), the magnetization of $M(2)$ is constrained by exchange coupling to an antiferromagnet (e.g., NiFe/$Fe_{50}Mn_{50}$), and N is a noble metal (Cu or Au). We summarize here the main results of that study. An almost linear decrease of $\Delta R/R$ is observed between 77 and 320 K (see also Ref. 18). $\Delta R/R$ extrapolates to zero at a temperature T_{0SV} characteristic of the ferromagnets comprising the spin-valve sandwich but independent of the nature and thickness of the noble metal. These characteristic temperatures T_{0SV} are significantly lower than the Curie temperatures (T_c) of the ferromagnetic materials but roughly scale with them: the higher T_c, the higher T_{0SV}. When the thickness of the N spacer layer is varied, $\Delta R/R$ decreases nearly exponentially, demonstrating that the role of the spacer layer is simply to decouple $M(1)$ and $M(2)$. The large mean free paths observed[9] for Cu, Au, and Ag imply adequate spin-conserving transmission of conduction electrons between $M(1)$ and $M(2)$. For both Cu and Au, the characteristic diffusion length was found to be nearly independent of temperature (47 Å for Cu, 36 Å for Au), showing that up to room temperature, phonon scattering in the N interlayer is of little importance. This indicates that the main source of the thermal decrease of $\Delta R/R$ lies within the ferromagnetic layers themselves. Spin-intermixing due to magnon scattering and in some cases spin-flip scattering from paramagnetic layers which form at the M/N interfaces have been suggested as being responsible for this thermal decrease.

In the present study we report the thermal variation of the MR of several series of samples with structure: glass/$M(1)$/Cu/$Ni_{80}Fe_{20}$/$Fe_{50}Mn_{50}$/Cu, where $M(1)$ is Co, Ni, $Ni_{80}Fe_{20}$. The MR was measured between 77 and

320 K. Details of sample preparation and measurement were given elsewhere.[7] In an earlier study,[9] we have shown that at room temperature $\Delta R/R$ exhibits a broad maximum at around 90 Å as the thickness of $M(1)$ is varied, in contrast to Fe/Cr multilayers where a much sharper peak is observed at about 10 Å.[6] This suggests that in the present sandwich structures the mechanism at the origin of the MR occurs in the bulk of the ferromagnetic layers. In this paper, we show that as $\Delta R/R$ increases with decreasing temperature, the shapes of the curves of $\Delta R/R$ versus ferromagnetic layer thickness ($t_{M(1)}$) are nearly independent of temperature. We propose a simple model to describe the dependence of the MR on $t_{M(1)}$ which takes into account bulk spin-dependent scattering as well as shunting.

TEMPERATURE DEPENDENCE OF RESISTIVITY

We discuss first the thermal variation of the sheet resistance in the configuration of parallel alignment of the magnetizations of $M(1)$ and $M(2)$. Figure 1 shows the results for a series of samples with the structure glass/Co(t Å)/Cu(22 Å)/NiFe(50 Å)/FeMn(80 Å)/Cu(15 Å). As is typical for metals, the resistance increases with temperature because of phonon and/or magnon scattering. Interestingly, the relative change of the resistance between 77 and 320 K increases with the thickness of the Co layer (i.e., with the ratio of thickness of the magnetic versus the nonmagnetic materials). The ratio $[R(320\text{ K})-R(77\text{ K})]/R(77\text{ K})$ varies from 70% for $t_{Co}=435$ Å to 28% for $t_{Co}=35$ Å. We already know[20] from the variation of $\Delta R/R$ with the thickness of the N spacer that the scattering in Cu or Au is almost independent of temperature up to 270 K. Hence the main source of the thermal rise of the resistance is magnon scattering occurring in the ferromagnetic layers. The slight curvature observed in these thermal variations can be characterized by exponents ranging between 1 and 1.5, consistent with a contribution from incoherent magnon scattering (usually leading to a $T^{3/2}$ dependence) together with temperature-independent scattering processes such as those arising from defects. Moreover, in thin films, significant interfacial scattering effects are known to occur when the mean free path of the conduction electrons becomes of the order of the layer thickness. Since the mean free path in the Co layer varies with temperature, the relative contribution of interfacial scattering to the overall resistance will also vary with temperature.

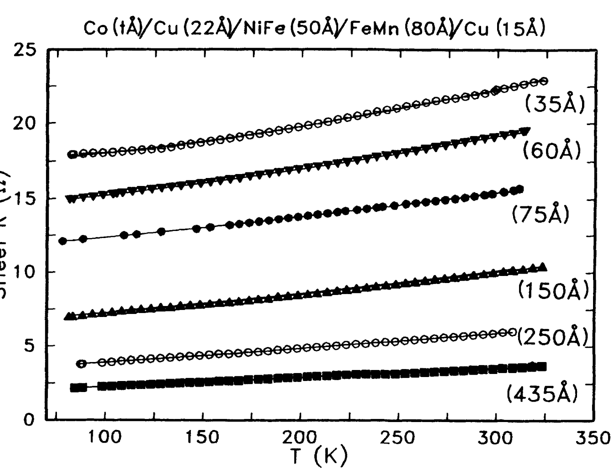

FIG. 1. Thermal variation of the sheet resistance when the magnetizations are parallel for samples of structures glass/Co (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å). Co thicknesses are shown on the right.

Data for sheet conductance versus $t_{M(1)}$ for $M(1)$=Co, NiFe, and Ni at various temperatures are shown in Figs. 2–4, respectively. To a first approximation, the various layers comprising the spin-value sandwich can be assumed to carry the current in parallel. In this approximation the sheet conductance versus the thickness of $M(1)$ is

$$G(t_{M(1)})=t_{M(1)}/\rho_{M(1)}+G_{\text{rest}} , \tag{1}$$

where $\rho_{M(1)}$ is the resistivity of $M(1)$ and G_{rest} is the conductance of the rest of the structure (i.e., Cu/NiFe/FeMn/Cu). In Figs. 2–4, we believe that deviations from the expected straight lines mostly reflect interfacial scattering, since the largest deviations from linear behavior occur at the lowest temperatures, for which the mean free paths in $M(1)$ are largest. From the slope of the sheet conductance versus ferromagnetic layer thickness in the large thickness regime, we derive the thermal variation of the resistivity of the various ferromagnetic transition metals. The results are plotted in Fig. 5. For comparison we have included the resistivity for Cu and Au obtained in a previous study[20] using the same method. A striking result is the difference in the amplitude of the thermal variation of the resistivity between magnetic and nonmagnetic materials ($\Delta\rho/\rho=10\%$ for Cu compared to 75% for NiFe between 77 and 320 K). This result demonstrates the dominant role of magnon versus phonon scattering in the ferromagnetic layers of spin-value structures.

In Fe/Cr multilayers,[17] a correlation was observed be-

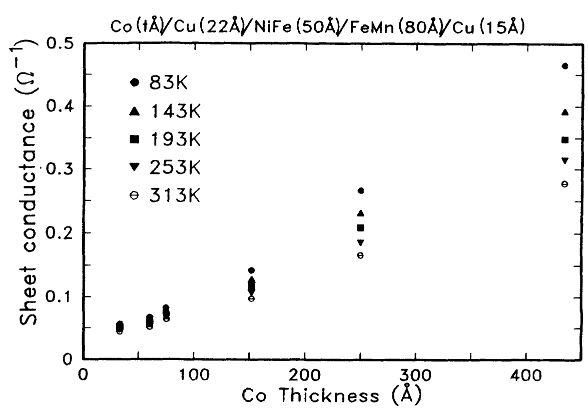

FIG. 2. Variation of the sheet conductance versus Co thickness for samples of structure glass/Co (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å) at different temperatures.

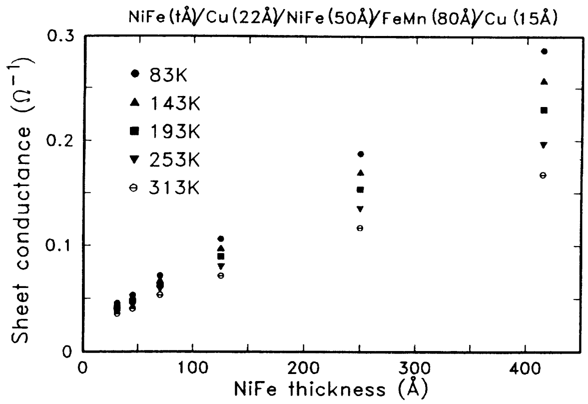

FIG. 3. Variation of the sheet conductance versus NiFe thickness for samples of structure glass/NiFe (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å) at different temperatures.

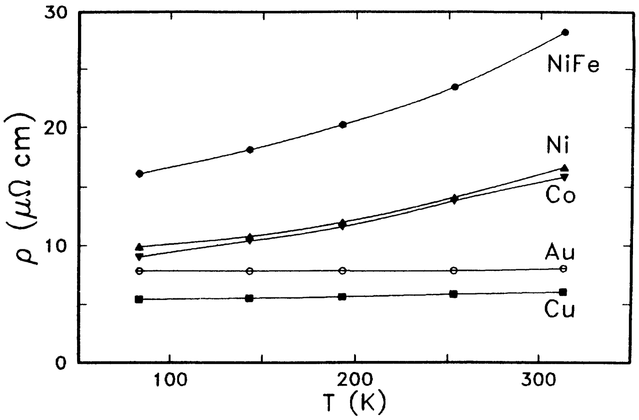

FIG. 5. Resistivity versus temperature for the materials used in our spin-valve structures.

tween the amplitude of the thermal variation of the sheet resistance and the amplitude of $\Delta R/R$ itself measured at low temperature. This correlation was attributed to the similarity between the effect of the spin intermixing created by magnon scattering as the temperature is increased and the spin intermixing that electrons experience as they traverse the Cr layer without scattering, from one Fe layer to the next with antiparallel magnetizations. In the present spin-valve structures, such a correlation does not seem to occur. The thermal variation of spin-valve sheet resistance is mainly governed by the temperature dependence of the resistivity of the various layers (especially that of the magnetic layers). For spin valves, as we show below, the amplitude of the MR is rather determined by the thicknesses of the magnetic and nonmagnetic layers, by the transmission across the interfaces and by the spin-dependent mean free paths.

TEMPERATURE DEPENDENCE OF MAGNETORESISTANCE

Figures 6–8 show the thermal variation of $\Delta R/R$ for $M(1)$=Co, NiFe, and Ni, respectively. The full lines are parabolic fits of the data. We discuss first Co and NiFe, for which two main results are apparent. First, for a given ferromagnetic material, fits to the nearly linear thermal variation extrapolate to zero $\Delta R/R$ at the same temperature T_{0SV}, independent of the thickness of the ferromagnetic material. Second, this characteristic temperature T_{0SV} depends only on the nature of the two ferromagnetic materials comprising the spin-valve sandwich, and not on the nature of the nonmagnetic spacer[20] or on the thicknesses of the various layers. When the two ferromagnetic layers comprising the spin-value sandwich have different Curie temperatures, T_c, we expect that the lower T_c determines the value of T_{0SV}. For bulk Co $T_c = 1400$ K, for NiFe $T_c = 800$ K, while for Ni $T_c = 630$ K. Thus for both Co/Cu/NiFe and NiFe/Cu/NiFe, $T_{0SV} \simeq 515$ K, respectively, while for thick Ni in Ni/Cu/NiFe, $T_{0SV} \simeq 435$ K.

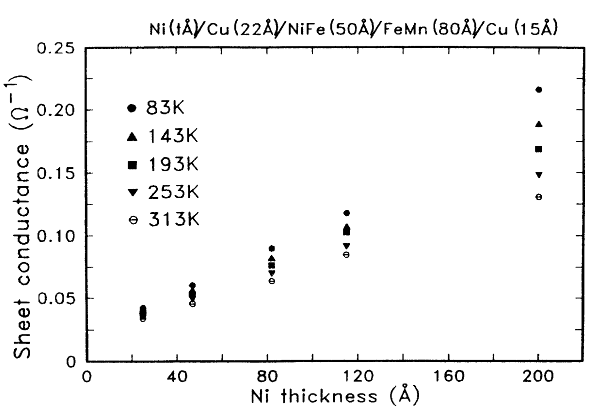

FIG. 4. Variation of the sheet conductance versus Ni thickness for samples of structure glass/Ni (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å) at different temperatures.

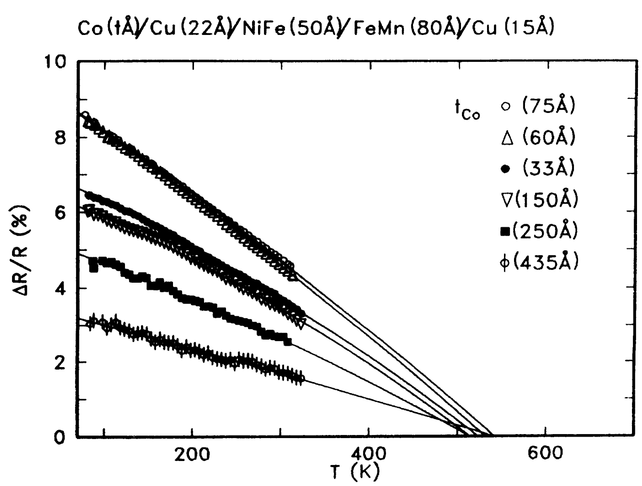

FIG. 6. Thermal variation of the magnetoresistance of samples with the structure glass/Co (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å) (as in Fig. 2). The lines are second-order polynomial fits.

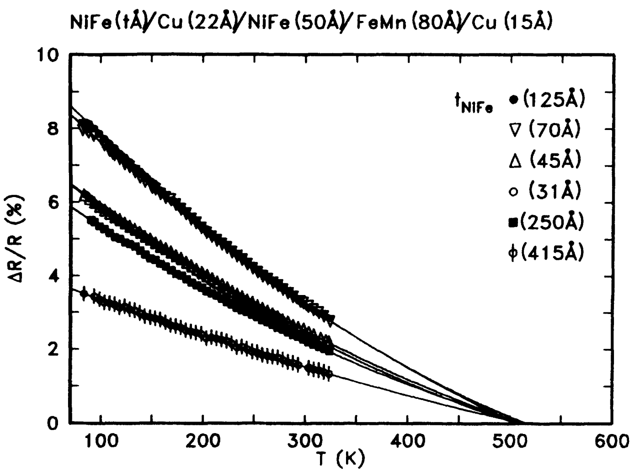

FIG. 7. Thermal variation of the magnetoresistance of samples with the structure glass/NiFe (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å) (as in Fig. 3). The lines are second-order polynomial fits.

In the case of Ni (Fig. 8), while the parabolic fits converge to the same T_{0SV} for most Ni thicknesses, a significant deviation arises when the Ni layer is very thin ($t_{Ni}=25$ Å). We ascribe this peculiar behavior to the magnetic properties of the $Ni_{(1-x)}Cu_x$ solid solution which seems to form along the Ni/Cu interface during the growth process. We have previously reported[9] that the equivalent of 15 Å of Ni is missing in the total moment of the Ni layer at room temperature. In contrast to Ni, for Co and NiFe the sum of the thicknesses of the nonmagnetic interfacial regions is only approximately 3 Å at room temperature.[9] We have attributed the reduction of the magnetic moment in our Ni films to the interdiffusion between Ni and Cu leading to the formation of paramagnetic layers at the interface. A continuous gradient of Cu concentration may exist in this area of intermixing. From the magnetic phase diagram of $Ni_{(1-x)}Cu_x$ solid solutions,[22] we expect a gradient of Curie temperature related to this concentration gradient. Thus in the Ni-based spin-valve structures a paramagnetic region forms at the Ni/Cu interface, whose width decreases with decreasing temperature. In such paramagnetic layers, we expect significant spin-flip scattering to occur. Consequently, the MR will be reduced since the polarization of electrons moving from one ferromagnetic layer to the next will be reduced. Since the magnetic properties of the NiCu alloy are temperature dependent between 77 and 320 K, the contributions from the NiCu alloy interface should vary with temperature. In particular, the influence of the alloy should be greatest for thin Ni layers. Therefore the reduction of T_{0SV} for 25-Å Ni layer thickness may be due to this interfacial spin-flip scattering. In addition, it is probable that the Curie temperature of the magnetic portion (10 Å thick) of the thinnest Ni sample is reduced, which should also lead to a lower T_{0SV}.

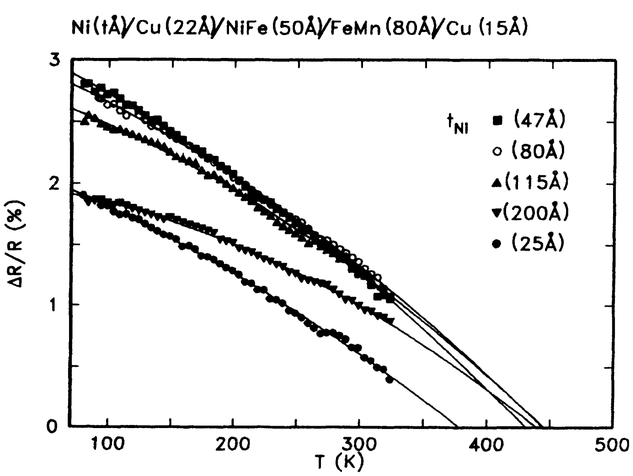

FIG. 8. Thermal variation of the magnetoresistance of samples with the structure glass/Ni (t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å) (as in Fig. 4). The lines are second-order polynomial fits.

PHENOMENOLOGY OF SPIN-VALVE MAGNETORESISTANCE

In the following we describe our results on the MR of spin-valve structures in terms of the variation versus the thickness of the nominally "free" ferromagnetic layer $M(1)$ at different temperatures. Figure 9 shows the variation of MR versus $t_{M(1)}$ at room temperature for the same samples as discussed above: $M(1)$(t Å)/Cu 22 Å/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å), with $M(1)$=Co, NiFe, or Ni. These measurements have been published previously;[9] we now describe a model used to obtain the fits. The observed variations with $M(1)$ have very similar shapes characterized by a broad maximum between 60 and 110 Å. This shape is different from that previously observed in Fe/Cr multilayers for which $\Delta R/R$ decreases monotonically for Fe layer thicknesses above 10 Å,[23] which was interpreted as demonstrating the dominant role of interfacial scattering in Fe/Cr.[1,2,4,6] Here the increase of MR up to a $M(1)$ layer thickness of about 60 Å and the broad maximum thereafter show that in the present structures the MR arises within an "active" part of the ferromagnetic layer, about 90 Å thick, located next to the Cu/M interface. The decrease of MR at larger thicknesses can be atrributed to increased shunting with increasing $M(1)$ layer thickness.

Figure 10 shows a schematic representation of a spin-valve structure. We chose for convenience to divide the ferromagnetic layer whose thickness is varied [$M(1)$], into an "active" and an "inactive" region. By "active" region we mean the part of the ferromagnetic layer which gives the main contribution to the MR. At 0 K the thickness of this "active" part, t_0, is linearly related to the longer of the two spin-dependent mean free paths, λ^+ and λ^-, corresponding to electrons with their spin parallel and antiparallel, respectively, to the magnetization of the ferromagnetic layer.[24] In addition, since t_0 corresponds to the angular average of the longer mean free

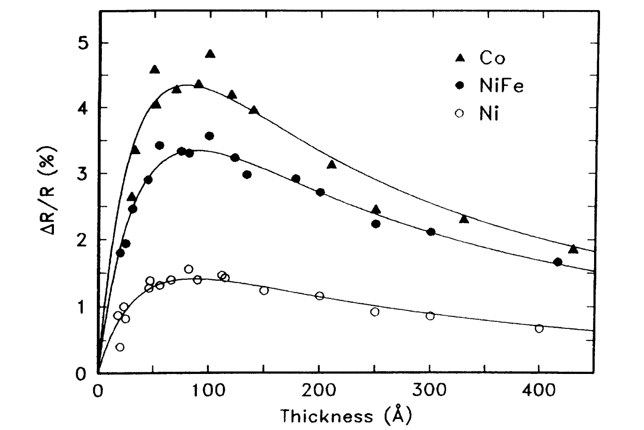

FIG. 9. Variation of the magnetoresistance versus the thickness of the "free" ferromagnetic layer $M(1)$, with $M(1)$=Co, NiFe, or Ni, at room temperature. The lines are two-parameter fits according to Eq. (7).

path in $M(1)$, it is expected to vary with the resistivity of the pinned layer $M(2)$.

We will assume in the following that λ^+ is the longer of the two mean free paths, as shown for $Ni_{80}Fe_{20}$ (Ref. 25) for which λ^+/λ^- is about 20. With the notation of Fig. 10 we can describe the "inactive" part of $M(1)$ as a resistance (R_1) which is independent of the orientation of the magnetizations, connected in parallel to the resistance (R_0) of the "active" part of the spin-valve structure. Neglecting for the moment the contribution of the rest of the structure (Cu/NiFe/FeMn/Cu), the measured MR is given by

$$\left[\frac{\Delta R}{R}\right]_{\text{measured}}=\frac{R_{\uparrow\downarrow}-R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}\ , \tag{2}$$

where

$$R_{\uparrow\uparrow}=\frac{R_0R_1}{R_0+R_1} \tag{3}$$

and

$$R_{\uparrow\downarrow}=\frac{(R_0+\Delta R_0)R_1}{R_0+R_1+\Delta R_0}\ . \tag{4}$$

Therefore

$$\left[\frac{\Delta R}{R}\right]_{\text{measured}}=\left[\frac{\Delta R_0}{R_0}\right]\frac{1}{1+R_0/R_1}\ . \tag{5}$$

We introduce now G_{rest}, the sheet conductance of the rest of the structure [namely, Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å)] which is obtained from Figs. 2–4 by extrapolating the sheet conductance to $t_{M(1)}=0$. Taking into account the experimental observation (Figs 2–4) that the conductance of the structure increases almost linearly with the thickness of the $M(1)$ layer (i.e., $G\simeq G_{\text{rest}}+t_{M(1)}/\rho_{M(1)}$), we obtain

$$\left[\frac{\Delta R}{R}\right]_{\text{measured}}\simeq\left[\frac{\Delta R_0}{R_0}\right]\frac{G_{\text{rest}}+t_0/\rho_{M(1)}}{G_{\text{rest}}+\dfrac{t_{M(1)}}{\rho_{M(1)}}}\ . \tag{6}$$

Thus for $t_{M(1)}>t_0$, a hyperbolic decrease of the MR is expected due to the shunting of the current in the "inactive" part of $M(1)$. Below the characteristic thickness t_0 we attribute the decrease of the MR to two effects. First, the ferromagnetic layer is now so thin that the incoming electrons with the longer mean free path λ^+ have a reasonable probability of scattering not within this layer but rather on the substrate or in the FeMn layer. Consequently the scattering loses some of its spin-dependent character leading to a reduction of ΔR. Second, some of the outgoing electrons with the longer mean free path which would have been available from a thick $M(1)$ layer are no longer present. Both phenomena can be described quantitatively, assuming that a continuous flow of electrons goes in or out of $M(1)$. For $\lambda^+ \gg \lambda^-$, most of this flow consists of spin-↑ electrons, so that the contribution

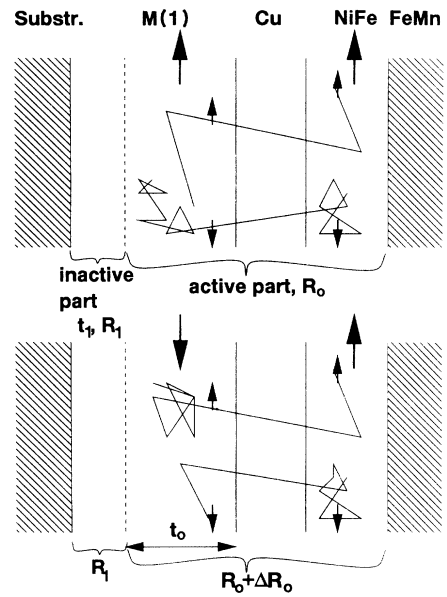

FIG. 10. Schematic representation of the spin-valve structure. Here the basic mechanism of giant MR (Ref. 1) is extended to spin-valves. The two species of electrons (spin ↑ and spin ↓) have different mean free paths due to the spin-dependent character of the scatttering in the ferromagnetic transition-metals. For parallel alignment of the magnetizations [part (a)], the spin ↑ electrons have a long mean free path everywhere in the structure. The short circuit caused by the spin ↑ electrons leads to a state of low resistance. For antiparallel alignment of the magnetizations [part (b)], both species are strongly scattered in either one or the other ferromagnetic layer. The short circuit no longer exists, leading to a state of higher resistance. The quantity t_0 is the thickness of the active part of the ferromagnetic layer, in the sense that this portion of the layer contributes most to the magnetoresistance. The quantities t_1 and R_1 are, respectively, the thickness and the sheet resistance of the inactive part of the ferromagnetic layer. The inactive part contributes to the resistance but very little to the *magneto*resistance. The sheet resistances R_0 and $(R_0+\Delta R_0)$ include only the active part of the spin-valve structure, and correspond to parallel and antiparallel alignments, respectively.

TABLE I. Characteristic MR parameter A and "active" layer thickness t_0 for three series of samples of structure glass/$M(1)$(t Å)/Cu (22 Å)/NiFe (50 Å)/FeMn (80 Å)/Cu (15 Å), with $M(1)$=Co, NiFe, or Ni. The third row lists the values of $G_{rest}\rho_{M(1)}$ corresponding to the shunting by the rest of the structure.

Ferromagnet	A (%)	t_0(Å)	$G_{rest}\rho_{M(1)}$(Å)
Co	14.5	72	65
$Ni_{80}Fe_{20}$	9.6	72	85
Ni	5.1	85	65

of spin-↓ electrons can be neglected. A part of this flow, $d\phi=-\phi\,dx/t_0$, experiences a scattering event within a thin layer dx during its propagation inside $M(1)$. Then, for a thickness $t_{M(1)}$, the probability for a spin-↑ electron to be scattered is $[1-\exp(-t_{M(1)}/t_0)]$.

Putting together these two contributions, one from the shunting effect, the other from the bulk scattering of spin-↑ electrons, we fitted the curves of Fig. 9 according to

$$\frac{\Delta R}{R}(t_{M(1)})=A\frac{[1-\exp(-t_{M(1)}/t_0)]}{[1+(t_{M(1)}/G_{rest}\rho_{M(1)})]} \quad (7)$$

with two adjustable parameters: A and t_0. The quantity A is characteristic of the materials involved in the essential part of the spin-valve sandwich [i.e., $M(1)$, N, and $M(2)$], since little current is carried by the FeMn layer and the oxidized Cu capping layer. According to our previous study,[20] this parameter A can be expressed approximately as $A_0\exp(-t_N/\lambda_N)$ with A_0 independent of the thickness t_N of the N spacer. The other parameter t_0 is the thickness of the "active" part of $M(1)$, i.e., the part which gives rise to the MR. The quantities G_{rest} and $\rho_{M(1)}$ are derived from the measurement of the sheet conductance (Figs. 2–4 and Fig. 5 of Ref. 9). The parameters derived from the fits of Fig. 9 are listed in Table I. The coefficient A is highest for Co, consistent with the large MR amplitude observed in Co/Cu/Co sandwiches[9] or multilayers.[10,11] The values of the thickness of the "active" part of the ferromagnetic layer are nearly the same for these three materials (abut 75 Å), suggesting nearly the same value for the longer mean free paths in Co, NiFe, and Ni.

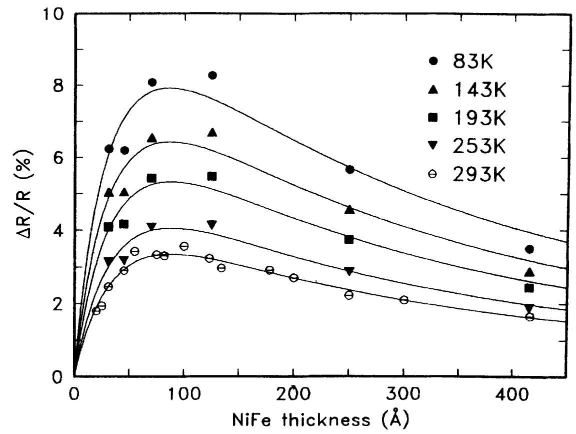

FIG. 12. Variation of the magnetoresistance versus the thickness of the NiFe layer at different temperatures for the same samples as in Figs. 3 and 7. The lines are two-parameter fits according to Eq. (7).

TEMPERATURE DEPENDENCE OF SPIN-VALVE CHARACTERISTIC PARAMETERS

In Figs. 11–13, the same data as in Figs. 6–8 are plotted versus the thickness of the ferromagnetic layer for several temperatures. The solid lines are two-parameter fits according to Eq. (7) already used at room temperature. The values of $G_{rest}\rho_{M(1)}$ for the various tempera-

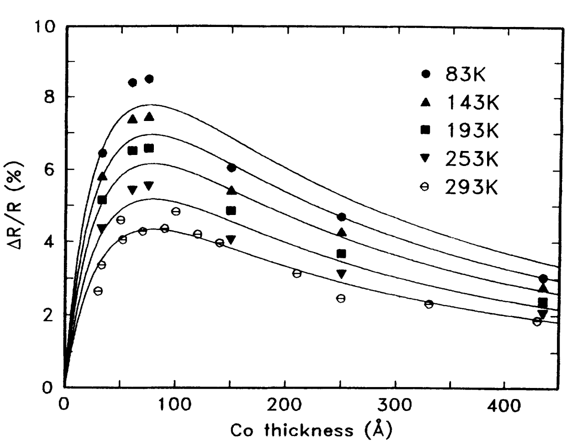

FIG. 11. Variation of the magnetoresistance versus the thickness of the Co layer at different temperatures for the same samples as in Figs. 2 and 6. The lines are two-parameter fits according to Eq. (7).

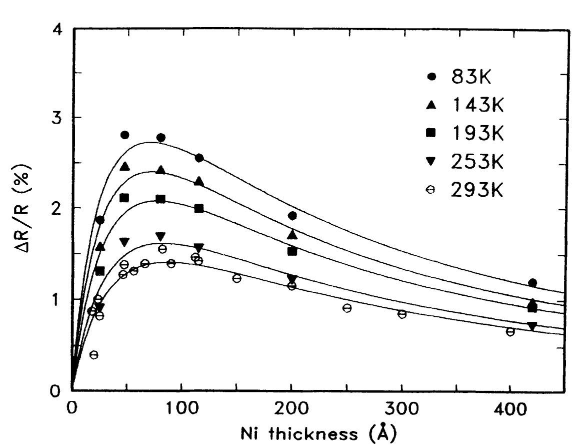

FIG. 13. Variation of the magnetoresistance versus the thickness of the Ni layer at different temperatures for the same samples as in Fig. 4 and 8. The lines are two-parameter fits according to Eq. (7).

tures were derived from Figs. 2–4. For Co and NiFe the shape of these curves does not change significantly with temperature, i.e., the curves are homologous to each other. This is related to the previous observation that the decrease of the MR versus temperature is quasilinear and extrapolates to zero at the same temperature independent of the thickness of $M(1)$. For Ni, the location of the maximum slightly shifts toward smaller thicknesses at low temperature.

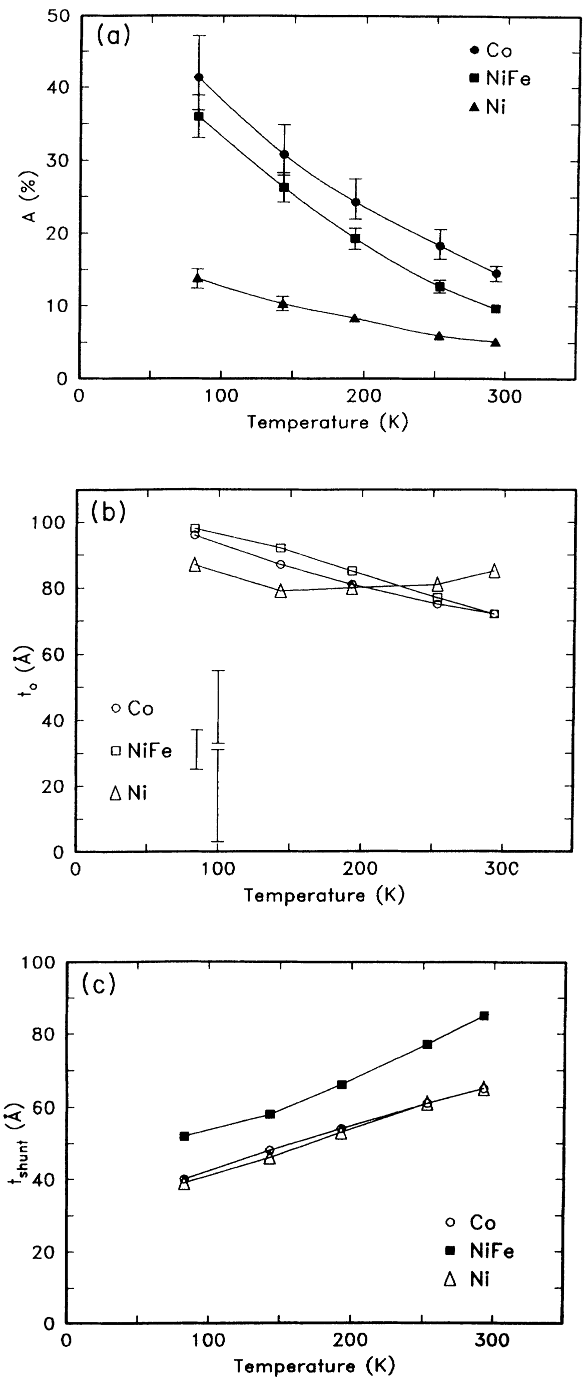

FIG. 14. Thermal variation (a) of the characteristic MR parameter A, (b) of the "active" layer thickness t_0, and (c) of the thickness $t_{\text{shunt}} = G_{\text{rest}}\rho_{M(1)}$ related to the shunting by the rest of the structure (Cu/NiFe/FeMn/Cu). The values in (a) and (b) are derived from the fits of Figs. 11–13. Indicated error bars correspond to a 67% confidence limits. Where not indicated in (a) and (c), error bars are smaller than symbols.

The characteristic MR parameter A and the thickness t_0 which are deduced from the fits are plotted in Fig. 14, together with the thickness $t_{\text{shunt}} = G_{\text{rest}}\rho_{M(1)}$ characterizing the shunting of the current in the rest of the structure.

The value of A decreases with temperature but not as linearly as for the MR itself. Actually the shape of the decrease versus temperature for the three ferromagnetic materials is similar to the thermal variation of the MR of the Fe/Cr multilayer reported in Ref. 17. We believe that the main source of the decrease of the A parameter is magnon scattering which leads to intermixing of spin-↑ and spin-↓ electrons.

The thickness of the "active" part of the layer decreases slowly with increasing temperature, at least for Co and NiFe. This small change can be ascribed to a decrease of the longer mean free path with temperature, induced by phonon and magnon scattering. In the case of Ni, although interpretation might be limited by the large error bars, we believe that the peculiar behavior of the variation of t_0 between 150 and 320 K is related to the paramagnetic interfacial alloy region already discussed. The longer mean free path for Ni probably decreases with temperature as for Co or NiFe but, because of the presence of the paramagnetic region, the "active" layer thickness t_0 would be the sum of the thickness of the paramagnetic region ($t_{\text{para}} \simeq 15$ Å at RT[9]) and of the "active" part of $M(1)$ itself.

SUMMARY

We have presented comprehensive results obtained on spin-valve sandwiches involving Co, NiFe, Ni ferromagnetic layers separated by a Cu spacer layer. The variations of the MR versus the thickness of the ferromagnetic layer and temperature were measured. The MR decreases with increasing temperature mainly because of spin-↑ and spin-↓ intermixing due to magnon scattering. Extrapolation to zero MR leads to a temperature $T_{0\text{SV}}$ characteristic of the ferromagnetic materials comprising the spin-valve sandwich. The higher the Curie temperature, the higher $T_{0\text{SV}}$. We interpreted the dependence of the MR on the thickness of the ferromagnetic layer with a simple model involving bulk spin-dependent scattering and shunting. The MR arises mostly within the "active" part of the ferromagnetic layer next to the Cu spacer layer. The thickness of this "active" region, which at low temperature is linearly related to the longer of the two mean free paths, is about 75 Å and decreases slightly with temperature.

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