Magnetic and transport properties of NiFe/Ag and Co/NiFe/Co/Ag multilayers

C. Cowache, B. Dieny, A. Chamberod, D. Benizri, F. Berthet, S. Auffret, L. Giacomoni, and S. Nossov*
CEA, Département de Recherche Fondamentale sur la Matière Condensée, 38054 Grenoble Cedex 9, France
(Received 26 December 1995)

We present a comprehensive study of the structural, magnetic, and transport properties of NiFe/Ag multilayers grown by magnetron sputtering onto substrates maintained at liquid-nitrogen temperature. The influence of the Ag thickness (t_{Ag}), NiFe thickness (t_{NiFe}), and number of bilayers (n) has been studied. These multilayers exhibit antiferromagnetic and biquadratic coupling for 9 Å$<t_{Ag}<$12.5 Å. For a given Ag thickness in this interval, the saturation field is inversely proportional to t_{NiFe}. Furthermore, giant magnetoresistance (GMR) is observed with a maximum amplitude for $t_{NiFe}\approx 25$ Å. However, the maximum GMR sensitivity $\Delta R/R/H$ is obtained at larger NiFe thicknesses. The dependence of the resistivity and magnetoresistance on the thickness of the NiFe layers has been analyzed within the Camley and Barnas semiclassical theory. The effect of adding thin layers of Co at the NiFe/Ag interfaces has also been investigated. A doubling of the GMR amplitude at room temperature and a significant increase in the saturation field are observed with the introduction of only one atomic plane of Co at each NiFe/Ag interface. A quantitative analysis of the data shows that the increase of the GMR is due to a better transmission of the spin-up electrons through the NiFe/Co/Ag interface than through the NiFe/Ag interface. The results are interpreted in terms of a reinforcement of the magnetic ordering at the NiFe/Co/Ag interfaces, and correlatively a reduction of the interfacial magnetic scattering caused by the presence of the Co layer. [S0163-1829(96)06022-5]

The giant magnetoresistance (GMR) first discovered in (Fe/Cr) multilayers,[1] and later observed in a large number of transition-metal-based multilayers or sandwiches,[2,3] has been the object of numerous experimental and theoretical studies stimulated by both fundamental and applied interests. Among the various systems investigated, (NiFe/Ag) multilayers appear to be good candidates for applications in magnetoresistive sensors since they have good sensitivity ($\Delta R/R/H\approx 0.1$ to 0.2%/Oe in a field range of 0–50 Oe) and, above all, good thermal stability.[4,5] Upon annealing up to 250 °C for 10 min, the GMR amplitude increases, while the saturation field decreases leading to an increase in the field sensitivity of the material.[4] In order to complete the data presented in Refs. 4 and 5, we have carried out a more systematic study of the structural, magnetic, and transport properties of (NiFe/Ag) multilayers grown by magnetron sputtering onto substrates maintained at liquid-nitrogen temperature. The preparation technique and structural characterization of the sample are described in the first part of this paper. Section II describes the influence of the Ag thickness (t_{Ag}) on the coupling between NiFe layers through the nonmagnetic spacer and on the GMR. In Sec. III, we discuss the influence of the NiFe thickness (t_{NiFe}) and number of bilayers (n) on the saturation field, GMR amplitude, and GMR sensitivity. The dependence of the resistivity and magnetoresistance on the thickness of the NiFe layers has been analyzed within the framework of the semiclassical theory of Camley and Barnas. This analysis is presented in Sec. IV.

The effect of adding thin layers of Co at the NiFe/Ag interfaces has also been investigated (Sec. V). A quantitative analysis of the data is given together with a physical discussion of the results.

I. SAMPLES PREPARATION AND STRUCTURAL CHARACTERIZATION

The samples are prepared by magnetron sputtering. The base pressure is 2×10^{-8} Torr, while the Ar pressure during deposition is 1.5×10^{-3} mbar. The distance between the targets and the substrates is of the order of 10 cm. The substrates are attached to a rotating plate controlled by a step motor. This plate positions the substrates in front of the appropriate target. A shutter located between the target and the substrate allows the control of the deposition time. In our geometry, the sputtered species impinge on the substrate with a normal incidence. The Ag is dc sputtered at a rate of 0.6 Å/sec, while the NiFe is rf sputtered at a rate of 1.2 Å/sec. We deliberately choose rf sputtering for NiFe because we noticed that the resistivity of the NiFe films prepared in our unit is lower for films prepared by rf than by dc (of the order of 24 $\mu\Omega$ cm at room temperature for rf as compared to 32 $\mu\Omega$ cm for dc). The structural quality of the film prepared by rf is definitely better. This has been confirmed by x-ray studies on single films of NiFe for which much narrower lines are observed in θ–2θ scans for films prepared by rf than for films prepared by dc.[6] Concerning the growth of the Ag layers, the key point is not the use of dc or rf power supply on the targets but the substrate temperature.[4,5] At room temperature, the growth of Ag on Ni or NiFe is tridimensional. Ag tends to coalesce and to form islands. Therefore it is very important to maintain the substrates at low temperature during the growth of the Ag layers in order to reduce the Ag surface mobility and obtain flat Ag layers. This effect of temperature on the structural quality of the Ag layers is illustrated in Figs. 1(a) and 1(b). These figures show, respectively, large- and small-angles θ–2θ scans for

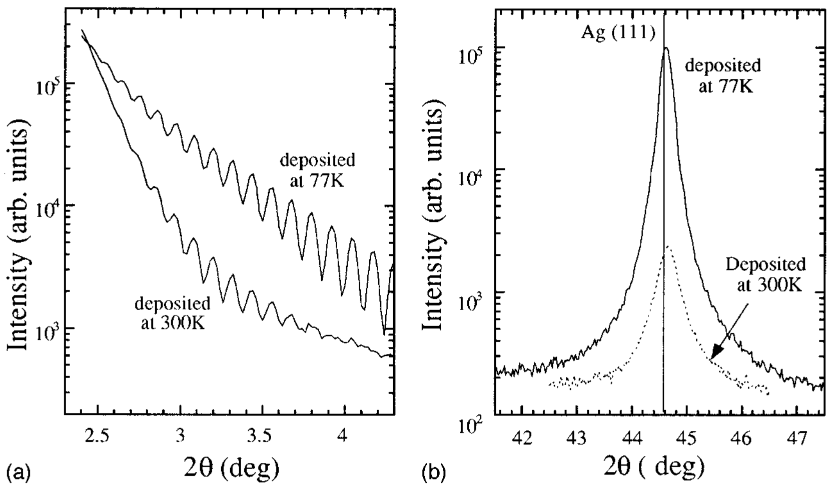

FIG. 1. Comparison of θ–2θ *RX* scans at small (a) and large (b) angles for two layers of Ag 800 Å thick deposited at room temperature, and at liquid nitrogen on SiO_2.

800-Å-thick Ag films prepared at 300 and 77 K. The much higher intensity [Fig. 1(b)] and slower damping of the oscillations of the Kiessig fringes [Fig. 1(a)] observed for the film prepared at 77 K indicate a better structural quality and smoothness for this film as compared to the one prepared at 300 K.

We grew several series of (NiFe t_{NiFe}/Ag t_{Ag})$_n$ multilayers on Si substrates covered with 5000-Å SiO_2. Our unit allows the preparation of ten different samples in the same pump-down, so that good reproducibility in the thicknesses of the various layers can be obtained from one sample to another. The determination of the thickness of the various layers is based on the deposition time assuming constant deposition rates (which is true over several hours of sputtering). The deposition rates are measured by depositing thick layers of a single material and measuring their thickness with a talistep. The thicknesses are later controlled by the analysis of the x-ray-diffraction scans. Figures 2(a) and 2(b) show typical diffraction scans obtained for a multilayer of the composition [40-Å FeNi/12-Å Ag]$_{50}$ at respectively small [Fig. 2(a)] and large angles [Fig. 2(b)]. The inset of Fig. 2(b) shows a rocking curve around the main line. The position of the satellite peaks in Fig. 2(b) as well as the position of the small-angle peaks, which are in both cases associated with the superperiod of the multilayered structure, allows an accurate determination of the chemical period of the multilayer. In this example, one finds $\Lambda = 51.9$ Å as compared to 52 Å expected from the deposition times. A (111) texture is found which is usual for sputtered fcc metals. However, the dispersion around this direction of growth is fairly large (see the rocking curve $\Delta\omega = 15°$). The width of the lines in Fig. 2(b) ($\Delta 2\theta = 0.714°$) indicates a coherence length in the growth direction of the order of 160 Å which corresponds in the present case to about three chemical periods. The clear observation of peaks associated with the superperiodicity at large and small angles indicates the good structural quality of these (NiFe/Ag) samples.

These multilayers were deposited at 77 K (liquid-nitrogen temperature) for the reasons stated above. During the deposition process, great care was taken to insure a good thermal exchange between the substrates and the substrate holder. As an example, we show in Fig. 3(a) a comparison of the magnetoresistive properties of two samples of the same nominal composition (NiFe 25 Å/Ag 12 Å)$_{20}$. One of the samples was stuck to the sample holder by indium solder, which insures a very good thermal contact, while the other was simply attached to the substrate holder by adhesive Kapton. For this Ag thickness, for which an antiferromagnetic coupling exists between NiFe layers through the Ag spacer, the first sample shows GMR while the second one does not. In fact, the second sample shows ferromagnetic coupling through the Ag layers. This coupling is most likely due to the presence of pinholes. A similar observation had been made on NiFe/Ag/NiFe/FeMn spin valves grown at room temperature.[3]

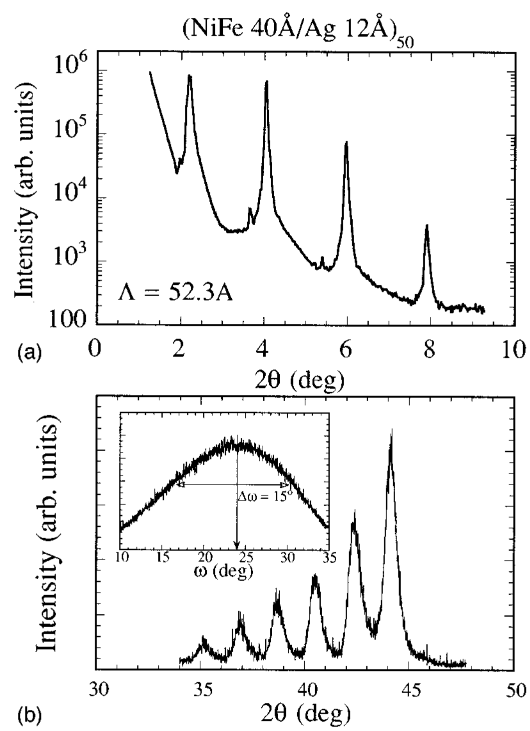

FIG. 2. θ–2θ *RX* scan of a multilayer of the composition 50* (40-Å FeNi/12-Å Ag). (a) Small-angle scan measured with Co radiation ($\lambda_{\mathrm{Co}} = 1.7902$ Å). (b) Large-angle scan measured with Cu radiation ($\lambda_{\mathrm{Cu}} = 1.5418$ Å). Inset of (b): rocking curve around the main line.

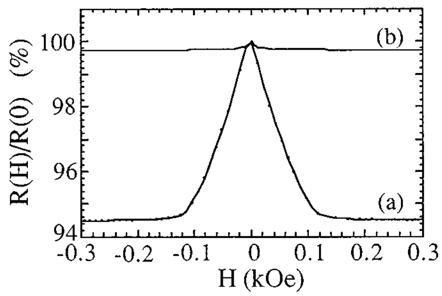

FIG. 3. Comparison of the GMR properties of two samples of the same composition (25-Å NiFe/12-Å Ag) both prepared at liquid-nitrogen temperature, except that one has good thermal contact to the substrate holder by indium solder (a), and the other poor thermal contact (Kapton) (b).

II. INFLUENCE OF THE THICKNESS OF THE SPACER Ag LAYERS

A series of multilayers of the composition Si/SiO_2 5000 Å/(NiFe 25 Å/Ag t_{Ag})$_{20}$ was prepared in order to study the influence of the Ag thickness on the magnetic and transport properties. A well-defined interval of Ag thickness (between 9 and 12.5 Å) has been determined in which an antiferromagnetic coupling exists between NiFe layers. In this range of Ag thickness, giant magnetoresistance is observed. We looked for a second antiferromagnetic peak around 20 Å of Ag but could not find any. For comparison, with the same preparation unit, we also studied (NiFe/Cu) multilayers, and have been able to observe three peaks of antiferromagnetic coupling.[7] This means that the second peak of antiferromagnetic coupling in (NiFe/Ag) certainly has a much weaker intensity than in (NiFe/Cu) multilayers at least at room temperature. Figure 4 shows the magnetoresistance of the series of (NiFe 25 Å/Ag t_{Ag})$_{20}$ samples. No GMR is observed below 9 Å and above 13 Å. The saturation field decreases monotonously between 9.5 and 13 Å, while the GMR amplitude shows a plateau in the range of Ag thickness in which the coupling is antiferromagnetic. The variations of the saturation field and GMR amplitude are shown in Fig. 5. As far as the field sensitivity of the material is concerned, Fig. 5 shows that in order to have a high $\Delta R/R/H$ ratio, one had better work at a Ag thickness which corresponds to the upper edge of the magnetoresistance plateau. Sensitivity of the order to 0.1–0.2 %/Oe have been obtained in as deposited samples in these conditions.

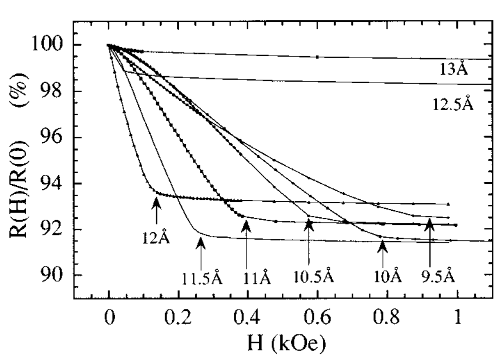

FIG. 4. Magnetoresistance at 300 K of a series of samples of the composition (25-Å NiFe/t_{Ag}-Å Ag)$_{20}$.

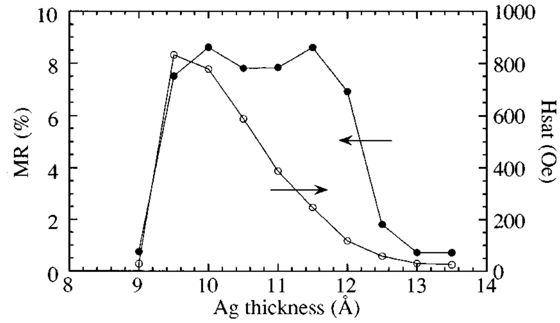

FIG. 5. Variation of the saturation field and of the GMR amplitude in a series of samples of the composition Si/SiO_2 5000 Å/(NiFe 25 Å/Ag t_{Ag})$_{20}$.

III. INFLUENCE OF THE THICKNESS OF THE MAGNETIC NiFe LAYERS

Several series of multilayers of the composition Si/SiO_2 5000 Å/(NiFe t_{NiFe}/Ag 12 Å)$_n$ with $n=10$, 20, and 50 have been prepared. $t_{Ag}=12$ Å corresponds to an antiferromagnetic coupling through the Ag. The magnetization curves and magnetoresistance curves are presented in Figs. 6(a) and 6(b). The magnetization curves are typical of predominantly antiferromagnetic interlayer coupling. They are characterized by no remnant magnetization and relatively large saturation field (large as compared to the saturation field of a single layer of NiFe, which would be a few Oe). The magnetization

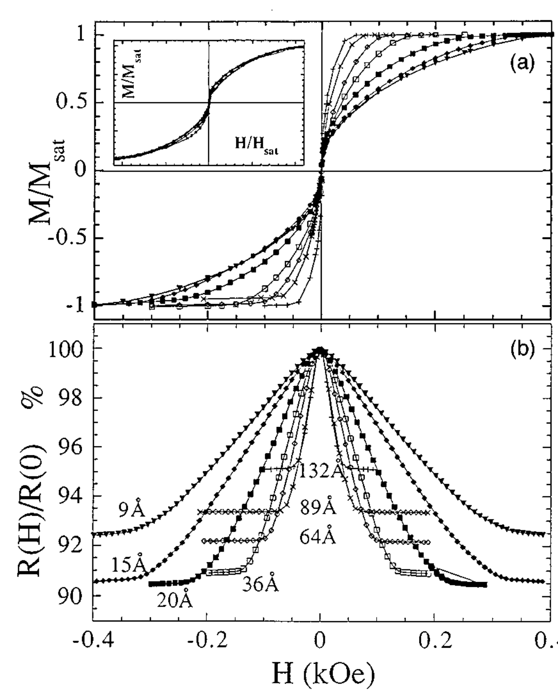

FIG. 6. (a) Magnetization curves at room temperature for a series of multilayers of the composition (NiFe t_{NiFe}/Ag 12 Å)$_{20}$. Inset: same data plotted in reduced units M/M_{sat} vs H/H_{sat} showing the scaling behaviors of these samples. (b) Magnetoresistance curves at room temperature for the same series of samples.

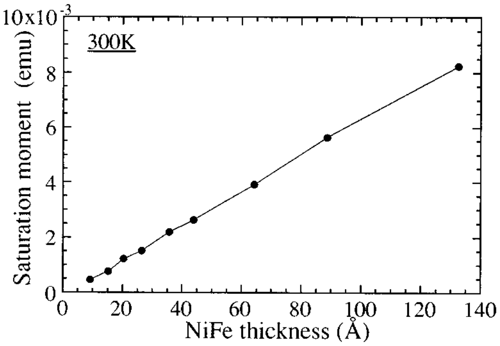

FIG. 7. Variation of the absolute magnetic moment at 300 K vs the thickness of the NiFe layers for a series of multilayers of the composition $[\text{NiFe } t_{\text{NiFe}}/12\text{-Å Ag}]_{20}$.

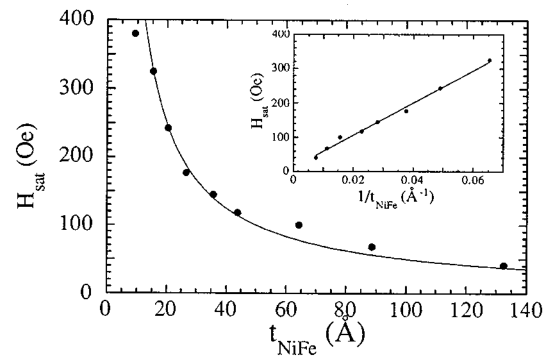

FIG. 8. Variation of the saturation in field vs the thickness of the NiFe layers in the same series of multilayers of the composition $[\text{NiFe } t_{\text{NiFe}}/12\text{-Å Ag}]_{20}$ as in Figs. 6 and 7. Inset: saturation field vs $(t_{\text{NiFe}})^{-1}$.

of the NiFe layers, deduced from the measurement of the absolute moment of the multilayer versus the thickness of the NiFe layer (Fig. 7), is equal to 525 emu/cm^3. For this determination, the thickness of the NiFe layers has been accurately determined from the x-ray-diffraction scans of the whole series of samples prepared in the same pump-down. This value of magnetization is much smaller than that of bulk $Ni_{80}Fe_{20}$: 750 emu/cm^3 at room temperature. The magnetization of a single film of NiFe 600 Å thick prepared in the same conditions is 722 emu/cm^3, which is much closer to the bulk value. Therefore, the low magnetization obtained in the multilayered structure is probably due to some internal strain effects and the lower density of the NiFe in the multilayered structure. Furthermore, the curve representing the absolute moment versus the NiFe thickness of each individual NiFe layer (Fig. 7) does not intercept the origin. An offset of about 4 Å along the x axis is observed which indicates a reduced moment at the interfaces. The equivalent of 2 Å of NiFe is missing at each NiFe/Ag interface. This may be ascribed to some intermixing between NiFe and Ag at the interfaces, leading to the formation of a thin paramagnetic interfacial layer.

When plotted in reduced units M/M_{sat} versus H/H_{sat} the magnetization curves show a very similar behavior [see the inset of Fig. 6(a)]. A certain curvature exists in these curves which can be interpreted in terms of biquadratic coupling.[8] The exchange energy which couples two successive ferromagnetic layers through the Ag spacer layer is written[8,9]

$$E_{\text{ex}} = JM_s^2(1-\cos 2\theta) + BM_s^2(1-\cos 4\theta),$$

in which 2θ is the angle between the magnetic moments of the two considered magnetic layers, J the constant of bilinear coupling, and B the constant of biquadratic coupling. Minimizing the total energy

$$E = E_{\text{ex}}(\theta) - HM_s t_{\text{NiFe}} \cos\theta$$

leads to the following implicit variation of M versus H:

$$H = \left(\frac{4M_s}{t_{\text{NiFe}}}\right)[(4B-J)\cos\theta - 8B\cos^3\theta].$$

A fit of the magnetization curves of Fig. 6(a) to this expression leads to values of JM_s^2 and BM_s^2 almost independent of the NiFe thickness and equal to -0.004 and -0.0008 erg/cm^2, respectively. The coupling is therefore dominantly antiferromagnetic for this Ag thickness. In particular, upon the condition $J/4B>1$ being fulfilled, the stable magnetic state in zero field is an antiparallel alignment of the magnetic moments of the successive NiFe layers. The values of the constant J and B are in good agreement with those previously determined on similar NiFe/Ag multilayers prepared by triode sputtering.[5,9] As a consequence of the independence of J and B from the NiFe thickness, the saturation field is found to vary with the inverse NiFe thickness, as shown in Fig. 8.[10] Indeed, the saturation field is determined from a balance between a volume energy (the Zeeman energy which is the energy associated with the coupling of the magnetic moment of the NiFe layers to the applied magnetic field) and a surface energy (the interlayer coupling through the nonmagnetic spacer layer).

The magnetoresistance (MR) curves of this series of samples measured at room temperature are plotted in Fig. 6(b). The MR amplitude goes through a maximum for an intermediate thickness of the NiFe layers of the order of 25 Å. The MR amplitude versus t_{NiFe} is plotted in Fig. 9. It can

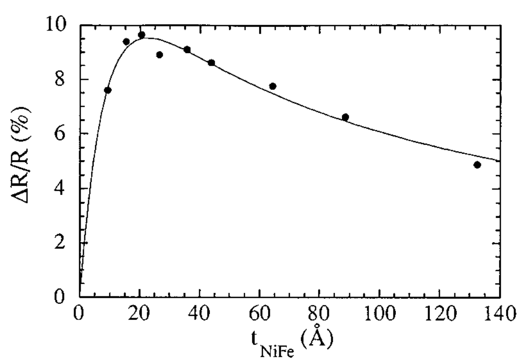

FIG. 9. Variation of the giant magnetoresistance amplitude measured at 300 K vs the thickness of the NiFe layers. These data are deduced from Fig. 6(b). The solid line is a fit of the data according to the phenomenological formula (1) (see text).

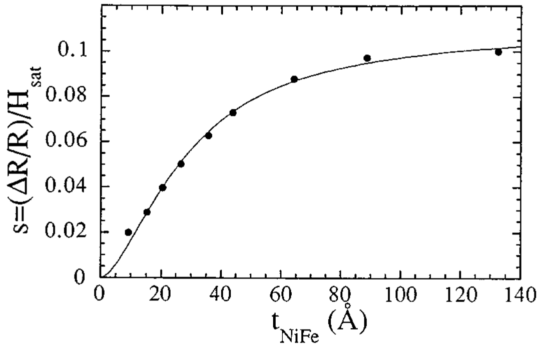

FIG. 10. GMR sensitivity at RT vs the NiFe thickness in the same series of multilayers of the composition (NiFe t_{NiFe}/12-Å Ag)$_{20}$ as in Figs. 6–9. The solid line is a fit of the data according to expression (2) (see text).

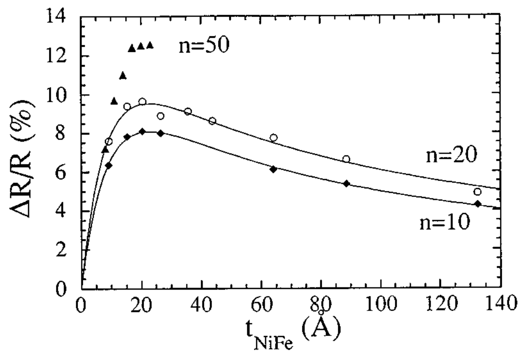

FIG. 11. GMR amplitude at room temperature vs the NiFe thickness in three series of multilayers of the composition: (NiFe t_{NiFe}/Ag 12 Å)$_n$, with $n=10$, 20, and 50. The solid lines are fit according to expression (1) (see text).

be fairly well fitted by the following phenomenological formula:[11]

$$\mathrm{GMR}(t_{\mathrm{NiFe}})=\left(\frac{\Delta R}{R}\right)_0\frac{\left[1-\exp\left(-\frac{t_{\mathrm{NiFe}}}{l_\downarrow}\right)\right]}{\left(1+\frac{t_{\mathrm{NiFe}}}{t_0}\right)}. \qquad (1)$$

In this expression, the numerator is related to the probability for a spin-down electron to be scattered as it traverses a ferromagnetic layer, while the denominator is related to the increasing shunting of the current in the ferromagnetic layer as the NiFe thickness is increased. The value of $l_\downarrow$ (8.4 Å) deduced from the fit gives an estimate of the mean free path of the spin-↓ electrons in the NiFe layers. The normalization constant $(\Delta R/R)_0$ depends on the couple of ferromagnetic/nonmagnetic (F/NM) materials and on the thickness of the nonmagnetic spacer as well as on the number of periods.

Regarding the field sensitivity of the material, Fig. 6(b) shows that although the maximum GMR amplitude is obtained at low NiFe thickness, the maximum GMR slope $\Delta R/R/H$ is reached at large NiFe thicknesses. This is illustrated in Fig. 10. The GMR sensitivity of the material defined as $s=(\Delta R/R)_{\mathrm{sat}}/H_{\mathrm{sat}}$ can be very well represented by the following expression resulting from the combination of expression (1) and the dependence of saturation field on inverse NiFe thickness:

$$s(t_{\mathrm{NiFe}})=s_{\max}\frac{t_{\mathrm{NiFe}}\left[1-\exp\left(-\frac{t_{\mathrm{NiFe}}}{l_\downarrow}\right)\right]}{\left(1+\frac{t_{\mathrm{NiFe}}}{t_0}\right)}. \qquad (2)$$

Sensitivity on the order of 0.1%/Oe is obtained in these as-deposited samples. This sensitivity increases after annealing up to 250 °C, which is a quite interesting point for applications in microelectronics.[4]

We also studied the influence of the number of periods on the transport properties. For that purpose, three similar series of (NiFe t_{NiFe}/Ag 12 Å)$_n$ multilayers have been prepared with $n=10$, 20, and 50. The results are plotted in Fig. 11, which represents the GMR amplitude versus the NiFe thickness in these three series of samples. The solid lines are fits according to expression (1). The GMR amplitude increases with the number of periods. This is due mainly to the reduction of the relative role of the diffuse scattering at the outer surfaces as the thickness of the multilayered structures increases. The optimal thickness of the NiFe layers (the thickness which gives the maximum GMR amplitude) does not depend much on the number of periods in the range of values of n investigated.

IV. QUANTITATIVE INTERPRETATION WITHIN CAMLEY AND BARNAS THEORY

Various classical[12–18] or quantum statistical[19,20] theoretical approaches have been proposed to interpret the spin-valve MR. Most of them rely on the same physical picture based on the existence of spin-dependent scattering centers located at the interfaces or in the bulk of the magnetic layers. Others emphasize the role of spin-dependent potential barriers between the adjacent layers[18] or focus on the role of interfacial random potentials due to intermixing[21] at the F/NM interfaces.

The theoretical approach which is the simplest for experimentalists is certainly the Fuchs-Sondheimer-type theory initiated by Camley and Barnas.[12] The meaning of the parameters which are introduced in the theory is simple to understand: these are the mean-free paths of the spin-↑ and spin-↓ conduction electrons in the various layers and the transmission and/or reflection coefficients at the interfaces. The principle of the theory, which is based on the solution of the Boltzmann equation of transport, has been explained in detail in Refs. 12–18. This approach has been used successfully to interpret quantitatively the transport properties (resistivity and magnetoresistance) of spin-valve sandwiches.[22,23] In their initial theory, Camley and Barnas took into account interfacial spin-dependent scattering only.[12] Later, the following improvements to their initial model were proposed.

(i) A contribution to the spin-dependent scattering originating from the bulk of the ferromagnetic layers was taken into account.[13,15,16]

(ii) A dependence of the transmission coefficients (T) on the incidence of the conduction electrons with respect to the

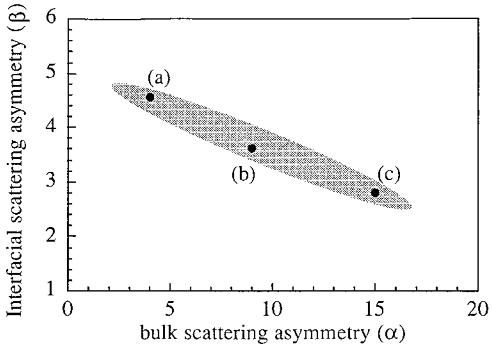

FIG. 12. Region in the (α,β) plane in which a good fit to the experimental data could be obtained. α is the bulk asymmetry of the scattering, β the interfacial asymmetry of the scattering.

TABLE I. Parameters deduced from the fit of both the absolute magnetoresistance and resistivity of a series of $[25\text{-Å NiFe}/t\ \text{Å Ag}]_{20}$ multilayers. a, b, and c correspond to three different points of the dashed area in Fig. 12, in which good fits can be obtained.

	a	b	c
$\lambda_\uparrow$ (Å)	75	72	64
$\lambda_\downarrow$ (Å)	5	8	16
$T_0^\uparrow$	0.75	0.75	0.78
$T_0^\downarrow$	0.3	0.1	0

normal to the interfaces was introduced.[17] This coefficient is assumed to vary as: $T(\cos\theta)=T_0^{1/\cos\theta}$, where θ represents the angle of incidence of the conduction electrons with respect to the normal to the interfaces and T_0 $(0<T_0<1)$ is the transmission coefficient for a normal incidence.

(iii) Potential barriers between adjacent layers was introduced.[18] These potential barriers result from the difference in energy between the Fermi energy and the bottom of the conduction bands in the adjacent materials. They lead to reflection and refraction of the conduction electrons at the interfaces.

(iv) A well-known problem raised by the Fuchs-Sondheimer theory is the divergence of the conductivity of a thin metallic film, in which diffuse scattering occurs on the outer surfaces, when the bulk mean free path λ goes to infinity. This effect is due to electrons which travel parallel to the interfaces. Such divergences, which do not exist in quantum theories,[24] lead to an underestimation of the scattering by the interfaces for very thin layers. However, the semiclassical model can be greatly improved with respect to this problem by introducing a cutoff in the incidence of the conduction electrons so that electrons are not allowed to travel parallel to the interfaces. The cutoff angle θ_c is given by[19]

$$\cos\theta_c=\arccos\left(\frac{1}{\sqrt{\lambda k_F}}\right).$$

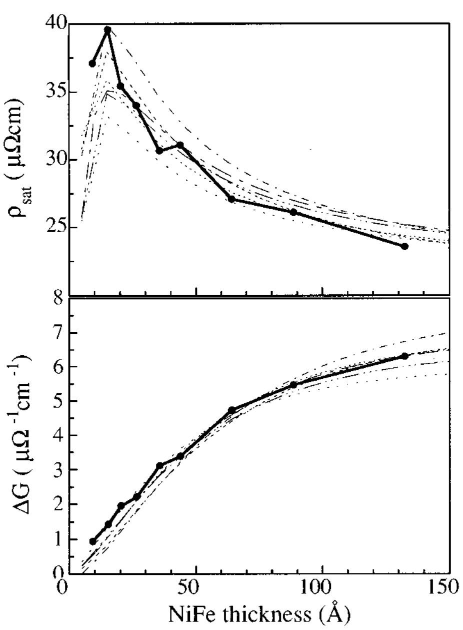

FIG. 13. Examples of fits of both the absolute magnetoresistance and resistivity at room temperature in the series of samples of the composition $[t_{\text{NiFe}}\ \text{Å NiFe}/12\text{-Å Ag}]_{20}$. The solid lines are the experimental curves. The parameters are taken in the dashed region of Fig. 12.

Following this approach with the improvements listed in points (i), (ii), and (iv), we fitted our experimental data of the variation of the resistivity and absolute magnetoresistance (expressed as the absolute change of sheet conductance between the parallel and antiparallel magnetic configurations[25]) versus the thickness of the NiFe layers. The parameters of the fits are (a) the mean free paths $\lambda_\downarrow$ and $\lambda_\uparrow$ in the NiFe layers, (b) the transmission coefficients $T_{0\downarrow}$ and $T_{0\uparrow}$ through the NiFe/Ag interfaces (and later on, through the NiFe/Co/Ag interfaces), and (c) the mean free path in the Ag layer: $\lambda_{\text{Ag}\downarrow}=\lambda_{\text{Ag}\uparrow}$. As usual in these approaches for in-plane GMR, there are many adjustable parameters as compared to the amount of data to be fitted. The solution is therefore not unique. Our goal was therefore to determine the region in the four dimension parameter space $(\lambda_\downarrow,\ \lambda_\uparrow,\ T_{0\downarrow},\ T_{0\uparrow})$, in which it was possible to fit our data of resistivity and magnetoresistance with the same set of parameters. The main result is that, in order to obtain good fits, both a bulk scattering asymmetry in the NiFe layers $(\alpha=\lambda_\uparrow/\lambda_\downarrow)$ as well as an interfacial scattering asymmetry at the NiFe/Ag interfaces $[\beta=(1-T_{0\uparrow})/(1-T_{0\downarrow})]$ must be considered. The sum of these two asymmetries is determined with good accuracy. However, the exact balance between the bulk and interfacial asymmetries is not easy to determine from the present data. Perpendicular-to-the-plane transport experiments provide a more straightforward way of discriminating between interfacial and bulk spin-dependent scattering.[26] Figure 12 shows the region in the (α,β) plane in which a good fit of the data could be obtained. Table I gives values of the parameters $(\lambda_\downarrow,\lambda_\uparrow,T_{0\downarrow},T_{0\uparrow})$ for the three points marked in Fig. 12. Figure 13 shows examples of fits of both the resistivity at saturation and absolute magnetoresistance obtained for a variety of values of the α and β parameters inside the grey region of Fig. 12. It turns out that a fairly accurate determination of the parameters associated with the weakly scattered electrons (spin-↑ electrons for NiFe) can be made, while a larger uncertainty exists on the parameters associated with

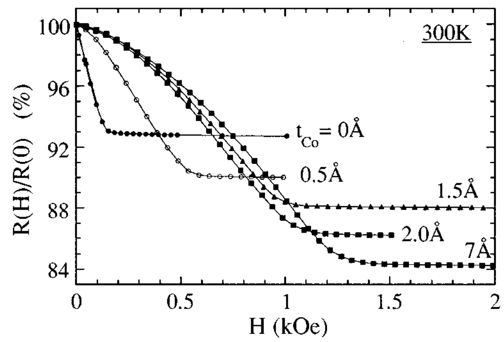

FIG. 14. Magnetoresistance at 300 K of a series of multilayers comprising ten periods of the composition: [t_{Co} Å Co/(25-2t_{Co}) Å NiFe/t_{Co} Å Co/12.8-Å Ag].

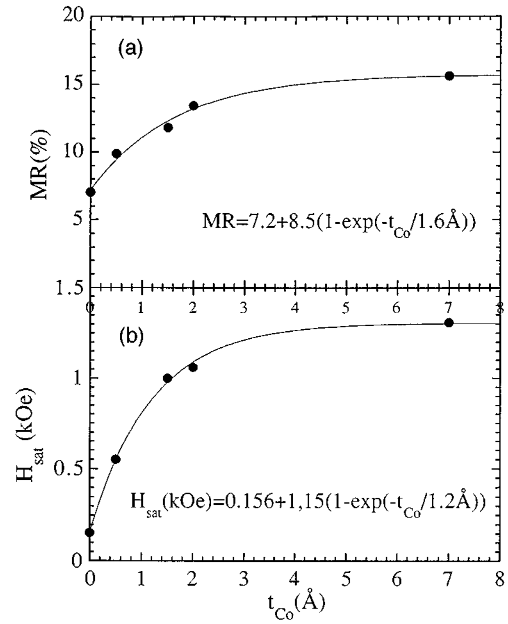

FIG. 15. Variation of the saturation field (a) and of the GMR amplitude (b) vs the thickness of the Co layer in the same series of samples as in Fig. 14. The solid lines are fits according to the phenomenological formula given in the figures.

the strongly scattered electrons. If a strong scattering of the spin-down electrons is introduced in the bulk of the NiFe layers, then a weaker scattering has to be introduced at the interfaces, and vice versa. However, it is not possible to fit our data correctly without taking into account any spin asymmetry in the bulk of the layer.

V. INTRODUCTION OF THIN LAYERS OF Co AT THE NiFe/Ag INTERFACES

We next studied the influence on magnetic and transport properties by the introduction of thin Co layers at the NiFe/Ag interfaces. In previous studies on NiFe/Cu-based spin valves and multilayers,[22,27,28] a strong enhancement of the GMR amplitude and of the interlayer coupling energy had been observed. We wanted to see if similar phenomena occurred in (NiFe/Ag) multilayers. We prepared a series of multilayers comprising ten periods of the composition [Co t_{Co}/NiFe (25 Å-2t_{Co})/Co t_{Co}/Ag 13 Å]. The total thickness of the magnetic layers was kept constant, equal to 25 Å. The thickness of the Ag layer was chosen such that the magnetic layers were coupled antiferromagnetically. Figure 14 shows the magnetoresistance of these samples at room temperature. A very large increase in the GMR amplitude [a doubling of the amplitude at room temperature (RT)] is observed when 1 ML of Co is introduced at the NiFe/Ag interface. Correlatively, the saturation field increases by a factor 4 (see Fig. 15). These results are quite similar to those obtained on NiFe/Cu multilayers,[22,27,28] which is not very surprising considering the similarity in the band structures of Cu and Ag. From a more quantitative point of view, we tried to analyze in more detail the origin of the enhancement of GMR caused by the interfacial Co layer. Table II gives the resistivity at saturation of the considered series of samples, as well as the absolute magnetoresistance (expressed as the absolute change of sheet conductance between the parallel and antiparallel magnetic configurations). This table shows that the saturation resistivity decreases quite significantly as one monolayer of Co is introduced at the NiFe/Ag interfaces. A quantitative analysis of these variations of resistivity and magnetoresistance, using the semiclassical approach presented above, leads to the conclusion that the increase of GMR amplitude is due to a significant increase in the transmission of the spin-up electrons through the NiFe/Co/Ag interface as compared to the transmission though the NiFe/Ag interface. Quantitatively, an increase of the transmission from $T_{0\uparrow}=0.75$ for a NiFe/Ag interface to $T_{0\uparrow}=0.9$ for a NiFe/Co/Ag interface can explain the measured data. In contrast, the resistivity and GMR amplitude do not depend much on the exact value of the transmission of the highly scattered electrons, so that the decrease in the resistivity and increase in GMR amplitude cannot be explained by a change in the transmission of the spin-down electrons.

In order to understand the change in the transmission of electrons (especially of the spin-up electrons) through the interfaces caused by the introduction of one interfacial monolayer of Co, we have measured the magnetization curves and GMR of two similar samples, one without Co (sample A), the other with an interfacial monolayer of Co (sample B) as a function of the temperature. The results are plotted in Figs. 16 and 17. From the magnetic measurements, a steeper decrease in saturation magnetization is observed for the sample without Co [Fig. 17(a)]. Furthermore, the saturation field of sample B almost does not change with temperature while it changes by a factor 2 between 4 and 300 K for sample A. Regarding the transport properties, a steeper decrease in GMR amplitude with temperature is observed for the sample without Co (A) than for the other. The GMR

TABLE II. Resistivity at saturation of the considered series of samples, as well as the absolute magnetoresistance (expressed as the absolute change of conductance between the parallel and antiparallel magnetic configurations).

Co thickness (Å)	0	0.5	1.5	2	7
Resistivity ($\mu\Omega$ cm)	32.2	29.7	24.4	21.5	25.07
ΔG $(\mu\Omega\ \mathrm{cm})^{-1}$	0.81	1.23	1.79	2.31	2.30

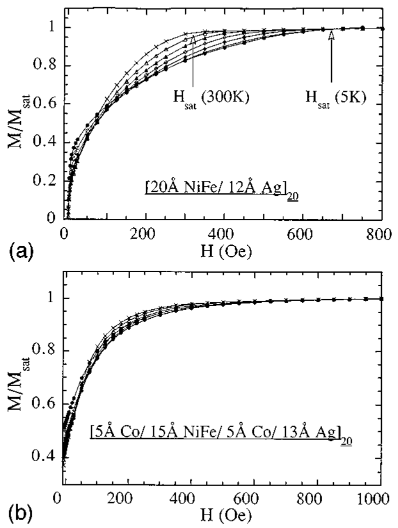

FIG. 16. Comparison of the magnetization curves of two samples of the composition, (a) one without interfacial Co layers [(NiFe 25 Å/Ag 12 Å)$_{20}$], and (b) with interfacial Co layers [(Co 2 Å/NiFe 21 Å/Co 2 Å/Ag 12 Å)$_{20}$] measured at various temperatures.

amplitude of sample B is only 20% higher than that of sample A at 4 K, while it is 100% higher at room temperature. Correspondingly, the saturation magnetization drops by 30% in sample A while it decreases by 10% in sample B. All these experimental observations can be interpreted by considering that the role of the Co interfacial layer is to reinforce the magnetic order at the NiFe/Ag interface, so that the interfacial magnetization decreases less rapidly with temperature. As a result, there is less interfacial scattering by magnetic fluctuations at room temperature at the NiFe/Co/Ag interfaces than at the NiFe/Ag interfaces. The idea that nonferromagnetic atoms present at Ni/Cu or NiFe/Cu interfaces in sputtered spin-valve magnetoresistive layered structures can cause a significant reduction of magnetoresistance has already been proposed by various authors.[29,30] Furthermore, according to this physical picture, the polarization of the conduction electrons in Ag induced by the adjacent magnetic layers would decrease less rapidly with temperature in sample B than in sample A. Since this polarization is directly related to the strength of the antiferromagnetic coupling, this would be consistent with our experimental observation of a slower thermal decrease of the saturation field in sample B than in sample A.

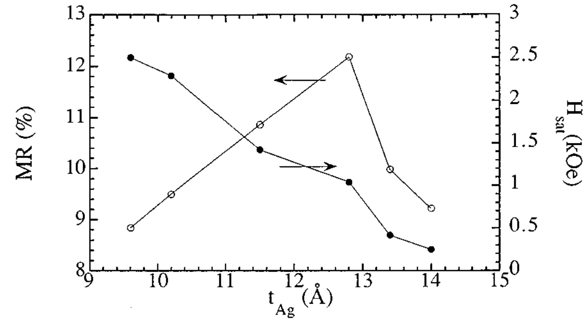

FIG. 18. Variation of the GMR amplitude, and of the saturation field at room temperature vs the thickness of the Ag layer in a series of multilayers comprising ten periods of the composition: (Co 2 Å/NiFe 21 Å/Co 2 Å/Ag t_{Ag}).

Concerning the interlayer coupling, Fig. 18 represents the variation in the GMR amplitude and in the saturation field versus the Ag thickness for a series of samples of the composition (Co 2 Å/NiFe 21 Å/Co 2 Å/Ag t_{Ag})$_{10}$. An antiferromagnetic coupling through the Ag layer is observed in the interval of Ag thickness from 9 to 14.5 Å. The first antiferromagnetic peak is therefore significantly broader with the interfacial layers of Co than without these layers. While the lower limit is approximately the same with and without Co, the upper limit shifted from 12.5 to 14.5 Å. Such a shift in the position of the peak of antiferromagnetic coupling with the nature of the magnetic layers is in agreement with the theory of Bruno and Chappert.[31] The increase in the intensity of the coupling indicates that the polarization of the conduction electron within the Ag layer induced by the Co adjacent layers is certainly much higher than that induced by NiFe.

In conclusion, we have studied the magnetic and transport properties of sputtered NiFe/Ag and Co/NiFe/Co/Ag multilayers. The first peak of antiferromagnetic coupling has been clearly observed in the two series of multilayers. The peak is broader and slightly shifted toward larger thicknesses with the interfacial layer of Co than without. In antiferromagnetically coupled (NiFe/Ag) multilayers, a maximum of GMR amplitude is observed for a NiFe thickness of 22 Å. However, the maximum sensitivity $\Delta R/R/H$ is obtained at larger thicknesses (above 80 Å). The data have been analyzed quantitatively using a semiclassical approach. Both bulk and interfacial spin-dependent scattering must be considered, but the balance between the two is not easy to determine from current-in-plane measurements only. The introduction of thin interfacial Co layers at each NiFe/Ag interface leads to a

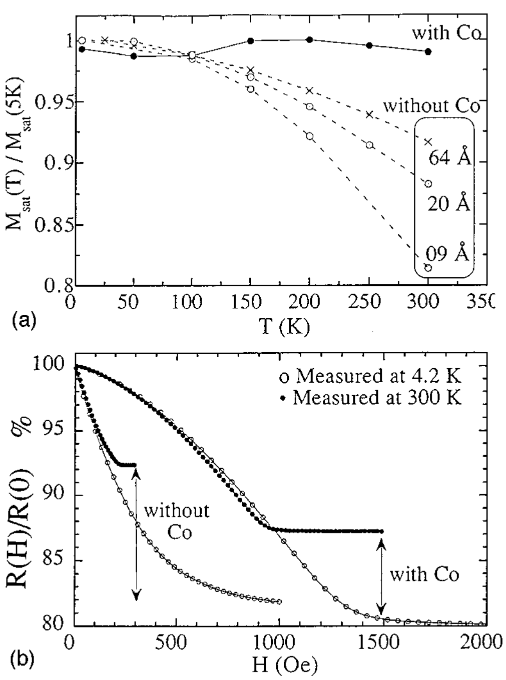

FIG. 17. Thermal variation of the saturation magnetization (a) and of the GMR (b) of the two same samples as in Fig. 16, one without Co, the other with a monolayer of Co introduced at each NiFe/Ag interface.

large increase in the GMR amplitude and saturation field. The increase in GMR is due to an increase in the transmission of the spin-up electrons through the interfaces associated with a reinforcement of the magnetic ordering at the interfaces by the Co layers (reduction of the interfacial magnetic fluctuations).

ACKNOWLEDGMENTS

We gratefully acknowledge J. P. Pezetti, R. Longobardi, and C. Decquier for their technical help, and B. Rodmacq and P. Gerard for stimulating discussions. This work has been funded by the European Communities under the BRITE EURAM II program, Grant No. BRE2-0546.

*Permanent address: Institute of Metal Physics, Ekaterinburg 620219, Russia.

[1] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).
[2] A. Fert and P. Bruno, in *Ultrathin Magnetic Structures*, edited by B. Heinrich and A. Bland (Springer-Verlag, Berlin, 1992).
[3] B. Dieny, J. Magn. Magn. Mater. **136**, 335 (1994).
[4] B. Rodmacq, G. Palumbo, and P. Gerard, J. Magn. Magn. Mater. **118**, L11 (1993).
[5] B. Rodmacq, K. Dumesnil, P. Mangin, and M. Hennion, Phys. Rev. B **48**, 3556 (1993).
[6] C. Cowache, Ph.D. thesis, University of Grenoble, 1995.
[7] B. Dieny and Luiz Nagamine *et al.* (unpublished).
[8] A. Fert and P. Bruno, in *Ultrathin Magnetic Structures*, edited by B. Heinrich and J. A. C. Bland (Springer-Verlag, Berlin, 1994), Vol. II, p. 82.
[9] A. Mallon, Ph.D. thesis, University of Grenoble, 1995.
[10] The existence of oscillations in the interlayer coupling through the nonmagnetic spacer vs the thickness of the ferromagnetic metal has been predicted [P. Bruno, Europhys. Lett. **23**, 615 (1993)]. Such oscillations have been observed experimentally by Bloemen *et al.* in epitaxial Co/Cu/Co(100) multilayers [Phys. Rev. Lett. **72**, 764 (1994)]. However, these oscillations are quite difficult to observe. They have a weak amplitude around a nonzero average value. In our sputtered films, considering the roughness of the interfaces and the slight intermixing between NiFe and Ag, one could expect these oscillations to be smeared out, so that it is reasonable that the coupling is independent on the NiFe thickness.
[11] B. Dieny, P. Humbert, V. S. Speriosu, and B. A. Gurney, Phys. Rev. B **45**, 806 (1992).
[12] R. E. Camley and J. Barnas, Phys. Rev. Lett. **63**, 664 (1989).
[13] J. Barnas, A. Fuss, R. E. Camley, P. Grünberg, and W. Zinn, Phys. Rev. B **42**, 8110 (1990).
[14] A. Barthelemy and A. Fert, Phys. Rev. B **43**, 124 (1991).
[15] B. Dieny, J. Phys. Condens. Matter **4**, 8009 (1992).
[16] D. M. Edwards, R. B. Muniz, and J. Mathon, IEEE Trans. Magn. MAG-27, 3548 (1991).
[17] B. L. Johnson and R. E. Camley, Phys. Rev. B **44**, 9997 (1991).
[18] R. Q. Hood and L. M. Falicov, Phys. Rev. B **46**, 8287 (1992).
[19] A. Vedyaev, B. Dieny, and N. Ryzhanova, Europhys. Lett. **19**, 329 (1992).
[20] H. E. Camblong and P. M. Levy, Phys. Rev. Lett. **69**, 2835 (1992).
[21] J. Inoue, H. Itoh, and S. Maekawa, J. Magn. Magn. Mater. **121**, 344 (1993).
[22] B. Dieny, V. S. Speriosu, J. P. Nozieres, B. A. Gurney, A. Vedyayev, and N. Ryzhanova, in *Magnetism and Structure in Systems of Reduced Dimension*, Vol. 309 of *NATO Advanced Study Institute, Series B: Physics*, edited by R. Farrow *et al.* (Plenum, New York, 1993).
[23] B. Dieny, Europhys. Lett. **17**, 261 (1992).
[24] Z. Tesanovic, M. Jaric, and S. Maekawa, Phys. Rev. Lett. **57**, 2760 (1986).
[25] B. Dieny, V. S. Speriosu, J. P. Nozières, and B. A. Gurney, J. Appl. Phys. Lett. **61**, 2111 (1992).
[26] T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).
[27] S. S. P. Parkin, Appl. Phys. Lett. **61**, 1358 (1992).
[28] S. S. P. Parkin, Phys. Rev. Lett. **71**, 1641 (1993).
[29] B. Dieny, P. Humbert, V. S. Speriosu, S. Metin, and B. A. Gurney, Phys. Rev. B **45**, 806 (1992).
[30] D. M. C. Nicholson *et al.*, J. Appl. Phys. **76**, 6805 (1994).
[31] P. Bruno and C. Chappert, J. Magn. Magn. Mater. **121**, 248 (1993).