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Dependence of the magnetoresistance of magnetic multilayers on the number of magnetic layers

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We have measured the dependence of the giant magnetoresistance of a magnetic multilayer (oriented in the current perpendicular to the plane of the layers mode) on the number of layers in the multilayer, with the thickness of the magnetic layers being held fixed. The results are discussed in terms of spin diffusion scattering and mean free path effects.

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INTRODUCTION

Although two decades have passed since the discovery of the giant magnetoresistance (GMR) in magnetic multilayers,[1] questions remain unresolved regarding GMR measurements in the current perpendicular to the plane of the layers (CPP) mode. To shed light on some of these questions, we performed CPP measurements for the GMR for multilayers having magnetic layers of given thickness t_o as a function of the number N of layers, denoted GMR(N,t_o). We compare our results with GMR measurements[2,3] that have dealt with the complementary case of a multilayer having a given number N_o of magnetic layers but varying layer thickness t, denoted GMR(N_o,t). We find a very significant difference between the dependence of GMR(N,t_o) and that of GMR(N_o,t) on the total thickness of all the magnetic layers. An explanation of this difference is presented, based on the electron mean free path. We also discuss the role played by spin-flip scattering in interpreting these results.

EXPERIMENTAL DETAILS

The multilayers were grown using a sputtering system consisting of dc magnetrons for the deposition of the metals, with a base pressure of typically 4×10^{-8} mbar and sputtering rates of about 3 Å/s. A Nb strip, of thickness 1500 Å, was first deposited on a native oxide silicon substrate, followed by 200 Å of Cu as a buffer layer. Our CPP measurements used the superconducting Nb electrode technique.[4] The multilayers were sandwiched between 0.2-mm-wide strips of Nb. The superconducting equipotential ensures that the current is perpendicular to the layers. We used a superconducting quantum interference device based current comparator, which enables us to measure changes in the sample resistance of order 10 pΩ. To avoid driving the Nb normal, the resistivity measurements were performed at 4.2 K in magnetic fields below 3 kOe.

SAMPLES

Attention has recently focused on CPP measurements of the GMR for multilayers containing two types of magnetic layers (denoted 2M multilayers).[5–8] An interesting feature of 2M multilayers is that the same set of magnetic layers can be arranged in different structures. The structures most widely studied are $[\mathrm{M1/NM/M2/NM}]_N$ (interleaved configuration) and $[\mathrm{M1/NM}]_N[\mathrm{M2/NM}]_N$ (separated configuration), where M1 and M2 denote the two types of magnetic layers, NM denotes the nonmagnetic spacer layer, and the subscript N gives the number of repeats. The value for the GMR is always larger for the interleaved configuration.[7]

We report here CPP measurements of the GMR for 2M multilayers as a function of the number of repeats, with the thickness of the magnetic layers being held fixed. Thus, the total thickness of all the magnetic layers was determined by the number of repeats. For the two types of magnetic layers, we chose (i) Co and Py (Permalloy) and (ii) two different thicknesses of Co. The difference between the two magnetic layers is expressed in their different coercive fields. Therefore, layers of Co of different thicknesses are "different" types of magnetic layers. The nonmagnetic layer was sufficiently thick (200 Å of Cu for our samples) to ensure that there is no coupling between neighboring magnetic layers. We confirmed the absence of coupling by means of magnetic measurements.

One set of multilayers consisted of $[\mathrm{Py(80\ Å)/Cu(200\ Å)/Co(30\ Å)/Cu(200\ Å)}]_N$ (interleaved configuration) and $[\mathrm{Py(80\ Å)/Cu(200\ Å)}]_N[\mathrm{Co(30\ Å)/Cu(200\ Å)}]_N$ (separated configuration), whereas the other set of multilayers consisted of $[\mathrm{Co(10\ Å)/Cu(200\ Å)/Co(70\ Å)/Cu(200\ Å)}]_N$ (interleaved configuration) and $[\mathrm{Co(10\ Å)/Cu(200\ Å)}]_N[\mathrm{Co(70\ Å)/Cu(200\ Å)}]_N$ (separated configuration).

EXPERIMENTAL RESULTS

The magnetoresistance ΔR is the maximum change in resistance of the multilayer upon applying a magnetic field. The measured quantity is denoted $\Delta R(N,t_o)$, indicating that the number N of repeats changes from sample to sample, whereas the thickness t_o of the magnetic layers is held fixed.

Our results for $\Delta R(N,t_o)$ as a function of N are given by the symbols in Figs. 1 and 2 for the interleaved (squares) and separated (circles) configurations. The two magnetic layers are Py(80 Å) and Co(30 Å) in Fig. 1, and Co(10 Å) and

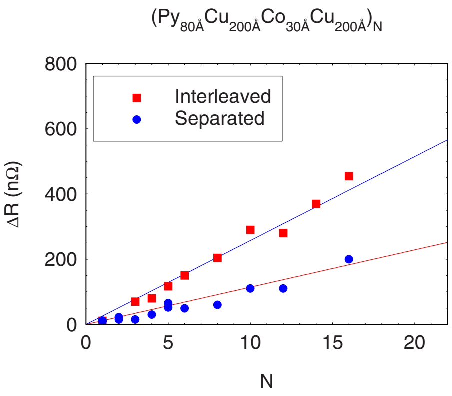

FIG. 1. (Color online) Dependence of ΔR on the number of repeats N of the 2M multilayer having Py(80 Å) and Co(30 Å) as the two magnetic layers. The straight lines were drawn to guide the eye.

Co(70 Å) in Fig. 2. The straight lines are drawn to guide the eye.

In all cases, $\Delta R(N,t_o)$ is seen to increase linearly with N, regardless of whether the magnetic metal is Py or Co, and regardless of whether one considers the interleaved or the separated configuration.

It is instructive to compare the present results with measurements of $\Delta R(N_o,t)$ as a function of magnetic layer thickness. One set of such measurements[2] dealt with a trilayer spin valve having Py as the magnetic layer, whose moment was oriented by the applied magnetic field. These $\Delta R(N_o,t)$ data are presented in Fig. 3 as a function of the thickness of the Py layer. (The line has been drawn to guide the eye.) Other previously measured $\Delta R(N_o,t)$ data having Py as the magnetic metal were obtained by electrodeposition into nanometer-sized pores of a template polymer membrane.[3] The results were very similar to those displayed in Fig. 3.

It is seen in Fig. 3 that the $\Delta R(N_o,t)$ data begin to tend toward saturation when the thickness of the Py reaches about 60 Å. By contrast, our values of $\Delta R(N,t_o)$ show no sign of saturating even for $N=16$, for which the total thickness of the Py exceeds 1000 Å. Clearly, the behavior of ΔR is very dependent on whether the total thickness of the Py is increased by making the Py layers thicker or by increasing their number.

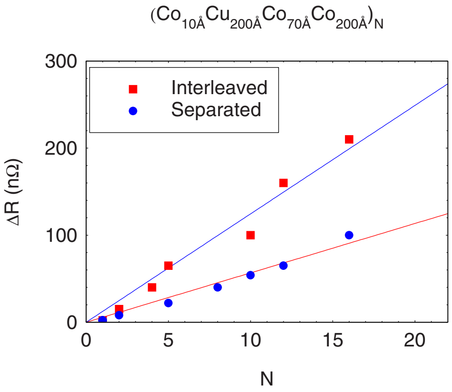

FIG. 2. (Color online) Dependence of ΔR on the number of repeats N of the 2M multilayer having Co(10 Å) and Co(70 Å) as the two magnetic layers. The straight lines were drawn to guide the eye.

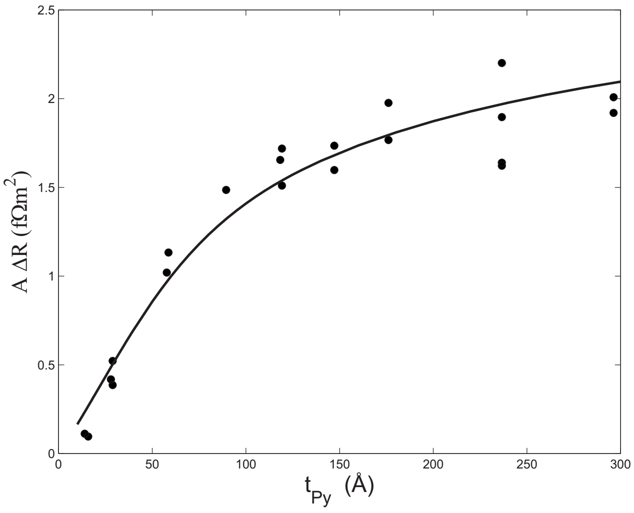

FIG. 3. Dependence of ΔR on the thickness t of the Py layer for a trilayer spin valve. The symbols represent the data of Ref. 2. The line has been drawn to guide the eye.

DISCUSSION

The data of Fig. 3 can be understood as follows. For thin multilayers, the electron mean free path is longer than the thickness of the magnetic layer. Consider the case for which the electron mean free path is long enough to include two magnetic layers. In such a case, the electron is scattered by the combined potential of both magnetic layers. Gittleman *et al.*[9] have shown that the contribution to ΔR due to spin-dependent electron scattering depends on the angle θ_{ij} between the moments of the two magnetic layers (denoted i and j). The larger the angle θ_{ij}, the greater will be the contribution to ΔR.[9,10]

For thin multilayers, every electron trajectory will include at least two magnetic layers. Since the number of electrons contributing to the current is linearly proportional to the thickness of the magnetic layers, this yields the observed initial linear increase in ΔR with the thickness of the magnetic layers.

As the magnetic layers become progressively thicker, the limit is eventually reached, in which the electron mean free path is shorter than the thickness of a single magnetic layer. In such a case, for some electrons, the mean free path lies entirely within a single magnetic layer. Since the magnetic field does not influence the resistance of such electrons, they do not contribute to ΔR. This is the explanation for the tendency of the data for ΔR toward saturation for thicker magnetic layers that is observed in Fig. 3.

In the CPP mode, the electron is scattered repeatedly as it drifts through all the layers in the direction perpendicular to the layers. If the mean free path is longer than the magnetic layer thickness, then the mean free path of the electron may include several magnetic layers. Mathon[11] has shown that, in such a case, the effective resistance of these several layers is equivalent to that of a fictitious layer whose resistance is the average resistance of the various layers, with the average being weighted by the fraction of the electron mean free path that takes place in each layer. Moreover, interface scattering must be taken into account. Each interface that is traversed by the electron along its mean free path also makes a contribution to the average resistance.

It should be noted that the present analysis invoking mean free path effects also explains the magnetic-field dependence of the magnetoresistance MR(H) measured for 2M multilayers[7] and for 3M multilayers.[12] These data include the detailed shape of the MR(H) curves both for the separated and the interleaved configurations, and the many differences between the MR(H) curves for the 2M and the 3M multilayers.

Spin-flip scattering

Neither the $\Delta R(N_o,t)$ data in Fig. 3 nor the other set of $\Delta R(N_o,t)$ data[3] were interpreted by the experimenters as described above. Rather, both groups of workers attributed the observed saturation for $\Delta R(N_o,t)$ to spin-flip scattering.[2,3] However, the above discussion indicates that mean free path effects also lead to saturation for $\Delta R(N_o,t)$ even in the absence of spin-flip scattering.

The need to include a finite spin-diffusion length to explain magnetoresistance data has recently been discussed by Baxter *et al.*[13] for Co/Cu/Co spin valves. Baxter *et al.* generalized the expression for the GMR by incorporating a realistic band structure and including interface proximity effects. When Baxter *et al.* analyzed the magnetoresistance data of Chiang *et al.*[14] for Co/Cu/Co spin valves in terms of their generalized expression,[13] they found that it is unnecessary to introduce a finite spin-diffusion length to explain the data.

There are currently three different proposed mechanisms that would explain the saturation effects exhibited by the data in Fig. 3 (see the recent review by Bass and Pratt[15]): (i) a finite spin-diffusion length, (ii) interface proximity effects, and (iii) mean free path effects. Further experiments will be necessary to determine the relative contributions of each of these mechanisms.

SUMMARY

The dependence of ΔR for 2M multilayers has been measured as a function of the number N of repeats. It was found that in all cases, ΔR increased linearly as a function of N. Saturation effects were not observed even when one of the magnetic layers was Py. A possible explanation for these results is presented.

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