Interpretation of the magnetoresistance in multilayered structures

S. Zhang*
Physics Department, University of California–San Diego, La Jolla, California 92093

Peter M. Levy
Physics Department, New York University, New York, New York 10003
(Received 2 August 1991)

Large ratios of the magnetoresistances for currents perpendicular to currents in the layer planes have been found in Co/Ag multilayered structures. We explain these by taking the zero-magnetization state, $H_{\rm coercive}$, in structures where the magnetic layers are nominally uncoupled, to be a superposition of statistically uncorrelated magnetic configurations. Also, we provide an interpretation for the magnetoresistance of Co/Cu and Fe/Cr by considering these multilayered structures to consist of, not only ferromagnetically and antiferromagnetically aligned layers, but also mixtures of the two that have zero magnetization.

Pratt *et al.*[1] have just shown that the magnetoresistance (MR) of the magnetic multilayered structure (MS) Co/Ag with the current *perpendicular* to the layer planes (CPP) is considerably larger than that measured for the current *in* the layer plane (CIP). The theory which predicted the CPP MR was developed for multilayered structures that are *antiferromagnetically* (AF) coupled;[2] it does *not* explain the data because the thicknesses of the nonmagnetic silver layers in the recent experiments are so large, $t_{\rm Ag} \leq 600$ Å, that the magnetic cobalt layers are to a large extent *uncoupled*.[1] To help us interpret the results on Co/Ag, we have relied on the recent data on the CIP MR in Co/Cu.[3,4] Up until now, the conventional interpretation has been that peaks in the MR represent MS's with layers that are AF aligned, and troughs represent F-aligned layers. However, this is *not what has been seen.* For Co/Cu the troughs do not go to zero as they should for F-aligned MS, *and* as we will show, the peaks are not as high as they would be if the layers were AF aligned. Here we provide a model that reproduces these new findings; among other things, it provides an interpretation of magnetoresistance data in multilayered structures.

Our explanation for this unexpected behavior is as follows. For thin nonmagnetic layers ($t_{\rm NM}$), the coupling is sufficiently strong to overcome random coercive or pinning forces that oppose realignment within the magnetic layers, so that the MS is purely F or AF aligned. However, near the nodes where the coupling goes through zero and for larger $t_{\rm NM}$, the coupling is no longer strong enough compared to the pinning forces to define uniquely the magnetic configuration of the multilayers. While the zero-field and magnetization states are *unique* for AF-coupled layered structures, these states are ill defined when the layers are not magnetically coupled.[5]

We have formulated the theory of the MR effect in the MS by taking the zero magnetization $H=H_c$ state in *uncoupled* systems as a superposition of statistically uncorrelated magnetic configurations which satisfy the condition $\sum_i \mathbf{M}_i=0$ ($\mathbf{M}_i$ is the magnetization of individual layers). We find that the CIP MR is *diminished* relative to systems that are AF coupled, but otherwise identical, while the CPP MR is unchanged. Therefore, the ratio π of the CPP MR to CIP MR is *enhanced* for uncoupled systems relative to its value for AF-coupled MS's. Taken together with the trend for π to increase for the MS as the thickness of the layers increases [the CIP MR, sensitive to mean-free-path (MFP) effects decreases faster than the CPR MR], this new feature of our model is able to explain the large ratios of π, of the order of 5, observed in the Co/Ag MS.[1] *In addition,* it can explain the *attenuated* in-plane MR observed in other nominally uncoupled systems.[6]

The local conductivity of multilayered structures $\sigma(z)$ depends on the position z (the direction perpendicular to the layers).[7] The amplitude of the variation in the conductivity is controlled by the thicknesses d of the layers relative to the MFP's of the electrons λ.[2,7] For small values of this ratio, the variation is negligible; for large values, the variation is big. For currents parallel to the layers, the CIP resistivity is an average of the *conductivities*

$$\rho_{\parallel}=\frac{L}{\int_L \sigma_{\parallel}(z)dz} , \tag{1}$$

while for currents perpendicular to the layers, the CPP resistivity is the average of the *resistivities*

$$\rho_{\perp}=\frac{1}{L}\int_L \rho_{\perp}(z)dz , \tag{2}$$

where L is the overall thickness of the MS in the z direction. To compare $\rho_{\parallel}$ to $\rho_{\perp}$ for Co/Ag, we assume that the local conductivity tensor for the sputtered Co/Ag samples is diagonal and isotropic; i.e., we set $\rho_{\perp}(z)=[\sigma_{\parallel}(z)]^{-1}$. In the limit $d/\lambda \ll 1$, $\rho_{\parallel}$ and $\rho_{\perp}$ are equal because the local conductivity σ is independent of position z. For large d/λ they are quite different, but $\rho_{\perp}$ is always greater than $\rho_{\parallel}$, because for the in-plane geometry the resistivity [Eq. (1)] is dominated by the regions with high conductivities (one has the effect of a short circuit), whereas Eq. (2) is a straight average.

The magnetoresistance of these multilayered structures is governed by the random spin-dependent potentials that scatter the conduction electrons. These potentials are varied by an external field. In fields H_s high enough to saturate the magnetization of the MS, the magnetic moments of the individual layers are nominally aligned (ferromagnetically), while in zero field they are partially aligned, $M_r < M_s$. To demagnetize it is necessary to apply a coercive field H_c, which is comparable to H_s for a Co/Ag MS [see Fig. 2(c) of Ref. 1].[8] In the fully aligned (saturated) state, the scattering experienced by the conduction electrons with one direction of their spin (a spin channel) is less than the scattering for electrons with the opposite direction. For the $M=0$ state (both for the statistical mixture of F and AF, and AF configuration) the scattering is independent of the direction of the spin of the conduction electrons and is the average of the scatterings encountered in the opposite spin channels when $M = M_s$. As the current is the sum of those carried in each channel, one has a "short-circuit" effect when $M = M_s$; consequently, $\rho(M=0) > \rho(M_s)$. As we have not included spin-orbit coupling, this result is independent of the direction of the current; therefore, it *adds* to the short-circuit effect above, i.e., $\rho_\perp > \rho_\parallel$.

The MR ratio is defined as[9]

$$R(H) = \frac{\rho(H) - \rho(H_s)}{\rho(H_s)} . \tag{3}$$

For currents perpendicular to the layer planes, $R_\perp(H)$ is relatively independent of the MFP of the electrons. However, for in-plane currents, the $R_\parallel(H)$ rapidly decreases as the spacing d_{Ag} between magnetic layers becomes larger than the MFP of the electrons, i.e., $d_{\mathrm{Ag}}/\lambda > 1$. Therefore, one finds that the ratio of the two,

$$\pi(H) = \frac{R_\perp(H)}{R_\parallel(H)} , \tag{4}$$

increases as d_{Ag}/λ increases.

One final consideration that increases $\pi(H_c)$ is the degree of magnetic alignment between the layers. The $R_\parallel(H_c)$ is lower for MS's which are statisticall mixtures of F- and AF-aligned layers than it is for structures with only AF-coupled layers, while $R_\perp(H_c)$ is unchanged. The reason is that for uncoupled systems the $M=0$ state for $H = H_c$ is not unique and one has a spatial distribution of the magnetic moments of the individual cobalt layers that is statistically distributed to yield $M=0$. As the conduction electrons decay within the distance of a MFP, one finds, as one traverses the MS moment, configurations (regions), which are *locally* ferromagnetic. These regions short-circuit the CIP, and we find $\rho_\parallel(M=0)$ for an uncoupled MS is always less than it is for AF-coupled structures. For currents perpendicular to the layers, $\rho_\perp(M=0)$ is *independent of the sequence* of the moment distribution and, therefore, is the same for uncoupled and AF-coupled MS's.

For more *quantitative* results on the MR, we evaluate $\sigma(z)$ (Ref. 7) by specifying the orientations of the magnetic moments of the cobalt layers. For H_s they are nominally aligned, while for H_c we have taken the $M=0$ states described above for all samples with large nonmagnetic layer spacings t_{NM}; for thinner t_{NM} we include F and AF configurations. Also, we have not made a distinction between the moment configurations for $H_c(M=0)$ and H_m where the maximum in the MR is observed [see Figs. 2(a) and 2(b) of Ref. 1]. The parameters entering our expression for $\sigma(z)$ (Refs. 2 and 7) are the MFP for cobalt λ_{Co} and silver λ_{Ag}, the ratio of the spin to potential scattering in the cobalt p_{Co} and at the interfaces, p_s, and w_s the ratio of the scattering at interfaces

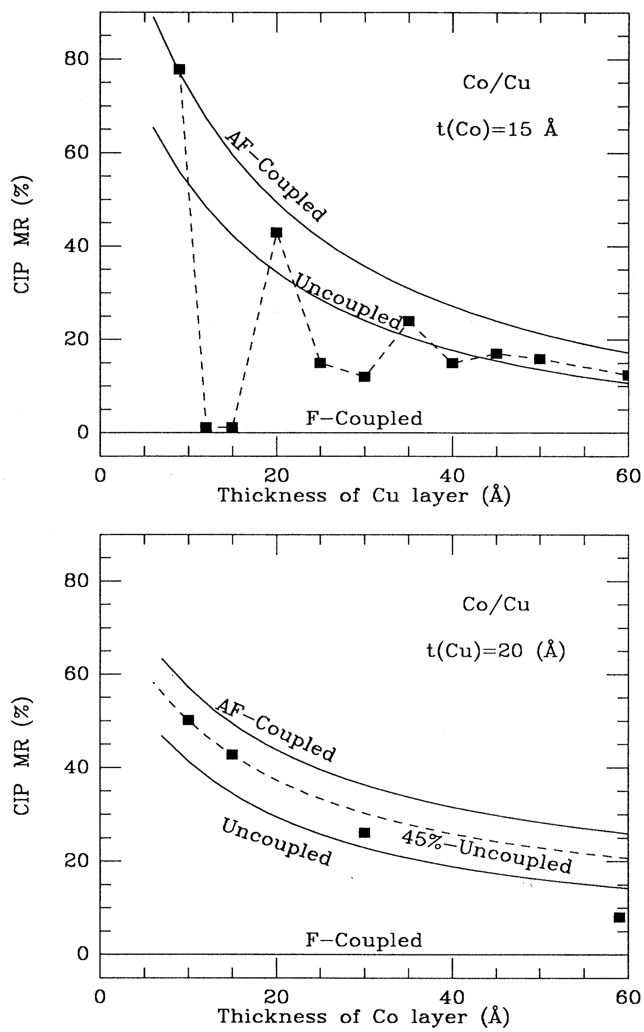

FIG. 1. (a) CIP MR for Co(15 Å)/Cu(t) as estimated by taking the layers F and AF aligned and mixtures of the two with $M=0$. The latter is labeled as "uncoupled." The squares represent data at $T=4.2$ K from Ref. 4 and A. Fert (private communication). (b) The CIP MR for Co(t)/Cu(20 Å) by assuming F, AF, and "uncoupled" and the dashed curve which represents the MS at 55% AF and 45% "uncoupled." The latter is obtained by fitting the data in (a). The data represented by squares come from A. Fert *et al.* (private communication). The parameters we use in the fits are $\lambda_{\mathrm{Co}}=40$ Å, $\lambda_{\mathrm{Cu}}=75$ Å, $w_s=0.3$, $p_{\mathrm{Co}}=0.2$, and $p_s=0.52$. That the datum at $t_{\mathrm{Co}}=60$ Å falls far below our predicted value may be due to a change in the cobalt layer structure at larger thicknesses; S. S. P. Parkin (private communication).

compared to that in the layers.[10]

As the data in Ref. 1 are primarily for large t_{NM}, it is difficult to reliably estimate these parameters from the tail of the MR curves. For this reason we have fit the data of Mosca *et al.*[4] on Co/Cu which is similar to Co/Ag. In Fig. 1(a) we show our fit to Co(15 Å)/Cu(t_{Cu}) by using $\lambda_{\mathrm{Co}}=40$ Å, $\lambda_{\mathrm{Cu}}=75$ Å, $w_s=0.3$, $p_{\mathrm{Co}}=0.2$, and $p_s=0.52$.[11] Except for the first AF peak at $t_{\mathrm{Cu}}=9$ Å and the F points at $t_{\mathrm{Cu}}=12$ and 15 Å, the MS is neither *completely* AF nor F coupled; for $t_{\mathrm{Cu}}\gtrsim 50$ Å we suggest it is completely uncoupled. With these same parameters we fit the unpublished data of Mosca *et al.*[4] for Co(t_{Co})/Cu(20 Å) [see Fig. 1(b)] when we interpret the data on Co(15 Å)/Cu(20 Å) [see Fig. 1(a)] so that the MS is a mixture of 55% AF and 45% uncoupled. This is reasonable for those thicknesses of copper where the interlayer coupling may be close to the AF peak.

In our interpretation [see Fig. 1(a)] the peaks (other than the first) in the MR oscillations do not correspond to MS's where *all* layers are AF aligned. If we make this assumption, we would find smaller MFP's ($\lambda_{\mathrm{Co}}=19$ Å, $\lambda_{\mathrm{Cu}}=30$ Å), smaller $w_s=0.16$, and unreasonably large $p_s=0.65$ ($\alpha=22$, where α is the ratio of the resistivity in the majority- and minority-spin channels[2]). With these parameters the fit to the data in Fig. 1(b) would not be as good, and the resistivities would much too large, e.g., $\rho_{\parallel}(H_s)=37$ $\mu\Omega$ cm for Co(15 Å)/Cu(9 Å), whereas the experimental value is 17.1 $\mu\Omega$ cm.[5] With the parameters used in Fig. 1, we find $\rho_{\parallel}(H_s)=20$ $\mu\Omega$ cm.

To fit the data on Co/Ag (Fig. 3 of Ref. 1) we use the same λ_{Co} and p_{Co} as in Co/Cu, and we adjust $\lambda_{\mathrm{Ag}}=200$ Å, $w_s=1.0$, and $p_s=0.49$ to best fit the data on the CIP and CPP MR. With these parameters we find the ratios $\pi(H_c)$ for the MS with 60 Å of Co and $t_{\mathrm{Ag}}=60$, 90, 120, 180, 220, 350, and 600 Å are 5(4.8), 5.4.(5.3), 5.9(4), 6.1(6.7), 6.2(5.9), 6.5(5.3), and 7.0(13).[12] These compare reasonably well with the experimental values in parentheses except for $t_{\mathrm{Ag}}=120$ and 600 Å. For the latter the CIP MR is quite small; a change from 1% to 2% would make $\pi(H_c)=6.5$, which is more in line with values of this ratio for other thicknesses. It is instructive to note that if we assumed the layers were all AF coupled, we would have severely *underestimated* the ratio $\pi(H_c)$.

Another example of our interpretation that MS's have mixtures of F- and AF-aligned regions is given in Fig. 2, where we have fit the data on sputtered samples of Fe/Cr.[13] Here it is clear that the oscillation in the MR asymptotically approach the uncoupled curve and that only the first peak represents a MS in which all layers are AF coupled. If we assumed all peaks represented MS's in

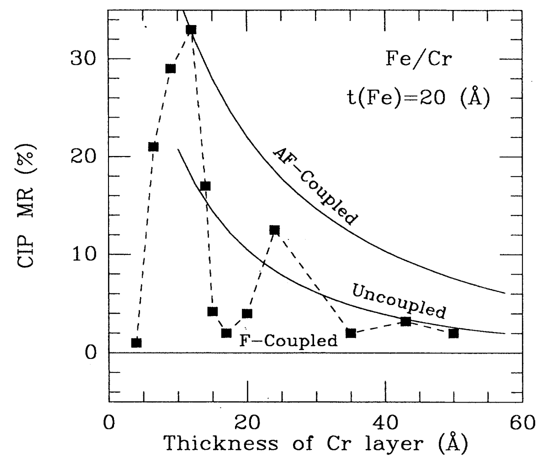

FIG. 2. CIP MR for Fe(20 Å)/Cr(t) as estimated by taking the layers F, AF, and "uncoupled." The squares represent data from Ref. 13 at $T=4.5$ K. The parameters used in the fits are $\lambda_{\mathrm{Fe}}=\lambda_{\mathrm{Cr}}=40$ Å, $w_s=0.3$, $p_{\mathrm{Fe}}=0.23$, and $p_s=0.42$.

which all layers are AF aligned, we find $\lambda_{\mathrm{Fe}}=\lambda_{\mathrm{Cr}}=19$ Å, which is unreasonably small, these parameters yield, for Fe(20 Å)/Cr(9 Å), $\rho_{\parallel}(H_s)=46$ $\mu\Omega$ cm, while we find 26 $\mu\Omega$ cm by using the parameters quoted for Fig. 2.[14]

In summary, we are able to explain the large ratios $\pi(H_c)$ of the CPP to CIP MR seen in Co/Ag by assuming the magnetic layers are not coupled. However, at this stage we can make only a qualitative conclusion that CPP MR is considerably higher than CIP MR. As there is a large number of parameters in the theory, one needs more data on Co/Ag before meaningful fits can be made. In addition, we have provided an interpretation of the CIP MR for Co/Cu and Fe/Cr which considers the MS as a mixture of F- and AF-aligned layers. With this interpretation we find parameters which yield resistivities that are much closer to the data than if we interpret the peaks in the MR as corresponding to MS's with only AF-coupled layers.

We would like to thank W. P. Pratt, Jr. for sharing with us his unpublished data and his invaluable help in interpreting it, P. A. Schroeder and J. Bass for very useful discussions, A. Fert for sending us data and a copy of his work prior to publication on Co/Cu, and S. S. P. Parkin for copies of his work on Co/Cu prior to publication. This work was supported in part by National Science Foundation and Center for Magnetic Recording Research of UCSD and by a grant from the New York University Technology Transfer Fund.

*Present address: Department of Physics, New York University, 4 Washington Place, New York, NY 10003.

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[8]For strongly coupled AF systems, eg., Fe/Cr [M. N. Baibich *et al.*, Phys. Rev. Lett. **61**, 2472 (1988)], the fields needed to achieve $M=0$ are *small* compared to H_s, and the MR curves have a single peak rather than the twin peaks observed in nominally uncoupled systems as Co/Ag; see Figs. 2(a) and 2(b) of Ref. 1.

[9]We previously defined the MR ratio with $\rho(H=0)$ in the denominator; see Ref. 2.

[10]In our work on Fe/Cr (see Ref. 2), we set $p_{\mathrm{Fe}}=p_s$ and $\lambda_{\mathrm{Fe}}=\lambda_{\mathrm{Cr}}$.

[11]It is not possible to use $\lambda_{\mathrm{Cu}}=75$ Å to fit the MR data on Co/Cu found by Parkin *et al*; see Ref. 3. The MFP for Cu in their multilayered structures is larger by a factor of at least 2. The resistivity for their samples of Co(10 Å)/Cu(9.3 Å) is about 10 $\mu\Omega$ cm (converted from the sheet resistance given in Fig. 4 of Parkin, Bhadra, and Roche; see Ref. 3), while for the Co(15 Å)/Cu(9 Å) sample of Mosca *et al.* (see Ref. 4), $\rho=17.1$ $\mu\Omega$ cm. When we account for the resistivity coming from scattering at the interfaces, we find that the λ_{Cu} in the samples of Parkin, Bhadra, and Roche is at *least* twice as large as for that of Mosca *et al.*

[12]We have not tried to fit the $\pi(H_c)$ for $t_{\mathrm{Ag}}=160$ Å, as there is an unusually large scatter in the data; see Fig. 3 of Ref. 1.

[13]S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).

[14]These parameters are different from those found by fitting the data on the CIP MR for molecular-beam epitaxially grown Fe/Cr MS's for thin chromium layers; see M. N. Baibich *et al.*, Phys. Rev. Lett. **61**, 2472 (1988); A. Barthelemy *et al.*, J. Appl. Phys. **67**, 5908 (1990).