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"Field-dependent interface resistance" of Ag/Co multilayers

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For Ag thicknesses large enough to magnetically decouple the Co layers, the resistances in magnetic field of a series of Ag/Co multilayers with the current flowing perpendicular to the layer plane are consistent with a simple series summation of resistances due to the Ag and Co layers plus an "interface resistance," $R_{\text{Ag-Co}}(H)$, that depends upon the relative orientations of the magnetizations in neighboring ferromagnetic layers in different magnetic fields, H. The resulting Co resistivity is weakly field dependent, and $R_{\text{Ag-Co}}(H)$ is strongly field dependent: $AR_{\text{Ag-Co}}(H)$, where A is the sample area, decreases from $\approx 0.6\ \text{f}\Omega\,\text{m}^2$ at the initial field, $H_0=0$, to $\approx 0.2\ \text{f}\Omega\,\text{m}^2$ at the saturation field, H_S.

Magnetic multilayers composed of thin layers of ferromagnetic (F) metals, such as Co or Fe, alternated with thin layers of nonmagnetic (N) metals, such as Cu, Cr, or Ag, display large decreases in electrical resistance—i.e., several percent to well over 50%—with increasing magnetic field H when measured with the *c*urrent *i*n the layer *p*lane (called the CIP geometry) and the magnetic field also in this plane.[1,2] These large resistance decreases —called giant magnetoresistances (MR)—have excited scientific and technological interest.[3]

While the giant CIP MRs of different multilayer systems show diversity in details, two elements seem common: (a) The CIP MR is due to a complex process involving transfer between F layers of spin-polarized electrons that encounter spin-dependent scattering, both within the F layers and at the F/N interfaces, which causes the MR to depend upon the relative alignment of the in-plane magnetizations M_i of neighboring F layers. (b) The largest CIP MR occurs when application of a magnetic field H directed in the layer planes causes this alignment to change from antiparallel at low field $H \approx 0$, to parallel at the saturation magnetic field, H_S.

The CIP geometry contains inherent complications for experimentally separating bulk from interface scattering, because the current density in the sample is nonuniform, and the current channels in the two different metals are connected by transmission of electrons through the interfaces. Such measurements have led to disagreement over the fundamental question of the relative importance of bulk and interface scattering in giant MR.[4-7]

We argue that the preferred geometry for separating bulk from interface scattering is the CPP geometry, where the *c*urrent flows *p*erpendicular to the layer *p*lanes. Here, since the current density is uniform across the sample area, and since electrons pass sequentially through the individual metals and the interfaces, it is natural to try a simple series resistance model in which the contributions from the individual metals and the interfaces are merely summed. We previously described how to measure the CPP MR,[8] and showed that, as predicted,[9] in Ag/Co it was substantially larger than the CIP MR. In the present paper, we show that a wider set of Ag/Co data is consistent in both form and magnitude with a series resistance model. We are enabled, thereby, to make a direct determination for a magnetic multilayer of what, for ease of discussion, we call the "field-dependent interface resistance," and designate by $R_{F\text{-}N}(H)$. We caution, however, that $R_{F\text{-}N}(H)$ is *not* simply the field-dependent resistance of an isolated F-N interface at the field H. Rather, as noted above, $R_{F\text{-}N}(H)$ measures how spin-dependent scattering at successive F/N interfaces changes, when increasing the magnetic field causes the relative orientations between the magnetizations M_i of neighboring F layers to change. We note, also, that the series resistance model need not always be valid; unfortunately, a complete analysis of when it is, and what to do when it is not, is not yet available.[10]

To apply the series resistor model at a given field, we must have similar M_i alignments for samples with wide ranges of thicknesses of the F and N layers. In several magnetic multilayer systems, F-layer interactions produce a spontaneous antiparallel alignment of the M_i's at $H=0$ for certain N layer thicknesses, and the F-layer interaction oscillates in sign, with decreasing magnitude, as the N-layer thickness increases.[11] To avoid the complications of oscillatory interactions, we have studied first the Ag/Co system, where no oscillations have been seen with Co-layer thicknesses, t_{Co}, as large as those we use,[8] and we analyze only data with Ag layer thicknesses $t_{\text{Ag}} \geq 4$ nm, where F-layer interactions should be weak. We also omit data for $t_{\text{Co}} > 20$ nm, as we have found that the M's and MR's of such samples can be complicated.[12]

We focus upon three fields shown in Fig. 1: (1) H_S, defined above; (2) H_0, zero applied field for the as-prepared sample; and (3) H_M, at which the total CPP resistance $R_T(H)$ is maximum after cycling through H_S. Figure 1 shows that $M \approx 0$ at both H_0 and H_M. However, the detailed relative orientations of the M_i's in Ag/Co are not yet known, and we have no advance guarantee that they will be the same at H_0 or H_M for different Ag- and Co-layer thicknesses. For specificity, we follow Johnson[13] and assume that at H_M the M_i are oriented randomly in the layer plane, and that at H_0 the ordering is nearly (but probably not completely) antiparallel along a single axis.

Our sample preparation techniques, and procedures for simultaneous measurements of the CIP MR and CPP

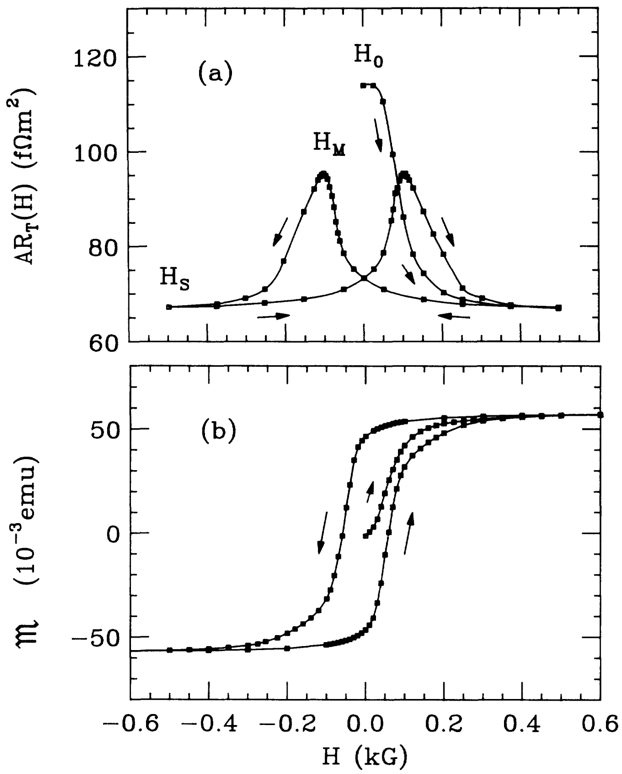

FIG. 1. Illustrative behaviors of (a) $AR_T(H)$ and (b) magnetization $M(H)$, for $t_{Co}=t_{Ag}=6$ nm. The arrows indicate the direction of field change.

MR, have already been described.[8] The samples in this paper were sputtered onto c-axis oriented single-crystal sapphire substrates cooled to temperatures between −30 and 30 °C, using Ar pressure ≈ 2.5 μm and sputtering rates Nb=9–10, Ag=10–13.5, and Co=9–10 Å/sec. The substrates were ≈ 12 cm from the targets. We focus upon the CPP MR, leaving the CIP MR to be discussed later.[12] A sample consists of an $\approx$ 1-mm-wide underlying strip of Nb, then a Ag/Co multilayer about 4 mm in diameter, and finally an overlying $\approx$ 1-mm-wide Nb strip oriented perpendicular to the first one.[8] At a measuring temperature of 4.2 K, the Nb strips superconduct, which ensures a uniform current density across the sample area, $A \approx 1$ mm^2 (measured to a few percent), corresponding to the overlap area of the crossed Nb strips. The "short and wide" sample geometry—length/width$\approx 10^{-3}$—makes fringing currents small.[12] Each sample in this paper had a total thickness t as near as possible to 720 nm, consistent with an integer number of Ag/Co bilayers. The bottom layer was Co. The top layer was Ag, both to give an integer number of bilayers and to protect the last Co layer from the atmosphere. Measurements of Nb/Co/Nb, Nb/Ag/Nb, and Nb/Ag/Co/Ag/Nb sandwiches indicate that contact with Nb causes Ag layers of the thicknesses used here to superconduct due to the proximity effect, and that the Nb/Ag/Co interface resistance is close to that for Nb/Co.[8,12,14]

As our measuring technique is inherently two terminal, the two interface resistances, $R_{\text{Nb-Co}}$, between the Nb cross strips and the outermost Co layers of the multilayer are included in $R_T(H)$. The intensive quantity for these two interfaces, $2AR_{\text{Nb-Co}}$, has been measured to be about 6 ± 1 fΩ m^2 for similarly sputtered Nb and Co,[14] and is independent of magnetic field at the fields used in this study.[8]

We have also independently measured the "bulk" residual resistivities of sputtered Ag and Co films and thin layers to be about 10 ± 2 and 60 ± 10 $n\Omega$ m, respectively, dominated by defects in the sputtered materials.[12,14] Such resistivities yield bulk elastic (non-spin-flip) mean free paths $\approx$ 80–100 nm for Ag (Ref. 15) and $\approx$ 10–40 nm (much less certain) for Co,[14,15] both *longer* than the respective Ag or Co layer thicknesses for most of our multilayers. The MRs of bulk Ag and Co with such high resistivities are negligible.

To analyze our data, we assume a series resistance model involving two contributions to the field dependence of $AR_T(H)$: (a) one proportional to t_{Co}, which we designate $\rho_{Co}(H)$, and (b) one proportional to the number of bilayers, N, which we have already called $R_{\text{Ag-Co}}(H)$. For the samples described above, we can then write $AR_T(H)$ as

$$AR_T(H)=2AR_{\text{Nb-Co}}+(N-1)\rho_{Ag}t_{Ag}+N\rho_{Co}t_{Co}+2(N-1)AR_{\text{Ag-Co}}(H)\,. \quad (1)$$

To simplify the analysis in this paper, we neglect the difference between N and $N-1$ and limit ourselves to fixed $t=Nt_{Ag}+Nt_{Co}$. We rewrite Eq. (1) for two cases.

Case No. 1: t_{Co}=const. Here,

$$AR_T(H)=[2AR_{\text{Nb-Co}}+\rho_{Ag}t]+N\{[\rho_{Co}(H)-\rho_{Ag}]t_{Co}+2AR_{\text{Ag-Co}}(H)\}\,. \quad (2)$$

Case No. 2: $t_{Ag}=t_{Co}=(t/2N)$. Here,

$$AR_T(H)=\{2AR_{\text{Nb-Co}}+[\rho_{Ag}+\rho_{Co}(H)](t/2)\}+N[2AR_{\text{Ag-Co}}(H)]\,. \quad (3)$$

For case No. 3, t_{Ag}=const, the measured values of $AR_T(H)$ for H_S, H_0, and H_M are consistent with the series resistor model, using global fit parameters given below, so long as $t_{Co}\leq 6$ nm. For $t_{Co}\geq 9$ nm, the values of $AR_T(H)$ decrease more quickly with decreasing N than predicted. The data and possible reasons for such behavior will be discussed elsewhere.[12]

Equation (2) predicts that a plot of $AR_T(H)$ vs N for fixed t_{Co} should give a straight line with intercept $2AR_{\text{Nb-Co}}+\rho_{Ag}t$ independent of both H and t_{Co}, and slope $[\rho_{Co}(H)-\rho_{Ag}]t_{Co}+2AR_{\text{Ag-Co}}(H)$. Figure 2 shows such a plot for $H=H_0$, H_M, and H_S, for both $t_{Co}=6$ nm (data points and solid line least-square fits) and $t_{Co}=2$ nm (dotted line least-square fits only). As predicted, the six least-square lines all intercept the ordinate axis at close to the same place and near the value of $2AR_{\text{Nb-Co}}+\rho_{Ag}t$ $=6\pm 1$ fΩ m^2$+7\pm 1$ fΩ m^2$=13\pm 2$ fΩ m^2 (arrow in Fig. 2) calculated from independent measurements of $AR_{\text{Nb-Co}}$ and ρ_{Ag}.[12,14] The data are thus compatible with Eq. (2).

For $t_{Ag}=t_{Co}$, Eq. (3) predicts a slope of $2AR_{\text{Ag-Co}}(H)$ and a field dependence of the intercept due only to

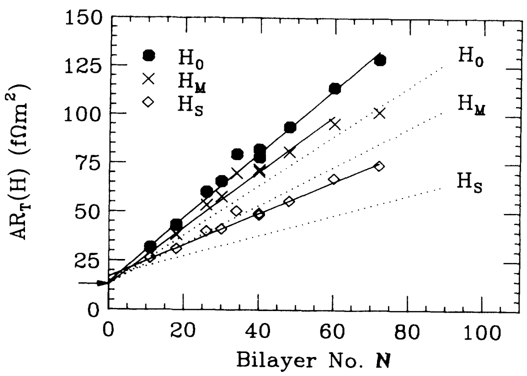

FIG. 2. $AR_T(H)$ vs bilayer No. N for samples with fixed $t_{Co}=6$ nm (symbols and solid best-fit lines) and $t_{Co}=2$ nm (dotted best-fit lines) at the fields H_0, H_M, and H_S defined in the text and indicated in Fig. 1. The arrow indicates the independently predicted ordinate intercept (see text).

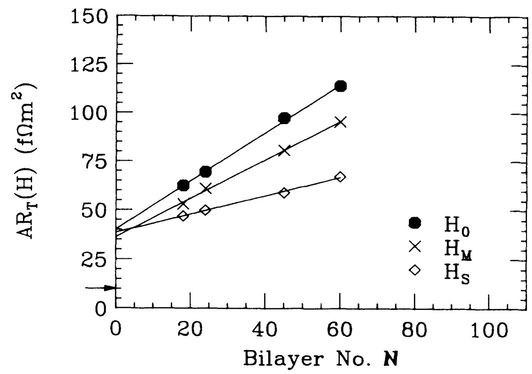

FIG. 3. $AR_T(H)$ vs bilayer No. N for samples with $t_{Co}=t_{Ag}$. The fields H_0, H_M, and H_S are defined in the text and indicated in Fig. 1. The solid lines are best fits to the data points. The arrow indicates the independently determined, field-independent component of the ordinate intercept due to $2AR_{Nb\text{-}Co}+\rho_{Ag}(t/2)$ (see text).

$\rho_{Co}(H)(t/2)$. Figure 3 shows $AR_T(H)$ vs N for $H=H_0$, H_M, and H_S. $AR_{Ag\text{-}Co}(H)$ is strongly field dependent, decreasing from 0.62 ± 0.05 $f\Omega\,m^2$ at H_0, to 0.50 ± 0.03 $f\Omega\,m^2$ at H_M, to 0.24 ± 0.03 $f\Omega\,m^2$ at H_S. Global fits of the three data sets in Figs. 2 and 3, at H_0, H_M, and H_S, respectively, without approximating $N=N-1$, mostly agree with the values of $AR_{Ag\text{-}Co}(H)$ obtained from the slopes of Fig. 3 to within mutual uncertainties: 0.55 ± 0.03 $f\Omega\,m^2$ at H_0; 0.43 ± 0.03 $f\Omega\,m^2$ at H_M; 0.20 ± 0.02 $f\Omega\,m^2$ at H_S. Per Co layer (i.e., 2 interfaces), $2AR_{Ag\text{-}Co}(H)$ thus decreases with field by ≈0.5 $f\Omega\,m^2$ from H_M to H_S and by ≈0.7 $f\Omega\,m^2$ from H_0 to H_S.

To obtain $\rho_{Co}(H)$ from Fig. 3, we must subtract out the contribution to the intercept due to $2AR_{Nb\text{-}Co}+\rho_{Ag}(t/2)\approx10$ $f\Omega\,m^2$, indicated by the arrow. We see immediately that the field dependence of $\rho_{Co}(H)(t/2)$ is much weaker than that of $AR_{Ag\text{-}Co}(H)$; in fact, any field dependence of the intercept is within experimental uncertainties for these data [i.e., $\rho_{Co}(H)$ is bounded by 79 ± 6 $n\Omega\,m$]. Global fits to the data in Figs. 2 and 3 yield $\rho_{Co}(H)\approx100$ $n\Omega\,m$ at H_0, ≈95 $n\Omega\,m$ at H_M, and the slightly smaller value ≈85 $n\Omega\,m$ at H_S—the field dependence of $\rho_{Co}(H)$ is thus still small. For an intermediate Co thickness, $t_{Co}=10$ nm, the decrease in $\rho_{Co}(H)t_{Co}$ is only of order 0.1 $f\Omega\,m^2$ from either H_0 or H_M to H_S, several times smaller than the comparable changes in $2AR_{Ag\text{-}Co}(H)$.

In our previous paper,[8] the CPP MR, defined as[16]

$$\text{CPP MR}=[AR_T(H_M)-AR_T(H_S)]/AR_T(H_S)\,, \quad (4)$$

was shown first to increase with increasing t_{Ag} up to $t_{Ag}\approx4$ nm, and then to decrease thereafter, with the rate of decrease being about twice as fast for case No. 2 as for case No. 1. We ascribe the initial increase in CPP MR to a decrease in the average ferromagnetic coupling between the Co layers with increasing t_{Ag}. Inserting our new parameters for Eqs. (2) and (3) into Eq. (4) shows that the main source of the decrease in CPP MR above $t_{Ag}\approx4$ nm is the decreasing number of interfaces $2N$ in these samples (which have fixed total thickness). The simultaneous growth of both t_{Ag} and t_{Co} in case No. 2 causes $2N$ to decrease about twice as fast as in case No. 1.

To summarize, the Ag/Co CPP data presented in this paper are consistent in form with the straight lines predicted by the series resistor model and in magnitude with independently derived values for $AR_{Nb\text{-}Co}$ and ρ_{Ag}. When analyzed in terms of this model, the data yield a weak field dependence of $\rho_{Co}(H)$ and a strong field dependence of $AR_{Ag\text{-}Co}(H)$. These results provide an explanation for most of the previously reported decrease in CPP MR with increasing $t_{Ag}>4$ nm.[8] Studies are underway to ascertain the extent to which the series resistance model can be applied to differently prepared Ag/Co multilayers, and to multilayers involving other F and N metals.

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[10]Reference 9 treats the CPP geometry for a two-spin model where the spin-flip scattering length is infinite, so that the spin-up and spin-down electrons carry current independently. For the random, or random plus antiparallel, M_i orientations at H_M and H_0 assumed in the text, spin-up and spin-down channels should then have the same resistances, because spin-up and spin-down electrons encounter equivalent M_i orderings. In such a case, the series resistance model will apply whenever the resistance for a given spin direction is a simple series sum. This latter condition will clearly be satisfied if the elastic mean free paths in both Ag and Co are much smaller than the respective layer thicknesses. In fact, however, we show elsewhere in this paper that the elastic mean free paths in our samples are longer than the respective layer thicknesses. Moreover, Johnson has argued (Ref. 13) that the spin-flip scattering lengths in Ag and Co may be no longer than these elastic lengths. The most general situation thus requires a two-spin calculation that combines arbitrary elastic mean free paths with arbitrary spin-flip scattering lengths, and no such calculation has yet been published.

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[16]Strictly, Eq. (1) shows that the CPP MR should be defined with twice the contribution of the Nb-Co boundary resistance, $2AR_{\text{Nb-Co}}$, subtracted from the denominator. Such a subtraction would increase the CPP-MR values given in Ref. 8 by amounts ranging from 6% to 25%.