Perpendicular Giant Magnetoresistances of Ag/Co Multilayers

W. P. Pratt, Jr., S.-F. Lee, J. M. Slaughter,[a] R. Loloee, P. A. Schroeder, and J. Bass
Department of Physics and Astronomy and Center for Fundamental Materials Research, Michigan State University, East Lansing, Michigan 48824
(Received 22 January 1991; revised manuscript received 11 April 1991)

We present measurements at 4.2 K of the magnetoresistance (MR) measured with the current perpendicular to the layer planes (CPP) of equal and unequal thickness Ag/Co magnetic multilayers that display giant MR measured with the current in the layer planes (CIP). For Ag layer thicknesses from 2 to 60 nm, and Co thicknesses from 6 to 15 nm, the CPP MR extends up to nearly 50% and ranges from 3 times to more than 10 times as large as the CIP MR for the same samples.

PACS numbers: 72.10.Fk, 72.15.Gd, 75.50.Rr

There has been great interest recently in the magnetoresistance (MR) of multilayers composed of a ferromagnetic metal such as Fe or Co alternated with a nonmagnetic metal such as Cr, Cu, Ru, or Ag, because such multilayers display MR that is several percent or greater—colloquially called giant MR.[1,2] Such multilayers are of interest for magnetic-field detectors, for which large MR at small fields is desirable.[3]

Published giant MR measurements all have the electric current flowing in the plane of the layers, and the field is usually also in this plane.[4] This current-in-plane (CIP) geometry yields resistances $\simeq 0.01-1\ \Omega$ that require only standard room-temperature measuring techniques.

Zhang and Levy have pointed out[5] that the MR with the field in the layer plane but the current flowing *perpendicular* to this plane (which we call the CPP-MR) is easier to analyze than the CIP-MR, because in the CPP-MR one merely adds the resistances of the layers and boundaries in series, instead of adding conductivities and then inverting to get the CIP-MR. They also predicted that CPP-MR $\geq$ CIP-MR.[5] The CPP-MR is, however, harder to measure than the CIP-MR since, unless one resorts to microfabrication techniques, the "short and wide" geometry leads to very small resistances; e.g., the resistance of a sample 1 mm^2 and 1 μm "long" is $\simeq 10^{-7}-10^{-8}\ \Omega$. A typical current of 10 mA then yields $10^{-9}-10^{-10}$ V, which requires special techniques for precision measurements, such as the use of SQUID, which is sensitive to magnetic fields. Care must also be taken in CPP measurements that the current density is uniform across the sample area.

In this Letter we present the first measurements of the CPP-MR on magnetic multilayers. After a brief, qualitative theoretical overview to provide context for our results, we focus upon our experimental techniques and the salient features of the data; more complete data[6] and comparisons by Zhang and Levy[7] with a multiparameter model will be given elsewhere.

The largest CIP-MR is found in Fe/Cr and Cu/Co multilayers with very thin (≈ 1 nm) nonmagnetic layers that couple neighboring ferromagnetic layers antiferromagnetically. In such multilayers, the CIP resistance is maximum at magnetic field $H=0$, and decreases monotonically with increasing H, as the magnetizations $\mathcal{M}$ of neighboring ferromagnetic layers rotate from antiparallel to parallel alignment;[1,2] the saturation fields H_s are typically $\simeq 10$ kG. For slightly thicker nonmagnetic layers, neighboring ferromagnetic layers in Fe/Cr and Cu/Co couple ferromagnetically, leading to very small MR. In both of these systems, the MR then oscillates with increasing nonmagnetic layer thicknesses, until above 5–6 nm the ferromagnetic layers become magnetically uncoupled, yet still display CIP-MR of several percent, typically with $H_s \leq 1$ kG. After stabilization by cycling above H_s, the maximum resistances in these uncoupled multilayers occur not at $H=0$, but rather near the coercive field H_c—i.e., where $\mathcal{M}=0$—after field reversal. We will see that Ag/Co multilayers display only the ferromagnetic and magnetically uncoupled states.

Zhang and Levy suggest[7] that the $\mathcal{M}=0$ state in an uncoupled multilayer can be viewed as a superposition of statistically uncorrelated magnetic configurations, in each of which the magnetizations $\mathcal{M}_i$ of the individual layers sum to a total magnetization $\mathcal{M}=0$. They predict that the transition from H_s to this uncorrelated state will yield a smaller CIP-MR than the transition from H_s to an antiferromagnetically aligned state, because each different magnetic configuration will contain some ferromagnetically aligned neighboring layers that reduce the CIP-MR compared to that for the fully antiferromagnetically aligned state. This prediction agrees with the largest CIP-MR being found in Fe/Cr and Cu/Co multilayers with antiferromagnetically aligned neighboring layers. In contrast, Zhang and Levy find the CPP-MR to be independent of the sequence of the layer magnetizations in the uncorrelated $\mathcal{M}=0$ states. They thus predict that the CPP-MR will be the same for uncorrelated and antiferromagnetically aligned states, all other parameters held constant, and that the ratio $\pi=$(CPP-MR)/(CIP-MR) will be larger for the uncorrelated than for the antiferromagnetically aligned state. In this Letter we show that π for Ag/Co is certainly large, ranging from 3 to more than 10. Comparisons between values of CPP-MR for antiferromagnetically coupled and uncoupled states will have to await measurements on Cu/Co or Fe/Cr.

Models of CIP-MR based upon changes with decreasing field from parallel neighboring-layer magnetizations to either antiparallel[8] or statistically uncorrelated $\mathcal{M}=0$ states[7] both require that the electrons have long enough mean free paths to sample at least two consecutive ferromagnetic layers and assume that the electrons can undergo spin-dependent scattering both in the ferromagnetic metal and at the ferromagnetic/nonmagnetic interfaces. In general, the giant MR thus depends upon such parameters as metal purities, layer separations, the relative amounts of potential and spin-dependent scattering in the ferromagnetic metal and at the interfaces, interface roughness, and the magnetic structures of both individual and neighboring ferromagnetic layers at H_M. Clearly, CPP-MR and CIP-MR together can provide much stronger constraints on these parameters than CIP-MR alone.

Ag/Co was chosen for these measurements because we had previously found CIP-MR of up to 10% in Ag/Co multilayers with H_s below 1 kG.[9] Since the SQUID-based system[10] used to measure the small CPP resistances is sensitive to vibration in magnetic fields, a smaller H_s simplifies such measurements.

We have described elsewhere our procedures for making sputtered multilayers with Nb cross strips by sputtering through contact masks onto 1.27-cm-wide sapphire substrates cooled to just below room temperature.[11] We start with a Nb strip of width ≈ 1 mm, add the multilayer, and finally add a Nb cross strip of width ~ 1 mm. In these experiments, each multilayer consisted of an integer number of bilayers with total thickness ~ 0.7 μm.

The geometry for simultaneously measuring CIP and CPP MR is more complex, as shown in Fig. 1. For CIP measurements, copper wires are soldered to pads A and B, and the MR is measured with a 17-Hz, self-balancing conductance bridge. For CPP measurements, the overlap region between the Nb strips defines the sample "area," and the sample's length/width ratio of $\approx (1\ \mu\text{m})/(1\ \text{mm}) = 10^{-3}$ makes fringing currents negligible. The sample is placed inside a small superconducting magnet coil that produces a field in the layer plane, perpendicular to the current direction. At 4.2 K, the 500-nm-thick Nb strips remain superconducting, and thus ensure a uniform current distribution for CPP measurements, up to almost 10 kG.

As our CPP measuring technique is inherently "two-

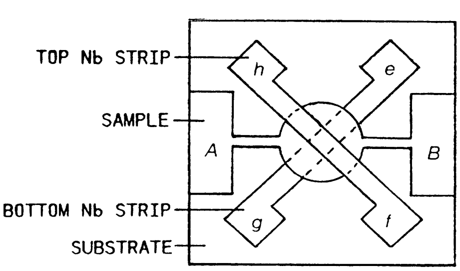

FIG. 1. The sample shape. The CPP-MR is measured using the top and bottom crossed Nb strips with the current injected at e and removed at f and the emf measured between g and h. The CIP-MR is measured by sending current from A to B and measuring the emf between A and B.

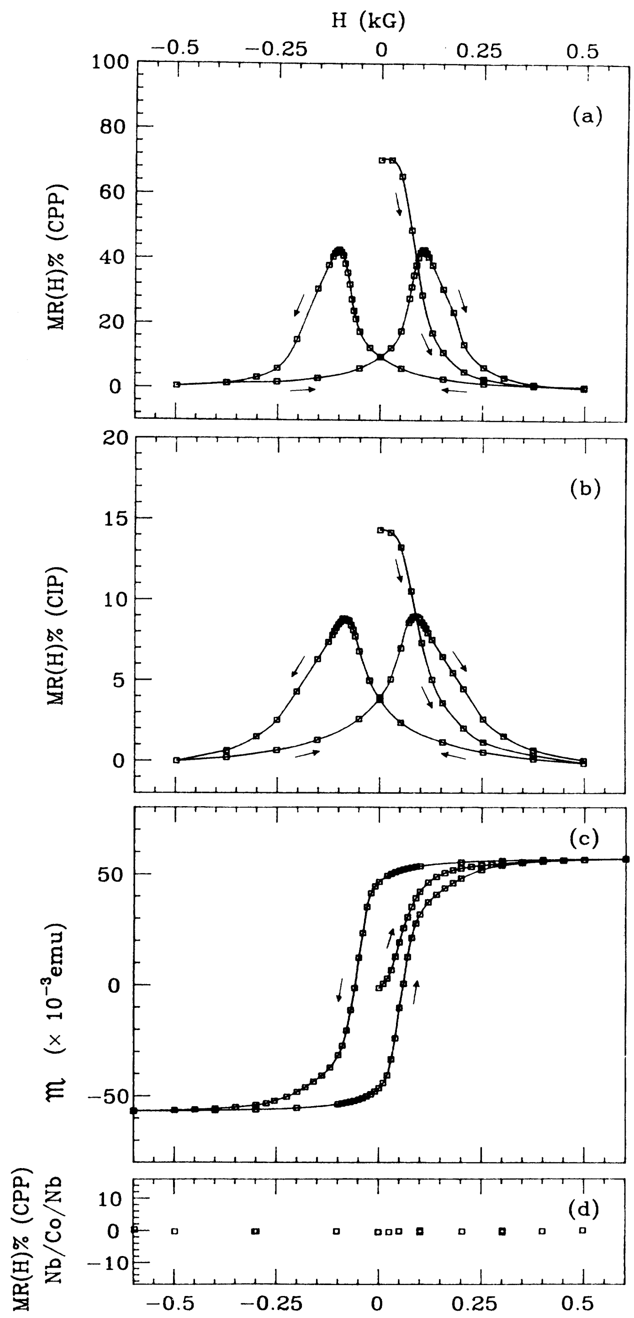

FIG. 2. (a)–(c) Data vs H for a Ag(6 nm)/Co(6 nm) multilayer with Nb cross strips. (d) Data for a Nb/Co(9 nm)/Nb sandwich. (a) MR(H) for CPP geometry. (b) MR(H) for CIP geometry. (c) Magnetization $\mathcal{M}(H)$. (d) MR(H) for CPP geometry.

terminal," we checked whether the Nb/Co boundaries of the multilayers contributed noticeably to the CPP-MR by separately measuring the MR of Nb/Co/Nb sandwiches in the CPP geometry. As shown in Fig. 2(d) for a sandwich with 9 nm of Co, the resulting MR was less than our measuring uncertainty of $\pm 0.5\%$. The Nb/Co boundary contribution to the MR of a multilayer is even smaller, since such boundaries produced 92% of the resistance of this sandwich,[12] but less than 30% of the resistance of any multilayer. These sandwich data show that (a) the contributions of the Nb/Co boundaries to our multilayer CPP-MR are small, and (b) isolated single Co layers do not produce significant CPP-MR.

We define the field-dependent magnetoresistance ratio $\mathrm{MR}(H)$ as

$$\mathrm{MR}(H) = [\rho(H) - \rho(H_s)]/\rho(H_s) , \quad (1)$$

where $H_s \approx 0.5$ kG in our Ag/Co multilayers.

To stabilize the $\mathrm{MR}(H)$ of an as-sputtered Ag/Co multilayer, it must be taken to above its H_s and then cycled through $H=0$. Typical data are shown in Fig. 2 along with magnetization data for a similar multilayer prepared simultaneously. We designate by H_M the field at which $\mathrm{MR}(H)$ is maximum after stabilization. As shown in Fig. 2, in Ag/Co multilayers, $H_M \neq 0$. We formally define the quantities of main interest in this Letter, CPP-MR and CIP-MR, as the values of $\mathrm{MR}(H_M)$ for the appropriate current orientations.

As illustrated in Fig. 2, for both the CPP and the CIP orientations, the initial MR of our samples at $H=0$ were larger than the stabilized MR at $\mathcal{M} \approx 0$, except for the (2 nm)/(6 nm) sample. We show elsewhere[6] that the ratio of the initial MR at $H=0$ to the stabilized MR at $\mathcal{M} \approx 0$ varied by only $\pm 20\%$ about its average. Such behavior suggests a simple relation between the magnetic structures of these states.

The most important features of Fig. 2 are that (a) the H_M's are somewhat larger than the coercive field, and (b) the $\mathrm{MR}(H)$ curves are similar in shape for the CPP and CIP orientations. For most samples, the values of H_M for the CPP and CIP orientations were the same to within experimental uncertainties, and the CPP and CIP curves had closely the same half-widths; in a few cases, the CIP and CPP H_M's were slightly different.[6]

From data such as those of Fig. 2, we derived the CIP-MR, CPP-MR, and $\pi = (\text{CPP-MR})/(\text{CIP-MR})$ for cooled equal-layer-thickness multilayers with Ag thicknesses 6 nm $\le t_{\mathrm{Ag}} \le$ 15 nm (open circles in Fig. 3) and for cooled multilayers with fixed Co thickness = 6 nm but variable Ag thicknesses 2 nm $\le t_{\mathrm{Ag}} \le$ 60 nm (solid circles in Fig. 3). To show data for these different sample sets on a single graph, we plot the MR vs t_{Ag}; we will show elsewhere[6] that the more rapid falloff of the open circles with increasing t_{Ag} above 6 nm is consistent with available models. Results of detailed reproducibility tests will also be given elsewhere.[6] We illustrate occasional large variations in CIP-MR between pairs of samples having the same nominal thicknesses of both Ag and Co by showing two data points (solid squares) for uncooled multilayers; note that the CPP-MR data show less scatter. To prove that the Nb cross strips do not substantially perturb our data, we show CIP-MR data (crosses) taken at 10 K for two nominally identical cooled multilayers, one deposited directly on sapphire

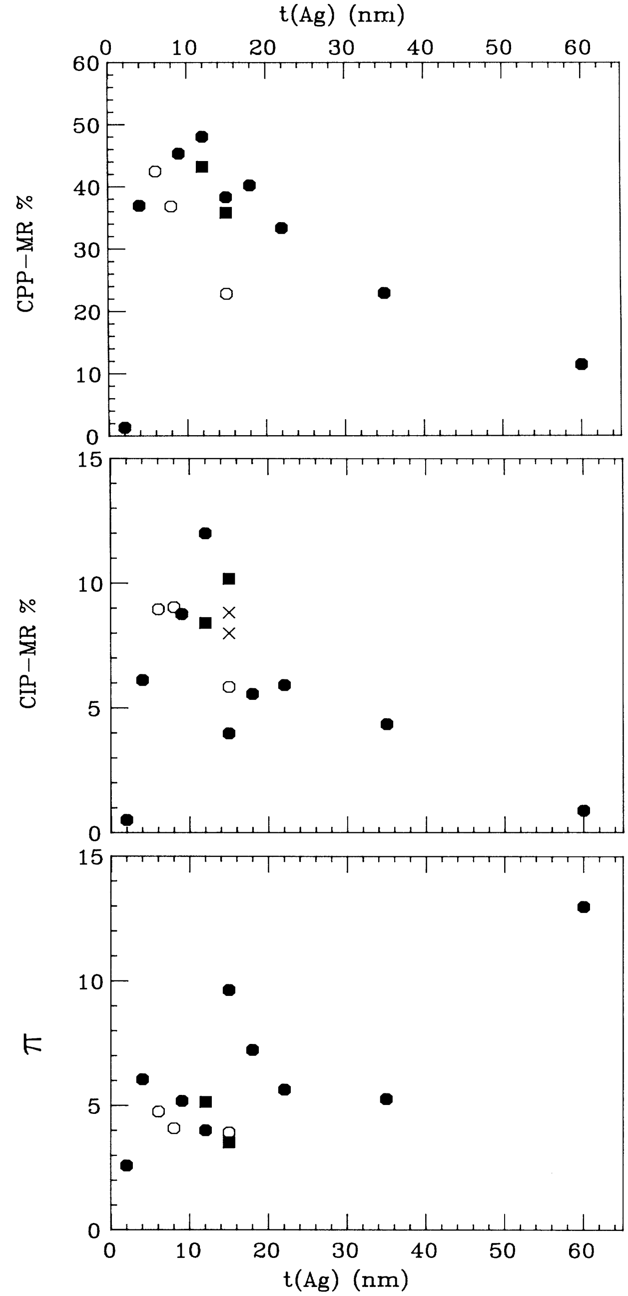

FIG. 3. CPP-MR, CIP-MR, and $\pi = (\text{CPP-MR})/(\text{CIP-MR})$ vs Ag layer thickness, t_{Ag}, for Ag/Co multilayers with equal Ag and Co layer thicknesses (open symbols) and fixed Co layer thickness of 6 nm (solid symbols and crosses). See text for meaning of squares and crosses.

and one with a 40-nm Nb buffer layer.

The most important features of Fig. 3 are the following: (1) The CPP-MR shows qualitatively the same variation with t_{AG} as the CIP-MR. (2) Unlike Fe/Cr or Co/Cu, the Ag/Co data do not seem to oscillate with t_{Ag}; rather, the Co layers appear to be coupled ferromagnetically for small t_{Ag} and uncoupled for $t_{Ag} \geq 9$ nm. (3) For a given t_{Ag}, the CPP-MR shows less variability than the CIP-MR. (4) The CPP-MR is several times larger than the CIP-MR, with a maximum value of nearly 50% and $3 \leq \pi \leq 13$.

To summarize, we have shown how to measure the CPP-MR at 4.2 K on ferromagnetic/nonmagnetic multilayers, presented the first such measurements, and compared the results with CIP-MR measurements on the same samples. As predicted by Zhang and Levy,[5] we find CPP-MR $\geq$ CIP-MR.

In conclusion, we note that CPP-MR measurements at 4.2 K can be extended to higher fields simply by winding a higher-field magnet, and to very high fields by replacing the Nb cross strips by NbTi. CPP-MR measurements can in principle be extended to much higher temperatures by microfabrication, but the moderate temperature dependences seen in most CIP-MR (Refs. 1-3) suggest that the technically much simpler procedures we have described should permit the extraction of most of the fundamental information contained in the CPP-MR.

We thank P. M. Levy for very helpful comments and suggestions, C. Fierz for preparing the Nb/Co/Nb test sample, and S. Renfrow for technical assistance. This research was supported in part by the U.S. NSF under Grant No. DMR-88-013287 and by the Michigan State University, Center for Fundamental Materials Research.

[a]Present address: Optical Sciences Center, University of Arizona, Tucson, AZ 85721.

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