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Magnetoresistance of magnetic multilayers containing three types of magnetic layers

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The magnetic-field dependence of the magnetoresistance MR(H) has been measured in the CPP mode (current perpendicular to the plane) for multilayers containing three different types of magnetic layers: permalloy Py(80 Å), Co(10 Å), and Co(70 Å). These data clarify the role of the electron mean free path in interpreting the MR(H) curves. A critical discussion is given of the view that denies the role of the electron mean free path for determining the MR(H) curves.

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Interest in the giant magnetoresistance (GMR) exhibited by magnetic multilayers has not abated since the effect was first discovered over a decade ago.[1] For the CPP mode (current perpendicular to the plane of the layers), the theoretical model of Valet and Fert[2] has proved especially useful, and has been very successful in explaining a wide variety of CPP GMR data.[3] Recently, CPP magnetoresistance measurements have been extended to multilayers having two different types of magnetic layers (denoted 2M multilayers). The emphasis of these measurements has been the magnetic-field dependence of the magnetoresistance MR(H).[4–6]

Interest has focused on the comparison between the MR(H) curves for a pair of 2M multilayers that differ *only* in the ordering of the magnetic layers. The pair of 2M multilayers chosen for comparative study has the following configurations: $[\mathrm{M1/NM/M2/NM}]_N$ (interleaved configuration) and $[\mathrm{M1/NM}]_N[\mathrm{M2/NM}]_N$ (separated configuration), where M1 and M2 are the two different magnetic layers, NM is the nonmagnetic layer, and N denotes the number of repeats. The nonmagnetic layer is sufficiently thick (typically 200 Å) to ensure that there is no coupling between neighboring magnetic layers.

In the simplest theoretical picture, one expects the MR(H) curves to be independent of the ordering of the magnetic layers. However, it was found that the resulting MR(H) curves are very different for the two different configurations.[4–6] The *reason* for this striking difference has become the subject of controversy.

Background. One school of thought has proposed spin-flip scattering as the reason for the difference in the measured MR(H) curves for the two different configurations.[7,8] It is certainly true that spin-flip scattering will lead to differences. However, a successful interpretation of the data must explain the detailed shape of the observed MR(H) curve for each configuration, including the number of peaks, their structure (symmetric or asymmetric), and the magnetic field at which each peak occurs. Therefore, we believe that a different interpretation is required.

We recently measured MR(H) for 2M multilayers, using Co layers of different thicknesses for the two different magnetic layers.[5] Our choice was guided by the fact that Co is known to have a long spin diffusion length[4,9] and, therefore, spin-flip scattering is not expected to be important. Nevertheless, we found very different MR(H) curves for the two configurations, as had been found for every other choice of magnetic layers.[4] We attributed our results to the long electron mean free path λ, which enables the electron to sample at least two magnetic layers before being scattered. On this basis, we explained *all features* of the MR(H) curves, including the structure and position of every peak observed for each configuration.

Present note. Our interpretation of the MR(H) curves for 2M multilayers was recently challenged.[7,8] Data were presented that claimed to show that λ is irrelevant for the MR(H) curves. This claim will be refuted in this paper in two ways. First, we shall show that the recent data do not, in fact, challenge our interpretation. Second, we present MR(H) curves for a type of magnetic multilayer that can be explained in detail *only* if one includes the effect of λ.

We have measured MR(H) for multilayers having three different magnetic layers (denoted 3M multilayers). The importance of these new data lies in the fact that the MR(H) curves for 3M multilayers exhibit a far richer structure of peaks, for both the interleaved and the separated configurations. Therefore, the 3M data constitute a much greater challenge in interpretation. Moreover, there are many additional possibilities for the ordering of the magnetic layers in 3M multilayers, each yielding a different MR(H) curve. A successful interpretation must explain all these differences. We shall show that *all the observed features* of the MR(H) curves for 3M multilayers find a natural explanation within the model that emphasizes the importance of λ.

Discussion. The physics that underlies the MR(H) curves is the following. The scattering probability of an electron in a magnetic multilayer is determined by the angle between the electron spin and the magnetic moment of the magnetic layer. This angle changes as the magnetic field rotates the moment of the magnetic layers. Hence MR depends on the magnetic field H.

Since λ is far longer than the thickness of the nonmagnetic layer,[7,8] one cannot speak of the electron being scattered by a single magnetic layer. Rather, one must consider the electron as being scattered by the combined potential of *a pair* of neighboring magnetic layers,[10] with the contribution to MR(H) from each scattering event given by the cosine of the angle $\theta_{i,j}$ between the moments of neighboring (denoted i and j) magnetic layers.[11,12] The value of MR(H) increases/decreases as the angle $\theta_{i,j}$ increases/decreases with magnetic field.

The interesting feature of 2M and 3M multilayers is that *more than one type* of magnetic layer is involved. Therefore, the angles $\theta_{i,j}$ between neighboring magnetic layers are very different for the interleaved and separated configurations, and it follows that the two configurations will yield very different MR(H) curves.

Criticism. Recently, it was proposed that the above interpretation is erroneous, and that λ is, in fact, irrelevant for the interpretation of the MR(H) curves for 2M multilayers.[7,8]

To support their proposal, these workers prepared 2M multilayers whose nonmagnetic layers consisted of Cu doped with Ge (hereafter CuGe). It was claimed that the electron mean free path in the doped nonmagnetic CuGe layer, λ_{CuGe}, was sufficiently short that the electron did not reach the neighboring magnetic layer before scattering in the nonmagnetic layer. According to our interpretation — so it is claimed — the MR(H) curves should be very different for samples having doped and undoped nonmagnetic layers. However, these workers reported that their measured MR(H) curves were qualitatively the same regardless of whether the nonmagnetic layers consisted of pure Cu or of doped CuGe.

A key feature of this claim is the value assumed for λ_{CuGe} for the doped samples. The quantity that is measured is, of course, not λ_{CuGe}, but the resistivity ρ_{CuGe} of the nonmagnetic layers of the doped samples, which was reported to be 8.0 $\mu\Omega$ cm. Therefore, the important question is how to convert the measured quantity, ρ_{CuGe}, into the theoretical quantity, λ_{CuGe}. These workers[7,8] used the following textbook expression,[13] based on the the simplest one-plane-wave, free-electron approximation[14]

$$\lambda = (92\ \text{Å}) r_s^2/\rho, \tag{1}$$

where r_s is the electron density parameter measured in Bohr radii, and ρ is the resistivity measured in $\mu\Omega$cm.

How reliable is the approximate Eq. (1) for the noble metals? This question has been answered by the comprehensive resistivity calculations of Bergmann and co-workers[15,16] for all three noble metals, both as a function of temperature and as a function of residual resistivity. As is well known, the noble metals differ from the free-electron model by the presence of necks on the Fermi surface. The calculations show that the scattering of the neck electrons *dominates* the resistivity, requiring a two-plane-wave pseudo-wave function, *both* for the Fermi surface *as well as* for the scattering matrix elements. Indeed, Eq. (1) underestimates the *average* mean free path of the noble metals by a factor of 3–4, and for electrons on certain parts of the Fermi surface, Eq. (1) underestimates λ_{CuGe} by an order of magnitude.

To consider the implications of these results, we take a factor-of-5 increase in λ_{CuGe} beyond the prediction of Eq. (1). This yields that λ_{CuGe} is equal to the doped layer thickness t_{CuGe}.[7,8] Therefore, the percentage of electrons that traverse the nonmagnetic layer without scattering is $\exp(-t_{CuGe}/\lambda_{CuGe}) = \exp(-1) = 0.37$. That is, 37% of the electrons will sample two neighboring magnetic layers before scattering, whereas 63% will be scattered within the nonmagnetic layer.

Within the framework of the phenomenological model,[12] it is straightforward to generalize the expression for MR(H) to the case in which some of the electrons are scattered within the nonmagnetic layer while the rest are not. The resulting curves[17] show that if as few as 20% of the electrons traverse the nonmagnetic layer without scattering, the MR(H) peaks are still *clearly present* but much diminished in magnitude, both for the interleaved and for the separated configurations.

The data of Ref. 7 (see their Fig. 1) show that, upon doping, the heights of the peaks in MR(H) are reduced by up to an order of magnitude, but their positions (as a function of field) are unchanged. These experimental results are thus in accord with the calculation.

It is not surprising to find that it is difficult to eliminate the peaks observed for MR(H) by simply doping the nonmagnetic layers. Mountain peaks do not disappear from view if the valley floor is raised. Gijs and Bauer[18] pointed out in their comprehensive review of MR(H) that the requirement for the applicability of the two-current series-resistor model is that $\lambda \ll t$.

Another important point regards the MR(H) curves for the CIP mode (current in the plane of the layers). As is well known,[19] in the CIP mode, the electron mean free path is a crucial parameter. Since the mean free path plays an important role in both the CIP and the CPP modes, one would expect to find that the MR(H) curves are qualitatively similar for the two modes, both for the interleaved and the separated configurations. Here, too, the prediction is in accord with the data.[20,21]

Our data — 3M multilayers. To settle this controversy, we measured MR(H) for 3M multilayers, for which there is a far richer array of possibilities. For 2M multilayers, only one angle $\theta_{i,j}$ is possible (i=M1, j=M2). However, for 3M multilayers, three such angles are possible (i=M1, j=M2; i=M1, j=M3; i=M2, j=M3).

For the three magnetic layers, we chose permalloy Py(80 Å), Co(10 Å), and Co(70 Å). The advantage of this choice is that the saturation field H_s of the magnetic layers spans a wide range, with H_s being several Oe for Py(80 Å), several tens of Oe for Co(70 Å), and several hundreds of Oe for Co(10 Å).

For our 3M multilayers, the ordering of the layers for the interleaved and the separated configurations was $[\text{M1/NM/M2/NM/M3/NM}]_N$ and $[\text{M1/NM}]_N[\text{M2/NM}]_N[\text{M3/NM}]_N$, with $N=3$ repeats. We performed magnetization measurements to confirm the absence of exchange and dipole coupling, obtaining identical magnetization curves for the 3M multilayers for the interleaved and separated configurations.

A description of the experimental details of the growing of the multilayers has been given previously.[5,6] Consistency between the different configurations was enhanced by growing the two configurations during the same run.

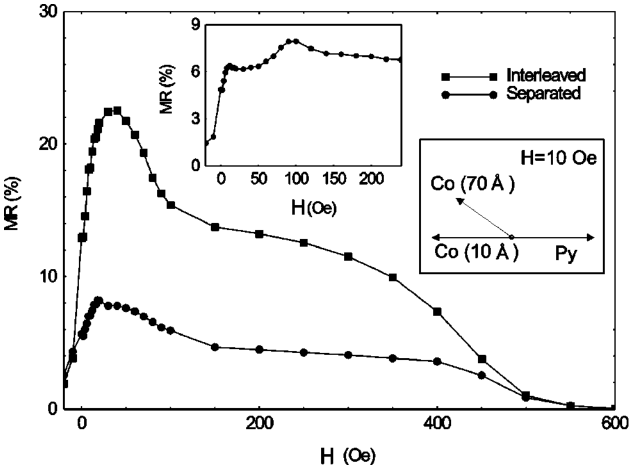

FIG. 1. Field dependence of the magnetoresistance MR(H) for the interleaved (squares) and separated (circles) configurations for 3M multilayers, measured at 4.2 K. The three magnetic layers were Py(80 Å), Co(10 Å), and Co(70 Å). The left-hand inset gives MR(H) for the separated configuration having a different order for the magnetic layers (see the text for details). The right-hand inset shows schematically the direction of the magnetic moments for each type of magnetic layer at a field of 10 Oe.

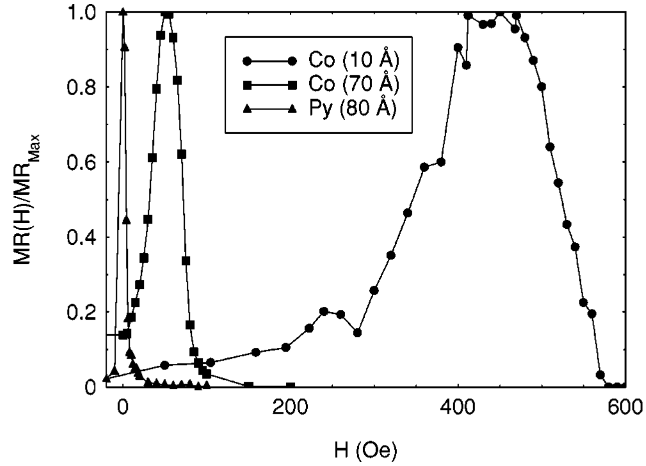

FIG. 2. Field dependence of the magnetoresistance MR(H) for three different 1M multilayers: Co(10 Å) (circles), Co(70 Å) (squares), and Py(80 Å) (triangles), all measured at 4.2 K.

Experimental results. The MR(H) curves for the 3M multilayers are presented in Fig. 1 for the interleaved and separated configurations. We note the following important differences between the 3M curves and those obtained previously[4–6] from 2M multilayers. (i) For 2M multilayers, the MR(H) curves are strikingly different for the two configurations, whereas for 3M multilayers, the MR(H) curves are qualitatively similar for the two configurations. For both configurations, the MR(H) curve has a narrow, distinct peak at small fields, followed by a broad, less distinct peak at higher fields. (ii) For the separated configuration the 2M multilayers exhibit two distinct peaks for MR(H), whereas for 3M multilayers there is only one distinct peak followed by a very broad peak. (iii) For the interleaved configuration the 2M multilayers exhibit only one peak for MR(H), whereas for 3M multilayers the low-field peak is followed by a broad, less distinct peak. We shall see that all these features of the MR(H) curves for 3M multilayers can be explained in terms of the λ dependence of MR(H).

Features of the 3M multilayers. There are important features of 3M multilayers both for the interleaved configuration and for the separated configuration. For the interleaved configuration, as the magnetic field increases, one the three angles $\theta_{i,j}$ *increases* while the other two angles $\theta_{i,j}$ are *decreasing*. Thus there is a *competition* between an increase in MR(H) (due to scattering by pairs of layers with increasing $\theta_{i,j}$) and a decrease in MR(H) (due to the scattering by pairs of layers with decreasing $\theta_{i,j}$). This leads to the complex structure we observe for the MR(H) curves for 3M multilayers.

The interesting feature for the separated configuration relates to the boundary layers, meaning the pair of different neighboring magnetic layers (say, M1/NM/M2) between the group of M1 magnetic layers and the group of M2 magnetic layers. For 2M multilayers, only one type of boundary layer exists. For 3M multilayers, however, there are *three* types of boundary layers (M1/NM/M2, M1/NM/M3, and M2/NM/M3). Since the 3M multilayer in the separated configuration has *two* boundary layers, there are *three* different possibilities (the three ways of choosing a pair from three objects) for the separated multilayer. Of particular interest is the fact that the MR(H) curves are quite different for the different possibilities of separated 3M multilayers.

Explanation of the MR(H) curves. (i) *3M multilayers — interleaved configuration.* The most important feature of 3M multilayers in the interleaved configuration is the competition between increasing and decreasing values of the angle $\theta_{i,j}$ between neighboring magnetic layers. Consider a magnetic field of 10 Oe. The Py layers will already have saturated in the field direction, but the Co(10 Å) layers will hardly be affected by the magnetic field because their saturation field is several hundred Oe. Thus, the moments of the Py and the Co(10 Å) layers are nearly antiparallel. Finally, the moments of the Co(70 Å) layers will be partially rotated at $H=10$ Oe (see schematic inset in Fig. 1), because their saturation field is several tens of Oe.

As the magnetic field is increased, the angle between the moments of Py and Co(70 Å) *decreases*, whereas the angle between Co(10 Å) and Co(70 Å) *increases*. As a result of this competition, the first peak of the MR(H) curve for the interleaved configuration continues to rise even after the Py layers saturate, thus shifting the position of the peak to larger fields. Since this effect does not occur for 2M multilayers consisting of Py and Co, the peak in the interleaved MR(H) curve occurs at a much smaller field.[4]

(ii) *3M multilayers — separated configuration.* In Fig. 2, we present the three MR(H) curves of multilayers containing only one type of magnetic layer (denoted 1M multilayers), that is, only permalloy Py(80 Å) or only Co(10 Å) or only Co(70 Å). As expected, each 1M multilayer MR(H) curve consists of a single symmetric peak.

The MR(H) curve for the 3M multilayer in the separated configuration is not simply the sum of these three 1M multilayer MR(H) peaks. The absence of three distinct peaks in the 3M multilayer in the separated configuration (Fig. 1) is due to the contribution to MR(H) arising from the two boundary layers. These boundary layers may wash out (or weaken) the peaks, depending on which boundary layers are present. Of the three possibilities — Py(80 Å)–Co(10 Å) or Py(80 Å)–Co(70 Å) or Co(10 Å)–Co(70 Å) — only two will be present in any given 3M multilayer. Therefore, the MR(H) curves are not expected to be the same for different choices for the ordering of the magnetic layers in the 3M separated configuration.

To test this prediction, we prepared a second 3M separated multilayer that was identical to the separated multilayer of Fig. 1, except for the ordering of the three groups of magnetic layers. The first separated configuration had the order Co(70 Å)–Py(80 Å)–Co(10 Å), whereas the order of the second separated configuration was Py(80 Å)–Co(10 Å)–Co(70 Å). The MR(H) curve of the second separated multilayer is given in the inset of Fig. 1, where one sees two distinct low-field peaks. The presence of a second peak can be explained[17] in terms of the different contributions to MR(H) arising from the different boundary layers: Py(80 Å)–Co(70 Å) is present in the first but absent in the second, whereas Co(10 Å)–Co(70 Å) is present in the second but absent in the first.

(iii) *Similarity between interleaved and separated configurations for 3M multilayers.* Unlike the case for 2M multilayers, the present MR(H) curves are qualitatively similar for the two configurations. If the first two peaks in the MR(H) curve for the separated configuration are washed out, then the result will be only one asymmetric peak at small fields. However, an asymmetric peak at small fields is the hallmark of the MR(H) curve in the interleaved configuration. Therefore, the MR(H) curves for the two configurations appear qualitatively similar for 3M multilayers.

Summary. We have shown that recent criticism of our interpretation of the MR(H) curves for 2M multilayers is misplaced. In addition, we have measured MR(H) for 3M multilayers and have explained all features of the curves on the basis of the interpretation in which the electron mean free path plays a central role.

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