Angular dependence of the giant magnetoresistance effect

L. B. Steren, A. Barthélémy, J. L. Duvail, A. Fert, R. Morel, and F. Petroff
Laboratoire de Physique des Solides, Batiment 510, Université Paris-Sud, 91405 Orsay Cedex, France

P. Holody, R. Loloee, and P. A. Schroeder
Department of Physics, Michigan State University, East Lansing, Michigan 48824
(Received 28 June 1994)

We have studied the angular dependence of the giant magnetoresistance (GMR) for $Ni_{80}Fe_{20}/Ag/Co/Ag$ and $Ni_{80}Fe_{20}/Cu/Co/Cu$ multilayers, in which the Co layers are discontinuous and composed of a collection of clusters. In these structures, the magnetization of the $Ni_{80}Fe_{20}$ layers can be rotated by a small applied field without affecting the remanent magnetization of the Co clusters. We analyze our results with a method that allows us to separate accurately GMR and anisotropic magnetoresistance and we find that the angular dependence of the GMR does not exhibit the features expected to arise from the existence of interface spin-dependent potential steps.

I. INTRODUCTION

Since the discovery of giant magnetoresistance (GMR) effects in Fe/Cr superlattices,[1] magnetic multilayers have attracted great interest. Similar and higher effects have been reported in systems such as Co/Cu.[2–4] Recently, effects of the same origin have been reported in granular and clustered systems.[5–8]

The fundamental mechanism of this giant magnetoresistance has been ascribed to conduction in parallel by the two-spin-direction electrons and to the spin dependence of the electron scattering at the interface or within the bulk of the magnetic layers. Several theoretical models based on this approach have been developed[9–12] and can account for the thickness and temperature dependence of the GMR. More recently theories taking also into account the influence of potential steps between successive layers have been developed.[13–15] In Ref. 15 Vedyayev *et al.* predict a linear variation of the conductivity with $\sin^2(\gamma/2)$, where γ is the angle between the magnetizations of adjacent ferromagnetic layers (in that case $Ni_{80}Fe_{20}$) when they take into account only spin-dependent scattering of the conduction electrons within the magnetic layers and no potential steps. Otherwise, in the presence of potential steps, they find that the angular dependence of the GMR is no longer linear with $\sin^2(\gamma/2)$.

II. EXPERIMENTAL DETAILS

In this paper, we report angular dependence measurements on hybrid structures composed of continuous $Ni_{80}Fe_{20}$ layers and clustered ultrathin Co layers separated by Ag or Cu.

(Co 4 Å/Ag t_{Ag}/$Ni_{80}Fe_{20}$ t_{NiFe}/Ag t_{Ag})$_{15}$ samples with t_{NiFe} equal to 20 or 40 Å, and t_{Ag} varying from 13 to 40 Å, and (Co 5 Å/Cu t_{Cu}/$Ni_{80}Fe_{20}$ 40 Å/Cu t_{Cu})$_{10}$ samples with t_{Cu} equal to 35 or 60 Å, were deposited on Si(100) substrates by dc magnetron sputtering at Michigan State University.

The magnetoresistance measurements were made in a four-probe configuration with the applied field in the plane of the layers. All measurements were performed at 4.2 K. Magnetic properties were measured using a superconducting quantum interference device magnetometer.

III. RESULTS

In Figs. 1(a) and 1(b) we present typical magnetic-field dependence of both magnetization and resistivity (here for a (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å)$_{15}$ multilayer). The magnetization curve [Fig. 1(a)] exhibits two well-defined steps: a sharp one at low field corresponding to the abrupt reversal of the soft $Ni_{80}Fe_{20}$ layer magnetizations (in a field range of 10 Oe), and a broader one at much higher field due to the progressive alignment of the Co clusters magnetization in the direction of the field.

The magnetoresistance curve [Fig. 1(b)] confirms what can be expected from the magnetization curve, with an abrupt increase of the resistivity at low field when the $Ni_{80}Fe_{20}$ magnetization turns from a parallel to an antiparallel arrangement with respect to the Co magnetization. The resistance then exhibits a plateau until about 180 Oe and decreases progressively when the Co magnetization rotates in the direction of the applied field. One of the characteristics of these samples is the high field sensitivity they exhibit. For the sample of Fig. 1 an average slope of 3.45% per Oe at low field is found (corresponding to a MR ratio of about 35% observed in 10 Oe), but values as high as 7.2%/Oe have been estimated from the steepest part of the curve. An extensive study of the low-field MR for various samples has been already presented in Ref. 16.

As, in our samples, it is possible to freeze the magnetization of the clustered Co layers in a saturated state and to rotate only the magnetization of the soft $Ni_{80}Fe_{20}$ layers, they are good candidates to study the dependence of the GMR with the angle between the magnetizations of the Co and the $Ni_{80}Fe_{20}$ layers. To obtain the absolute

 ©1995 The American Physical Society

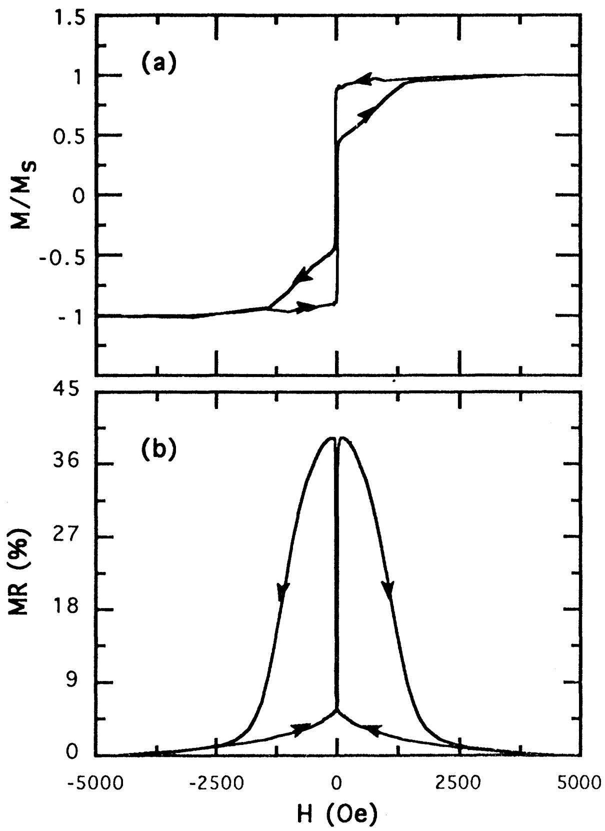

FIG. 1. (a) Magnetization versus in-plane magnetic field and (b) magnetoresistance curve for a (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{15}$ sample, measured at 4.2 K.

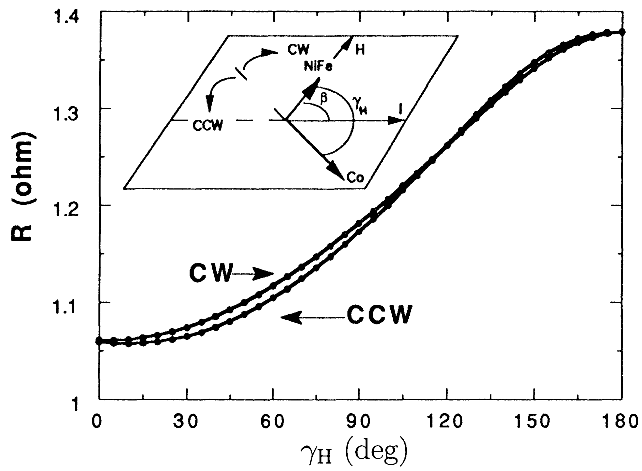

FIG. 2. Resistance, at 4.2 K, as a function of the angle γ_H, obtained for CW and CCW rotations for the (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{15}$ sample. The inset is a schematic of the relative configurations of the $Ni_{80}Fe_{20}$ and Co magnetizations, applied field H and the current I.

angular dependence of the GMR effect without anisotropic MR (AMR) contribution, we did the experiments in a particular way that allows us to separate the two contributions from symmetry arguments. We start by saturating the magnetization of the Co and $Ni_{80}Fe_{20}$ layers, in a field of -5000 Oe, at an angle of 45° relative to the current. Then the magnetization of the $Ni_{80}Fe_{20}$ layers is reversed by a small field which does not affect the Co magnetization (160 Oe for the (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/35 Å$)_{15}$ sample), and the resistivity is measured as the magnetization of the $Ni_{80}Fe_{20}$ layers is rotated with respect to that of the Co by sweeping the field angle γ_H (which, in first approximation, is equal to the angle γ between the Co and $Ni_{80}Fe_{20}$ magnetizations), clockwise (CW) and counterclockwise (CCW). Figure 2 shows the resistivity versus the angle $\gamma_H \simeq \gamma$ obtained for CW and CCW rotations. From symmetry arguments, if we call $\rho_{\parallel}(\gamma)$ and $\rho_{\perp}(\gamma)$ the diagonal elements of the resistivity tensor expressed in its principal axes, the resistivity can be written as

$$\rho=[\rho_{\parallel}(\gamma)+\rho_{\perp}(\gamma)]/2+[\rho_{\parallel}(\gamma)-\rho_{\perp}(\gamma)]\cos(2\beta)/2$$
$$=\rho(\gamma)[1+\varepsilon(\gamma)\cos(2\beta)]$$

with $\rho(\gamma)=[\rho_{\parallel}(\gamma)+\rho_{\perp}(\gamma)]/2$, and $\varepsilon(\gamma)=[\rho_{\parallel}(\gamma)-\rho_{\perp}(\gamma)]/[\rho_{\parallel}(\gamma)+\rho_{\perp}(\gamma)]$, where γ is the angle between the magnetizations of Co and $Ni_{80}Fe_{20}$ layers, and β the angle between the magnetization of the $Ni_{80}Fe_{20}$ layers and the current. The dependence of the GMR on the angle between Co and $Ni_{80}Fe_{20}$ is expressed by $\rho(\gamma)$, while the AMR of the $Ni_{80}Fe_{20}$ layers gives rise to the corrective term $\varepsilon(\gamma)\cos(2\beta)$. For a CW rotation (see inset of Fig. 2), β is equal to $\gamma-\pi/4$ and the measured resistivity ρ is then equal to $\rho_1=\rho(\gamma)[1+\varepsilon(\gamma)\sin(2\gamma)]$, while for the CCW rotation, $\beta=\gamma+\pi/4$, which leads to $\rho_2=\rho(\gamma)[1-\varepsilon(\gamma)\sin(2\gamma)]$. So that we can single out the GMR by averaging the two experimental curves:

$$(\rho_1+\rho_2)/2=\rho(\gamma) \qquad (1)$$

and the AMR term by subtracting them:

$$(\rho_1-\rho_2)/2=\rho(\gamma)\varepsilon(\gamma)\sin(2\gamma)$$
$$=[\rho_{\parallel}(\gamma)-\rho_{\perp}(\gamma)]\sin(2\gamma)/2\ . \qquad (2)$$

The angular variation of the AMR term, derived from Eq. (2), is shown in Fig. 3 by a dashed line. As expected this variation is sinelike and has a small amplitude (0.8%). However, as the crossover from positive to negative anisotropy does not occur at 90° but at an angle of 115°, this suggests the presence of some small ferromagnetic coupling between the magnetic layers across the nonmagnetic spacer. These coupling effects have already been observed in the variation of the MR ratio with the Ag thickness.[17] We have recorded magnetoresistance minor loops (by cycling the magnetization of the $Ni_{80}Fe_{20}$ in small fields without affecting that of the Co, see Fig. 4) to confirm the presence of this coupling and to calculate its strength. The coupling intensity and sign (positive for ferromagnetic and negative for antiferromagnetic) is given by the half-difference between the switching fields, H_1 and H_2 of the major and minor loops, respectively. Indeed, the magnetization of the Co is positive at H_1 and

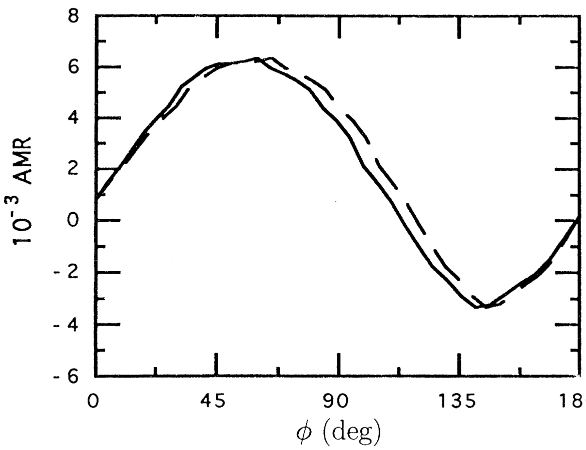

FIG. 3. Variation of the anisotropic magnetoresistance with ϕ, where ϕ represents: the angle γ_H between the field and the Co layer magnetization for the dashed line curve; the angle γ between the $Ni_{80}Fe_{20}$ and Co magnetizations for the solid line curve. These results have been obtained for the (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{15}$ sample at 4.2 K.

negative at H_2, so that, for the relative orientation of the Co and the $Ni_{80}Fe_{20}$, reversing the $Ni_{80}Fe_{20}$ to the negative orientation means going from a parallel to an antiparallel configuration at H_1 and from an antiparallel to a parallel one at H_2:

$$H_1 = -H_{C\underline{Ni}Fe} - H_{\text{coupling}} ,$$

$$H_2 = -H_{C\underline{Ni}Fe} + H_{\text{coupling}} ,$$

where $H_{C\underline{Ni}Fe}$ is the coercive field of the $Ni_{80}Fe_{20}$ layers.

This infers $H_{\text{coupling}} = (H_2 - H_1)/2$. In the sample with 35 Å of Ag and 20 Å of $Ni_{80}Fe_{20}$, a ferromagnetic coupling field of 17 Oe has been found. With 40 Å of Ag the coupling intensity becomes somewhat smaller, $H_{\text{coupling}} = 13$ Oe. For a sample with 40 Å of Ag, 40 Å of $Ni_{80}Fe_{20}$ and still 4 Å of Co, a small ferromagnetic coupling has been found, with a coupling field of 4.5 Oe.

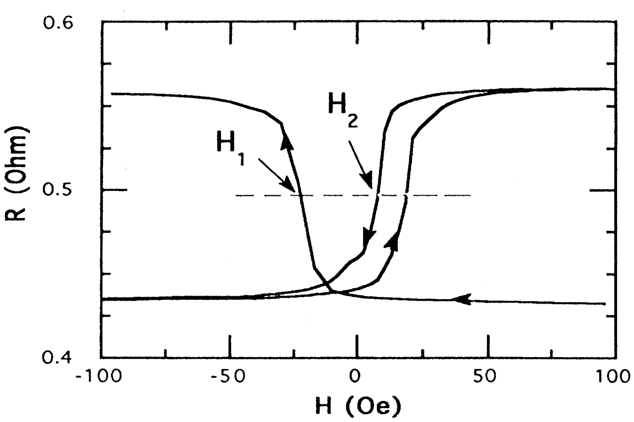

FIG. 4. Minor and major MR loops for (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{15}$ at 4.2 K.

Minor magnetization loops experiments confirm these values, for example, for the (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{10}$ sample a coupling field of 16 Oe is found in very good agreement with the magnetoresistance results.

Due to these couplings, the angle between the Co and the $Ni_{80}Fe_{20}$ magnetizations is no longer γ_H but,

$$\gamma = \arctan[H \sin\gamma_H / (H_{\text{coupling}} + H \cos\gamma_H)] . \quad (3)$$

The variation of the AMR of the $Ni_{80}Fe_{20}$ with the corrected angle γ is shown with a solid line in Fig. 3. The crossover from positive to negative is now closer to

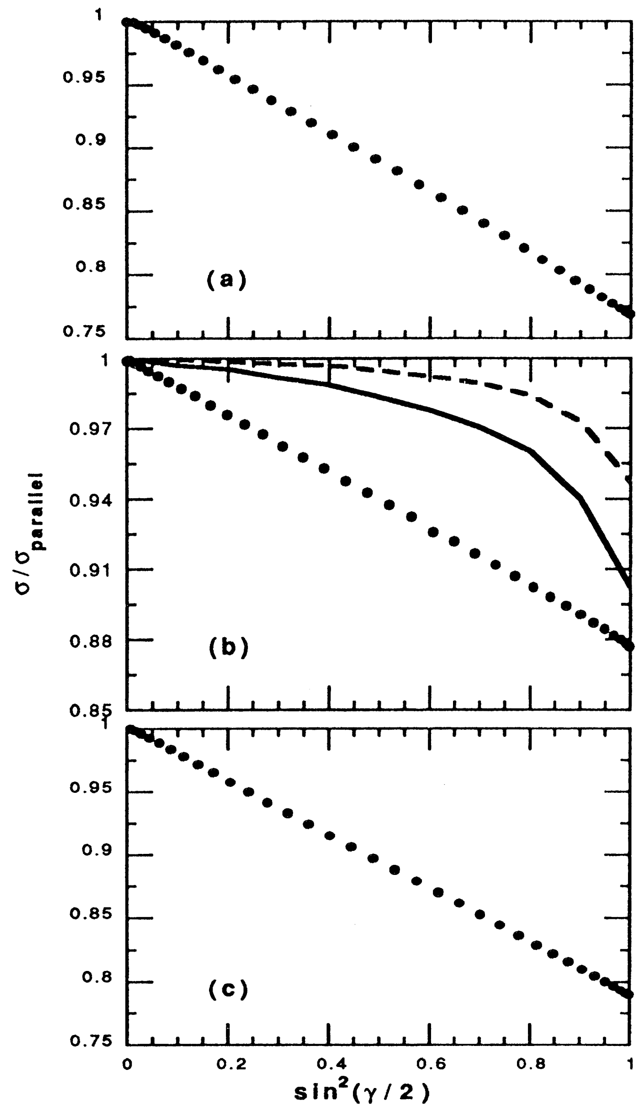

FIG. 5. Conductivity (●) as a function of $\sin^2(\gamma/2)$ for (a) (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{15}$, (b) (Co 5 Å/Cu 60 Å/$Ni_{80}Fe_{20}$ 40 Å/Cu 60 Å$)_{15}$, and (c) (Co 4 Å/Ag 40 Å/$Ni_{80}Fe_{20}$ 40 Å/Ag 40 Å$)_{15}$. The dashed and the solid lines indicate the nonlinear variation obtained in the simulation of Vedyayev *et al.* (Ref. 15) for ratios of 0.5 and 0.67 between the Fermi wave vectors for the two spin directions, $k_F\downarrow / k_F\uparrow$, respectively. This calculation has been done for a bilayer of $Ni_{80}Fe_{20}$.

90°, which checks that the small deviation of γ from γ_H has been correctly taken into account. We point out the asymmetry between the amplitudes of the positive and the negative maxima. This should be due to the dependence of $\varepsilon(\gamma)$ on γ, or, in other words, to the reduction of the AMR when the orientation of the Co and the $Ni_{80}Fe_{20}$ layers are antiparallel, and the spin ↑ and spin ↓ currents less different.[18]

In the same way, and from Eq. (1), we obtain the angular dependence of the GMR, that is the variation of the conductivity $(\sigma/\sigma_{\rm parallel})$ versus $\sin^2(\gamma/2)$, as shown in Fig. 5(a) for the (Co 4 Å/Ag 35 Å/$Ni_{80}Fe_{20}$ 20 Å/Ag 35 Å$)_{10}$ sample. As seen in this figure, the normalized conductivity varies almost linearly with $\sin^2(\gamma/2)$. We have observed such a linear or quasilinear dependence for several samples with Ag or Cu spacer layers. Figures 5(b) and 5(c) present two other examples of quasilinear variations: the first one, Fig. 5(b), for a sample with a spacer layer of Cu (60 Å), a $Ni_{80}Fe_{20}$ thickness of 40 Å and a Co thickness of 5 Å, and the second one, Fig. 5(c), for a sample with 40 Å of Ag, 40 Å of $Ni_{80}Fe_{20}$ and 4 Å of Co. Such linear variations of the GMR with $\sin^2(\gamma/2)$ have already been observed in ($Ni_{80}Fe_{20}$ 60 Å/Cu 26 Å/$Ni_{80}Fe_{20}$ 30 Å/FeMn),[19] (Co 25 Å/Cu 100 Å/$Ni_{80}Fe_{20}$ 25 Å) (Ref. 20) multilayers, (Co 40 Å/Cu 60 Å/$Ni_{80}Fe_{20}$ 60 Å) trilayers,[21] and (Fe 54 Å/Cr 13 Å/Fe 54 Å) sandwiches.[22] We think that our results are more conclusive because our experimental procedure allows us a rigorous separation of the AMR and GMR contributions.

IV. DISCUSSION

By analyzing experiments in current perpendicular to the plane of the sample (CPP) geometry Barnas and Fert[23] show that a good account of the interface resistances in Co/Cu and Co/Ag is found for a ratio of the potential height to the Fermi energy around 0.4 for the majority electrons and at a much smaller value for the minority ones. These potential heights correspond to a quite plausible ratio of the Fermi wave vectors for the two spin directions, $k_F\downarrow/k_F\uparrow\approx 0.77$. Looking at the theoretical prediction of Vedyayev *et al.* for similar values of $k_F\downarrow/k_F\uparrow$ [see dashed and solid line in Fig. 5(b)] we expect a fairly strong deviation of the angular dependence of the GMR from a linear variation in $\sin^2(\gamma/2)$. Since the calculation of Vedyayev *et al.* have been performed for a bilayer system ($Ni_{80}Fe_{20}$), a quantitative comparison has not a rigorous meaning. It turns out however that, in general and for reasonable values of the parameters, the deviation from linearity is always more pronounced in the results of Vedyayev *et al.* The nonlinear dependence obtained by Vedyayev *et al.* results from the specular reflections of the electron waves on interface potential steps. It turns out that such effects are not significant in our samples. It might be that the imperfection of the multilayers reduces considerably all the effects arising from the periodic potential and in particular the deviation from $\sin^2(\gamma/2)$ found by Vedyayev *et al.* Alternatively it might also be, as suggested by Barnas and Fert[23] that the interface roughness gives a significant contribution to the CPP interface resistance, which implies a smaller contribution from the potential steps and therefore smaller step heights.

Could some deviation from the $\sin^2(\gamma/2)$ appear in measurements on samples with thinner layers? Unfortunately in our samples reducing the thickness of Ag or Cu leads to stronger coupling between Co and $Ni_{80}Fe_{20}$, which does not allow us to determine the angular dependence as precisely for the samples with relatively thick spacer layers presented in this paper.

ACKNOWLEDGMENTS

This research was partially supported by the U.S.-France cooperation program Grant No. INT-92-16909, Companion Grant No. AI0693 and the ESPRIT Basic Research Project No. 6146 SMMMS. L.B.S. acknowledges financial support from the Consejo National de Investigaciones Científicas y Técnicas de la República Argentina.

[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, A. Barthélémy, P. Etienne, D. K. Lottis, D. H. Mosca, F. Petroff, and P. A. Schroeder, J. Magn. Magn. Mater. **104-107**, 1712 (1992).

[3] D. H. Mosca, A. Barthélémy, F. Petroff, A. Fert, P. A. Schroeder, W. P. Pratt, and R. Loloee, J. Magn. Magn. Mater. **94**, L1 (1991).

[4] S. S. P. Parkin, R. Bhadra, and K. P. Roche, Phys. Rev. Lett. **66**, 2152 (1991).

[5] J. Q. Xiao, J. S. Jiang, and C. L. Chien, Phys. Rev. Lett. **68**, 3749 (1992); A. E. Berkowitz, J. R. Mitchell, M. J. Carey, A. P. Young, S. Zhang, F. E. Spada, F. T. Parker, A. Hutten, and G. Thomas, *ibid.* **68**, 3745 (1992).

[6] B. Rodmacq, G. Palumbo, and P. Gerard, J. Magn. Magn. Mater. **118**, L11 (1993).

[7] T. L. Hylton, K. R. Coffrey, M. A. Parker, and J. K. Howard, Science **261**, 1021 (1993).

[8] R. Loloee, P. A. Schroeder, W. P. Pratt, J. Bass, and A. Fert, Physica B (to be published).

[9] Camley and J. Barnas, J. Phys. Rev. Lett. **63**, 664 (1989).

[10] P. M. Levy *et al.*, Phys. Rev. Lett. **65**, 1643 (1990).

[11] S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. B **45**, 8689 (1992).

[12] J. L. Duvail, A. Fert, L. G. Pereira, and D. L. Lottis, J. Appl. Phys. **75**, 7070 (1994).

[13] R. Q. Hood and L. M. Falicov, Phys. Rev. B **46**, 8287 (1992).

[14] A. Vedyayev, C. Cowache, N. Ryzhanova, and B. Dieny, J. Phys. Condens. Matter **5**, 8289 (1993).

[15]A. Vedyayev, B. Dieny, N. Ryzhanova, J. B. Genin, and C. Cowache, Europhys. Lett. **25** (6), 465 (1994).
[16]P. Holody, L. B. Steren, R. Morel, A. Fert, R. Loloee, and P. A. Schroeder, Phys. Rev. B **50**, 12 999 (1994).
[17]L. B. Steren, R. Morel, A. Barthélémy, F. Petroff, A. Fert, P. Holody, R. Loloee, and P. A. Schroeder, J. Magn. Magn. Mater. (to be published).
[18]I. A. Campbell and A. Fert, *Fcrromagnetic Materials,* edited by E. P. Wohlfarth (North-Holland, Amsterdam, 1982), p. 769.
[19]B. Dieny, V. S. Speriosu, S. S. P. Parkin, A. Gurney, D. R. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).
[20]T. Shinjo, T. Okuyama, and H. Yamamoto (unpublished).
[21]M. Patel, T. Fujimoto, E. Gu, C. Daboo, and J. A. C. Bland, J. Appl. Phys. **75**, 6528 (1994).
[22]A. Chaiken, G. A. Prinz, and J. J. Krebs, J. Appl. Phys. **67**, 4892 (1990).
[23]J. Barnas and A. Fert, Phys. Rev. B **49**, 12 835 (1994).