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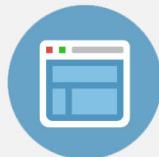
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Magnetoresistance in rf-sputtered (NiFe/Cu/Co/Cu) spin-valve multilayers

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A study of the variation of the magnetoresistance in (Ni₈₀Fe₂₀/Cu/Co/Cu) multilayers with the thicknesses t_{NiFe} , t_{Co} , and t_{Cu} of each type of component layer has been performed. The magnetoresistance (MR), which at 4.2 K is larger than 20% for many samples, has been measured for fields applied both parallel and perpendicular to the current. This allows a direct measurement of the anisotropic magnetoresistance as well as an estimate of the spin-valve contribution to the total MR. The dependence of the MR on t_{Cu} indicates the presence of an oscillatory interlayer exchange coupling through the Cu layers with a period of about 12 Å. The dependence of the MR on t_{NiFe} and t_{Co} was studied at $t_{\text{Cu}} = 50$ Å, for which the coupling is negligible. In this limit, the variation of the MR is dominated by the thickness dependence of the NiFe and Co component layer coercivities, which determine the degree of antiparallel alignment obtained during magnetization reversal.

I. INTRODUCTION

Metallic multilayered thin films in which ferromagnetic (F) and nonferromagnetic layers (N) alternate have been found to exhibit an intriguing new magnetoresistance (MR) phenomenon. For certain systems this effect is two orders of magnitude larger than the MR for isolated films of the F metal. Known as “giant magnetoresistance” (GMR)¹ or, more generally, the “spin-valve effect” (SVE),² this magnetoresistance is associated with changes in the relative orientations of the magnetization vectors in the F layers. The resistance is maximum when adjacent F layers have antiparallel magnetizations, and minimum when the relative orientation is parallel throughout the multilayer (ML). This dependence of the resistance on the ML’s overall magnetic configuration is generally accepted as arising from the inequivalence of the scattering rates of spin-up and spin-down conduction electrons.^{1,3} When all the F layers have parallel magnetizations, carriers in one spin channel are consistently less scattered, giving rise to a sort of short-circuit effect which vanishes when adjacent F layers have antiparallel magnetizations. This physical picture has been used as a starting point for several quantitative models.⁴

Establishing an optimum SVE requires, among other things, the existence of well-defined “antiferromagnetic” or more generally “antiparallel” (AP) configurations of the magnetization vectors of the F layers in low applied fields or during the magnetization reversal process. The Fe/Cr system in which the effect was first discovered exhibited such AP ordering due to the presence of very strong antiferromagnetic (AF) interlayer exchange coupling.¹ Uncoupled sandwiches with only two F layers can be made to exhibit AP states during magnetization reversal by biasing the magnetization in one layer via exchange anisotropy² or by preparing the two F layers so as to have sufficiently

different coercivities.⁵ The latter approach has been generalized to MLs with large numbers of periods by alternating Co layers with magnetically soft NiFe layers.⁶ In contrast with AF-coupled systems, these uncoupled MLs exhibit large resistance changes in relatively small applied fields, which is a desirable feature for many technological applications.

In order to achieve a deeper understanding of the mechanisms giving rise to the SVE in the (NiFe/Cu/Co/Cu) system, we have undertaken a survey of the effect’s variation with the thicknesses t_{NiFe} , t_{Co} , t_{Cu} of each type of component layer. In this article we report the results obtained for three series of samples denoted by S1, S2, and S3, respectively. Each series consists of samples in which the thickness of two of the component layers are fixed while that of the third is varied. S1 corresponds to variable t_{NiFe} with $t_{\text{Co}} = t_{\text{Cu}} = 50$ Å; S2 to variable t_{Co} with $t_{\text{NiFe}} = t_{\text{Cu}} = 50$ Å; and lastly in S3 t_{Cu} was varied with $t_{\text{Co}} = 20$ Å and $t_{\text{NiFe}} = 50$ Å.

II. EXPERIMENTAL DETAILS

Samples were prepared by rf sputtering on Si(100) wafers, and characterized using transmission electron microscopy (TEM) and x-ray diffraction (XRD). A buffer layer of iron was grown prior to deposition of the ML, which in turn began with a layer of NiFe and ended with a Cu layer. Samples belonging to series S1 and S2 were prepared with a total number of periods chosen to give a total thickness of about 2000 Å. TEM and XRD both indicated good ML stacking although the flatness degraded somewhat above several periods, with a waviness of amplitude close to 50 Å at the top surface. The MLs in S3 were all prepared with only three periods. XRD indicated that the samples were polycrystalline with some [111] texturing and predominantly fcc structure. Further details regarding the preparation and structural characterization of these samples are available elsewhere.⁷

Resistance measurements were performed using a four-point dc method. All data reported in this article were

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acquired at 4.2 K. Magnetic fields were applied to the horizontally mounted samples by means of an electromagnet which allowed an arbitrary in-plane orientation relative to the current direction. Resistance versus applied field (R - H) cycles were acquired both for H parallel to I and for H perpendicular to I , allowing the SVE and anisotropic magnetoresistance (AMR) (defined below) contributions to the total MR to be estimated. The MR ratio is defined as usual:

$$MR(H) = \frac{[R(H) - R_s]}{R_s}, \quad (1)$$

where R_s is the value of the resistance at the largest field used, typically 2 kOe for $S1$ and $S2$, and 5 kOe for $S3$. When written without the explicit dependence on H , the *maximum* value is implied:

$$MR = \frac{R_{\max} - R_s}{R_s}, \quad (2)$$

where R_{\max} is the maximum value of the resistance obtained for a given R - H cycle. The orientation of the field relative to the current is indicated by a subscript: MR_{\perp} and MR_{\parallel} . The experimentally accessible quantities MR_{\perp} and MR_{\parallel} include contributions from both the SVE and the anisotropic magnetoresistance or AMR.⁸ These terms correspond to physically different mechanisms and are expected to vary differently with the thicknesses of component layers. The AMR can easily be isolated from the SVE by comparing the saturation resistances obtained for $H \perp I$ and $H \parallel I$. The AMR⁸ is defined here as

$$AMR = \frac{(R_s)_{\parallel} - (R_s)_{\perp}}{(R_s)_{\perp}}. \quad (3)$$

A rigorous isolation of the SVE term, on the other hand, is not as simple as one might imagine, but a good estimate is given by the average value $MR_{\text{avg}} = (MR_{\perp} + MR_{\parallel})/2$.

III. RESULTS

The variation of MR_{avg} and of the AMR with the thickness of each type of component layer is shown in Fig. 1. Note that the AMR data have been multiplied by 10 for comparison with MR_{avg} , and that the range of thickness values for Fig. 1(c) is different from 1(a) and 1(b).

Figure 1(a) shows the variation with t_{NiFe} of MR_{avg} and of the AMR. Note the somewhat surprising rise of MR_{avg} , which begins to decrease only for the sample with the largest t_{NiFe} . The AMR rises smoothly with t_{NiFe} , but it appears that values typical of bulk NiFe would be reached only at thicknesses significantly larger than 100 Å. Figure 1(b) displays the variation of MR_{avg} and of the AMR with t_{Co} . In this case MR_{avg} goes through a maximum near $t_{\text{Co}} = 30$ Å, and the AMR is seen to vary more weakly than in Fig. 1(a). In 1(c) we show the variation of MR_{avg} and of the AMR with t_{Cu} . The striking oscillatory behavior of MR_{avg} signals the presence of an oscillatory interlayer exchange coupling with a period of about 12 Å, which is similar to what has been observed in Co/Cu (Ref. 9) and NiFe/Cu.¹⁰ As we have discussed elsewhere,⁷ the remark-

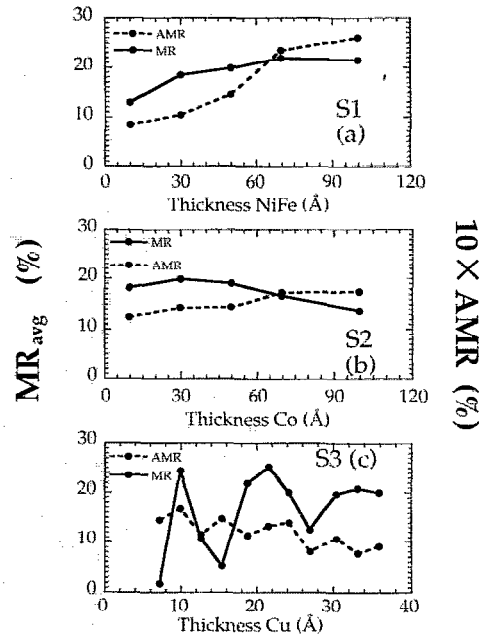


FIG. 1. Variation of MR_{avg} (left-hand scale) and of the AMR (right-hand scale) with (a) t_{NiFe} , (b) t_{Co} , and (c) t_{Cu} . Note that AMR values have been multiplied by 10. Note also that the horizontal scale in (c) spans a different range than in (a) and (b). See text for definitions.

ably weak decrease in peak height with t_{Cu} in this system is due to the interplay between *interlayer exchange coupling*, which is important when t_{Cu} is small, and the *contrasting coercivities* of the NiFe and Co layers, which drives the SVE at large t_{Cu} . An oscillatory exchange coupling has also been observed in MLs similar to these but with the NiFe replaced by an Ni-Fe-Co alloy.¹¹

Figure 2 illustrates the variation in the *shape* of the R - H cycles within each series. Here again the horizontal axis is different for $S3$, i.e., Fig. 2(c). In each case the peak shapes exhibit significant changes with the corresponding layer thickness. These changes must be taken into account in interpreting the MR's variation with t_{NiFe} , t_{Co} , and t_{Cu} .

IV. DISCUSSION

Studies of the thickness dependence of the MR in magnetic MLs are expected to give information about the scattering mechanisms responsible for the SVE. One important issue is whether the spin-dependent scattering takes place primarily within the F layers or at the interfaces between F and N layers. Quantitative models predict different thickness dependences in each case.⁴ For instance, if the spin-dependent scattering occurs in the volume, the MR is expected to vary relatively slowly with the thickness of the ferromagnetic layers, and will generally exhibit a maximum relative to this thickness.

In practice the interpretation of the MR in magnetic MLs is not so straightforward. Consider the fact that many samples never reach a well-ordered AP configuration. The experimentally measured maximum resistance corresponds to the state of "maximum antiparallelism," and not to the

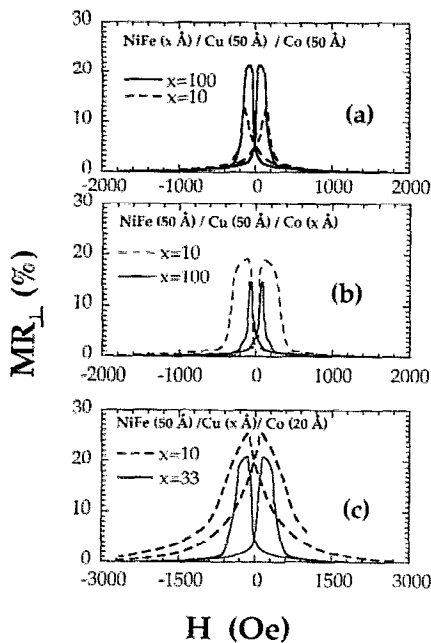


FIG. 2. Selected R - H cycles chosen to illustrate evolution of peak shape with component layer thickness. In (a) the blunt, plateau-like peak becomes truncated at small $t_{\text{NiFe}} = 10$. (b) Illustrates the suppression of the plateau as t_{Co} increases and the Co layers grow magnetically softer. (c) Shows the crossover of the MR from AF coupled to contrasting coercivities regimes as t_{Cu} increases.

ideal maximum R_{AP} corresponding to the full AP state. That is, a *partial* spin-valve effect is measured. It is conceptually useful to introduce the ratio

$$r = \frac{(R_{\text{max}} - R_s)}{(R_{\text{AP}} - R_s)} \quad (4)$$

of the observed MR to the ideal or *full* SVE. This ratio contains information about the “maximum degree of antiparallelism” obtained during the R - H cycle and it depends, of course, on the sign and strength of interlayer coupling J present in the system, and on pinning mechanisms with which this coupling competes. In addition to the SVE’s *intrinsic* variation with the thickness of the component layers, it is clear that MR_{avg} will in general be influenced by the variation of J and of the coercivity H_c with thickness. In fact, the oscillations of the MR with t_{Cu} in this and other systems can be described as the *modulation* of the monotonically decreasing *full* SVE by an r which oscillates with the interlayer exchange coupling. The variation of MR_{avg} with t_{NiFe} and t_{Co} displayed in Fig. 1 is due largely to changes in r . This conclusion is reached by considering the shape of the R - H cycles shown in Fig. 2. In the case of S1, it is clear that the permalloy films become magnetically *harder* as t_{NiFe} decreases. This means that for small t_{NiFe} the magnetization in the Co layers begins reversing before the NiFe layers have completed *their* reversal process. Thus the system never reaches an AP configuration, the peak in the R - H acquires a truncated appearance, and $r < 1$. As t_{NiFe} increases, the permalloy layers become softer and the

peak shape becomes relatively square, so that $r \approx 1$. The variation of MR_{avg} with t_{Co} shown in Fig. 1(b) is similarly dominated by the decrease of cobalt layer coercivity with increasing film thickness. Figure 2(b) illustrates the trend towards squarer peaks as t_{Co} decreases. The VSM magnetization cycles, which are not shown here, also reveal the evolution of component layer coercivities with thickness.

On the other hand, the variation of the AMR with F layer thicknesses which we have reported is not sensitive to the coercivities, since measurements are performed in the saturated state. The AMR does, however, depend on the same scattering mechanisms which give rise to the SVE and thus provides a useful reference for quantitative models.

V. CONCLUSION

The data presented in this paper establish the presence of an oscillatory interlayer exchange coupling in the $(\text{Ni}_{80}\text{Fe}_{20}/\text{Cu}/\text{Co}/\text{Cu})$ system. In the *weakly coupled* limit, the variation of the MR with the thickness of the *magnetic* layers was shown to be relatively gradual in the range of 10–100 Å, with maxima at $t_{\text{NiFe}} = 70$ Å for S1 and $t_{\text{Co}} = 30$ Å for S2. Comparison with quantitative models must proceed with caution, however, since there is considerable variation of the F layer coercivities with the thicknesses t_{NiFe} and t_{Co} . These variations carry over into the MR by altering the degree of AP alignment obtained during magnetization reversal. An extension of quantitative models which includes the AMR could provide additional insight into the spin-dependent scattering mechanisms present, since this quantity is not sensitive to the F layer coercivities.

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