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# Comparative study of the magnetoresistance of MBE-grown multilayers: $[\mathrm{Fe/Cu/Co/Cu}]_N$ and $[\mathrm{Fe/Cu}]_N[\mathrm{Co/Cu}]_N$

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We have carried out measurements of the magnetic-field dependence of the magnetoresistance $[\mathrm{MR}(H)]$ in the current perpendicular to the plane (CPP) mode for magnetic multilayers having the following configurations: $[\mathrm{Fe/Cu/Co/Cu}]_N$ and $[\mathrm{Fe/Cu}]_N[\mathrm{Co/Cu}]_N$. The two configurations had the same number, types, and thicknesses of magnetic and nonmagnetic layers; their only difference lay in the ordering of the magnetic layers. Nevertheless, the measured MR($H$) curves are found to be completely different for the two configurations. The implications of these results are discussed for the spin-diffusion length. [S0163-1829(99)00229-5]

## I. INTRODUCTION

A subject of recent interest in the study of magnetic multilayers is the magnetic-field dependence of the magnetoresistance $[\mathrm{MR}(H)]$ in the current perpendicular to the plane (CPP) mode, that is, with the current perpendicular to the plane of the layers.[1–5] Measurements of MR($H$) are technically more difficult in the CPP mode than in the current in-plane (CIP) mode. However, there are advantages to the MR($H$) data in the CPP mode. For example, a short electron scattering mean free path does not diminish MR($H$) in the CPP mode, as it does in the CIP mode.[6,7] Also, it has been suggested[8,9] that experimental values of MR($H$) in the CPP mode can shed light on the spin-diffusion length. These important features of CPP data for MR($H$) provided the motivation for the present study.

As is well known, the phenomenon of the giant magnetoresistance occurs because in ferromagnetic metals, the spin-up electrons and the spin-down electrons have different scattering rates. If the electron does not flip its spin upon scattering, then the spin-up and spin-down electrons constitute two separate currents, with different resistivities, as if flowing in two parallel wires. At low temperatures, spin-flip scattering mechanisms may be assumed to be weak, and theoretical analyses of MR($H$) have usually been based on this assumption. Therefore there is great interest in experimentally examining systems for which electrons *may* flip their spin, in order to measure the corresponding change in the values of MR($H$).

We report here the results of such a study. Measurements have been carried out of the magnetic-field dependence of the magnetoresistance MR($H$) in the CPP mode for magnetic multilayers having the following configurations: $[\mathrm{Fe/Cu/Co/Cu}]_N$ and $[\mathrm{Fe/Cu}]_N[\mathrm{Co/Cu}]_N$. These two configurations are identical except for the ordering of the magnetic layers. Nevertheless, we found that the measured MR($H$) curves are completely different for the two configurations. The implications of these results for spin-flip scattering are discussed.

## II. PREVIOUS WORK

A similar study[10] was recently reported by Pratt and coworkers at Michigan State University, using Co and Py as the two ferromagnetic metals. These workers (Chiang *et al.*[10]) found that although they measured the magnetoresistance in the CPP mode, the resulting MR($H$) curves were completely different for the configurations $[\mathrm{Py/Cu/Co/Cu}]_N$ and $[\mathrm{Py/Cu}]_N[\mathrm{Co/Cu}]_N$ (denoted henceforth as ‘‘interleaved’’ and ‘‘separated,’’ respectively). For measurements in the CPP mode, Chiang *et al.* pointed out that one should obtain identical MR($H$) curves for the interleaved and the separated configurations. When this proved not to be the case, they attributed their results to the short spin-diffusion length in Py. (Co is known to have a long spin-diffusion length.[11]) Analyzing their resistivity data within the framework of the Valet-Fert theory,[8,9] they obtained[12,13] for Py a spin-diffusion length of about 55 Å, a value so short as to imply significant mixing between the spin-up and spin-down electron currents. Chiang *et al.* proposed that because of this spin flipping, the separated and interleaved configurations yield different MR($H$) curves even though measured in the CPP mode.

We here extend the work of Chiang *et al.* to other ferromagnetic metals that are *not* expected to have a short spin-diffusion length. In particular, we used Fe instead of Py as the second ferromagnetic metal (in addition to Co). Since the spin-diffusion length of Fe is probably not as short as Py, one would expect to obtain identical (or, at least, similar) CPP-mode MR($H$) curves for the interleaved and separated configurations. However, as already pointed out, this was not found to be the case.

## III. EXPERIMENTAL DETAILS

The multilayers were grown in our VG-80M MBE facility using a base pressure of typically $4\times10^{-11}$ mbar. Our CPP measurements used the superconducting Nb electrode technique, developed in collaboration with Pratt and co-workers.[1] As in our previous CPP measurements,[2,3] the superconduct-

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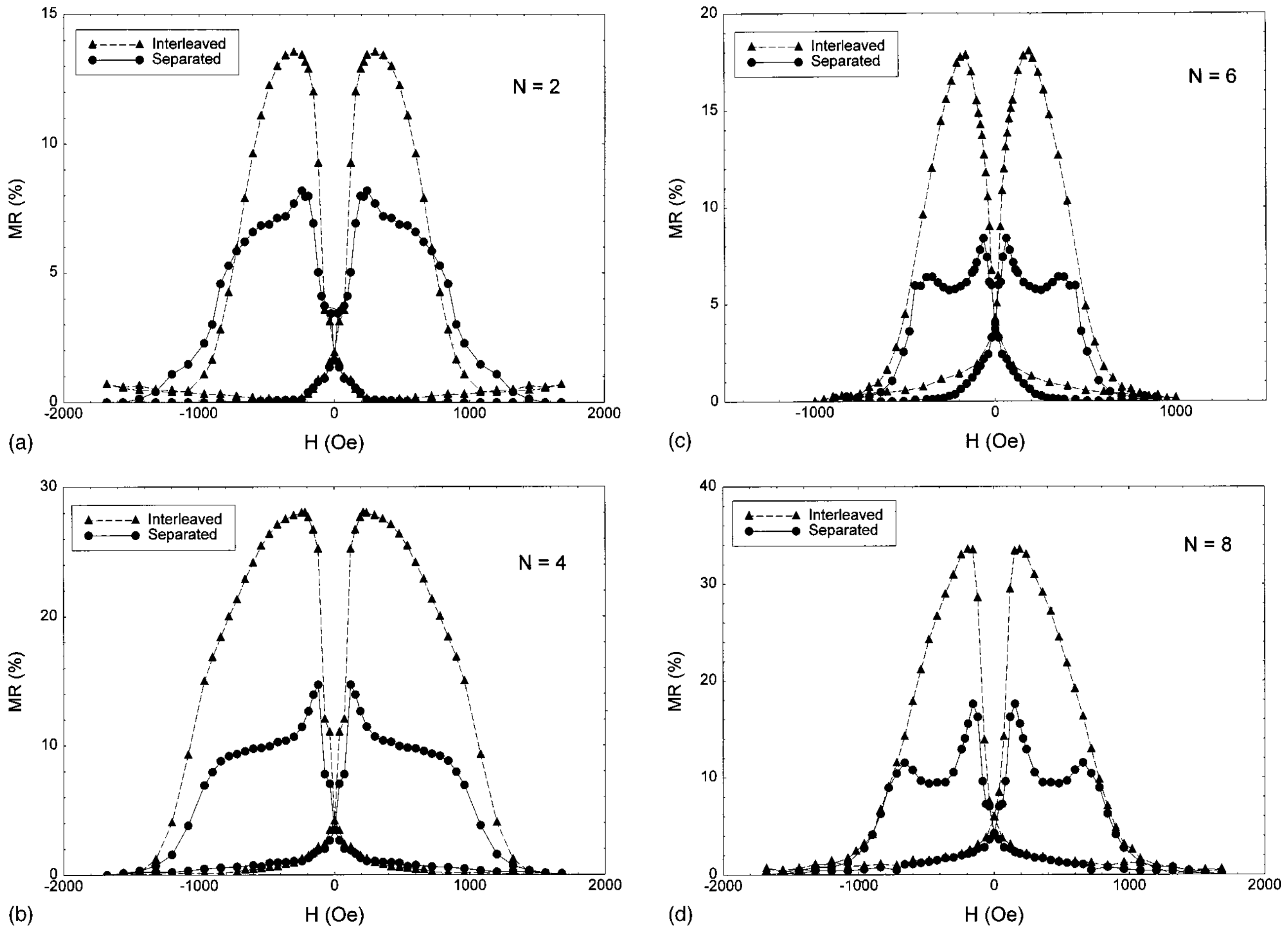

FIG. 1. Magnetic-field dependence for the magnetoresistance MR($H$) for interleaved multilayers (triangles) and separated multilayers (circles) containing Fe and Co as the two ferromagnetic metals, for the following number (N) of layers: (a) 2; (b) 4; (c) 6; (d) 8.

ing equipotential ensures that the current is perpendicular to the layers. We used a superconducting quantum interference device based current comparator, working at 0.1% precision to measure changes in the sample resistance of order 10 p$\Omega$. In order to avoid driving the Nb normal, the CPP measurements were performed at 4.2 K in magnetic fields below 3 kOe. Consistency between the interleaved and separated samples was enhanced by growing the two configurations during the same growth run for each value of $N$.

The thicknesses of the ferromagnetic layers were chosen to be 20 Å for Fe and 50 Å for Co, which allows a difference of about 700 Oe in the coercive field of the two materials. The thickness of the nonmagnetic layers was chosen to be 200 Å to ensure magnetic decoupling between the ferromagnetic layers.

## IV. RESULTS

We have measured the magnetoresistance in the CPP mode for the two configurations $[\mathrm{Fe/Cu/Co/Cu}]_N$ and $[\mathrm{Fe/Cu}]_N[\mathrm{Co/Cu}]_N$ for $N=2,4,6,8$. The measured curves for MR($H$) are presented for the four values of $N$ in Figs. 1(a)–(d). The triangles represent the MR($H$) data in the ''interleaved'' configuration $[\mathrm{Fe/Cu/Co/Cu}]_N$, whereas the circles represent the data in the ''separated'' configuration $[\mathrm{Fe/Cu}]_N[\mathrm{Co/Cu}]_N$. The lines were drawn to guide the eye. In each case, the saturation magnetic field was about 1 kOe.

The most important feature of these data is the striking difference between the MR($H$) curves for the two configurations, both in shape and in magnitude.

For each $N$, the maximum value of MR($H$) is seen to be nearly twice as large for the interleaved configuration. Moreover, the MR($H$) curve for the interleaved configuration exhibits a single peak, whereas for the separated configuration, the MR($H$) curve displays a double peak, with the two peaks becoming better delineated for larger values of $N$. The position of these peaks corresponds approximately to the coercivity of the Fe (≈180 Oe) and that of the Co (≈700 Oe).

## V. DISCUSSION

The MR($H$) curve for the interleaved configuration can be understood. The coercive fields for Fe and Co are very different. Therefore as the field increases beyond zero, the magnetic moments of the Fe layers are rotated significantly while the direction of the Co moments is still almost unchanged. This leads to a large angle between neighboring ferromagnetic layers, which is the criterion for a large value of MR. This explains the initial rapid rise in MR($H$). Then, as the field increases still more, the Co moments also rotate, and therefore there is a decrease in the angle between the moments of a Co layer and the moments of the neighboring Fe layer. This explains the subsequent decrease in MR($H$).

The results for the separated configuration are more difficult to interpret. Since the contribution to the resistance due to each layer adds *in series* in the CPP mode,[6] one might expect that the ordering of the ferromagnetic layers should be of no consequence for the total resistance of the sample. Nevertheless, it is clearly observed from the figures that the order of the layers matters very much for the MR($H$) curves.

The MR($H$) curve for the separated configuration appears to be the sum of two curves, with each curve being characteristic of MR($H$) for a multilayer having only one type of ferromagnetic metal—either $[\mathrm{Fe/Cu}]_N$ or $[\mathrm{Co/Cu}]_N$. In other words, the observed MR($H$) curve corresponds to the situation in which the current through one type of ferromagnetic layers has no connection with the current through the other type of ferromagnetic layers. Each current produces its own MR($H$) curve, with its own peak, and the observed MR($H$) curve is simply the sum of the two separate contributions. Such a result would be expected if the spin-diffusion length were very short.

For the separated configuration, the delineation of the two peaks with increasing $N$ is probably due to the lessening importance of ‘‘boundary effects.’’ This means that at the boundary between the Fe/Cu layers and the Co/Cu layers, the Co layer has a neighboring magnetic layer of Fe, rather than of Co (and similarly for the Fe layers). For $N=2$, one of the two Co layers (50%) are ‘‘boundary’’ layers, whereas for $N=8$, one of the eight Co layers (only 13%) are ‘‘boundary’’ layers. Thus as $N$ increases, the effect of the boundary layers becomes less important and the two peaks become sharper.

The fact that these two configurations lead to very different results for MR($H$) was reported previously by Chiang *et al.*[10] using Co and Py as the two ferromagnetic metals. They attributed the difference between the two configurations to the usually short spin-diffusion length (55 Å) in Py. However, this explanation seems less likely here, because the spin-diffusion length of Fe is not expected to be as short as Py. Perhaps the observed difference in the MR($H$) curves between the two configurations can be explained in terms of interfacial spin-flip scattering, because the magnetic-nonmagnetic interfaces are replete with surface spin waves, roughness, disordered spins, etc. We are also examining the possibility that nonlocal electron scattering may be important. Further experiments and calculations are necessary to resolve this question.

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