Temperature dependence of the magnetoresistance in Co/Re superlattices on Al_2O_3 $(11\bar{2}0)$

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Using a patterned hcp [Co (17 Å)/Re (7Å)]$_{20}$ antiferromagnetically coupled superlattice, with the c axis in the film plane, magnetoresistance (MR) measurements were made in the temperature range between 5 K and room temperature. The MR was simulated and decomposed into its anisotropic magnetoresistance (AMR) and giant magnetoresistance (GMR) components using the magnetization as a function of angle determined from neutron reflectivity experiments. We find that the GMR is anisotropic and has a different temperature dependence than the AMR when $I\perp c$ and a similar dependence when $I\| c$, where I is the applied current. This implies that interface spin-dependent scattering plays a more significant role when $I\perp c$ than when $I\| c$.

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I. INTRODUCTION

By combining the anisotropic magnetoresistance (AMR) and the giant magnetoresistance (GMR) it is possible to boost the overall value of the magnetoresistance in antiferromagnetically coupled superlattices.[1] However, a detailed study of the interaction between these two effects is necessary. Neither the GMR, discovered in the late 1980's,[2] or the AMR, which was studied extensively in the 1930's,[3] are new effects, but only relatively recently have these two effects been studied in the same system. Some previously studied systems with both AMR and GMR include Co/Cr,[1] Fe/Cr,[4,5] Co/Ru,[6] Co/Cu,[7,8] and Permalloy/Cu (Ref. 9) multilayers. These include experiments which separate the AMR and GMR in the same system[7] and experiments which focus on the enhancement of the GMR by AMR in systems with magneto-crystalline anisotropy, like Co/Cr multilayers.[1]

One other topic of great current interest is determining the nature of the spin-dependent scattering which results in GMR. Experiments where a monolayer or two of a magnetic material were added to the interface of a spin-valve[10] and the dependence of the GMR on interface roughness on Fe/Cr (Ref. 5) show that in those systems the GMR depends strongly on scattering at the interfaces. But other studies show that the GMR depends on the film layer thickness,[11] and that the GMR is dominated by bulk spin-dependent scattering.[12]

In this work we present a detailed study of the temperature-dependent magnetoresistance for a [Co (17 Å)/Re (7 Å)]$_{20}$ superlattice. The magnetoresistance has been simulated assuming that the total magnetoresistance is the sum of a GMR and an AMR component. We show that when the current is applied parallel to the c axis, the spin-dependent scattering is bulklike, and when the current is perpendicular to the c axis, the scattering depends on the interfaces.

II. EXPERIMENT

The superlattice's growth conditions, structural, and magnetic properties as well as neutron reflectivity measurements were reported previously.[13,14] To summarize, the superlattice was grown via DC magnetron sputtering on Al_2O_3 $(11\bar{2}0)$ substrates with a 50 Å Re buffer layer. X-ray diffraction shows that the superlattice grows epitaxially in the hcp structure with the c axis, hcp(0001), in the film plane. Using low angle x-ray reflectivity techniques, the interface roughness between the Co-Re layer was determined to be 4 Å. The superlattice is antiferromagnetically coupled with an in-plane magnetic easy axis parallel to the c axis. Neutron reflectivity experiments are consistent with the previous magnetic measurements and also show a gradual spin-flop transition when the external magnetic field is applied parallel to the c axis.

Magnetoresistance measurements were made using a cryostat with a 5.5 T superconducting magnet. The sample was patterned into the shape shown in Fig. 1 using standard photolithography techniques. One of the arms of the pattern was oriented parallel to the c axis, while the other was perpendicular. This enabled us to apply the current both parallel and perpendicular to the magnetic easy axis on the same sample.

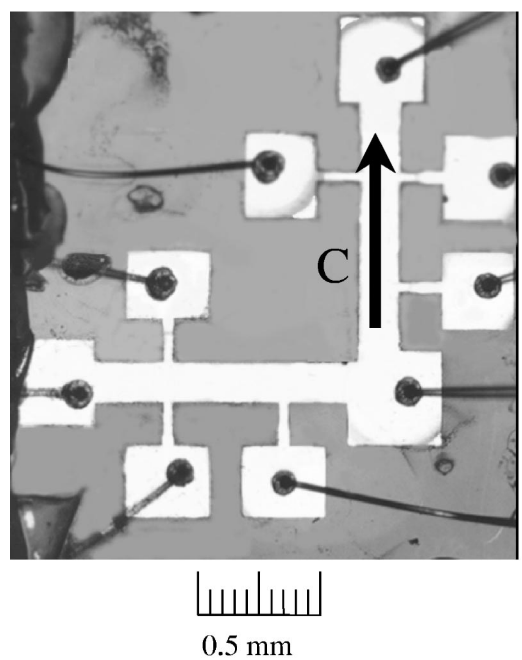

FIG. 1. Photograph of the sample pattern with the direction of the c axis The electrical contacts, using gold wire bonds, can also be seen clearly in the picture.

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Four probe resistance measurements using a constant current source and a nanovoltmeter were made in each of the following configurations: $H\|c/H\|I$, $H\|c/H\perp I$, $H\perp c/H\|I$, and $H\perp c/H\perp I$ as a function of temperature from 5 to 250 K and in an applied field H ranging from -3 to 3 T.

III. RESULTS AND DISCUSSION

An important piece of information extracted from neutron reflectivity measurements is the vector direction of the magnetization in adjacent layers of cobalt with respect to the c axis.[14] From this we can build an empirical model for the total magnetoresistance (MR) based on conventional definitions for the AMR and the GMR. It is known that the AMR depends on the angle the magnetization ($\vec{M}$) makes with the sensing current ($\vec{I}$). The angular dependence of the AMR for one magnetic layer can be written as

$$\rho_{AMR}(H)=\rho_{\|}\cos^2\gamma(H)+\rho_{\perp}\sin^2\gamma(H), \qquad (1)$$

where $\cos\gamma(H)=\vec{M}(H)/|\vec{M}(H)|\cdot\vec{I}/|\vec{I}|$ and $\rho_{\|(\perp)}$ is the resistivity with $\vec{M}\|(\perp)\vec{I}$. This can easily be extended to include two adjacent magnetic layers and normalized to the saturation value at high field. For the $H\|I$ geometry,

$$\frac{\rho_{AMR}(H)-\rho_{sat}}{\rho_{sat}}=\frac{\rho_{AMR}(H)-\rho_{\|}}{\rho_{\|}}=\left[1-\frac{1}{2}\cos^2\gamma_1(H)-\frac{1}{2}\cos^2\gamma_2(H)\right]\times\left(\frac{\rho_{\perp}}{\rho_{\|}}-1\right), \qquad (2)$$

and for $H\perp I$ geometry,

$$\frac{\rho_{AMR}(H)-\rho_{sat}}{\rho_{sat}}=\frac{\rho_{AMR}(H)-\rho_{\perp}}{\rho_{\perp}}=\left[\frac{1}{2}\cos^2\gamma_1(H)+\frac{1}{2}\cos^2\gamma_2(H)\right]\left(\frac{\rho_{\|}}{\rho_{\perp}}-1\right), \qquad (3)$$

where ρ_{sat} is the resistivity at saturation, and γ_1 and γ_2 are the angles that the magnetization in adjacent Co layers make with the applied current. Phenomenologically the GMR depends only on the antiferromagnetic alignment of the adjacent magnetic layers, so

$$\frac{\rho_{GMR}(H)-\rho_{sat}}{\rho_{sat}}=A\frac{|\vec{M}_1(H)-\vec{M}_2(H)|}{|\vec{M}_1(H=0)-\vec{M}_2(H=0)|}, \qquad (4)$$

where $\vec{M}_1$ and $\vec{M}_2$ are the magnetizations in adjacent layers of cobalt as functions of applied magnetic field and A is a constant. $\vec{M}_1$, $\vec{M}_2$, γ_1, and γ_2 were experimentally determined from previous neutron reflectivity measurements performed at room temperature.[14] Note that Eq. (4) implicitly assumes a parallel resistor model where the spin-up and spin-down electrons scatter independently,[15,16] and that the magnetic layers polarize the transport electrons. Equations (2) and (3) assume a parallel resistor model that includes a spin-orbit interaction, which in turn causes the s-d electron scattering to be anisotropic.[15] The latter is the standard explanation for the existence of AMR in bulk ferromagnetic transition metals.

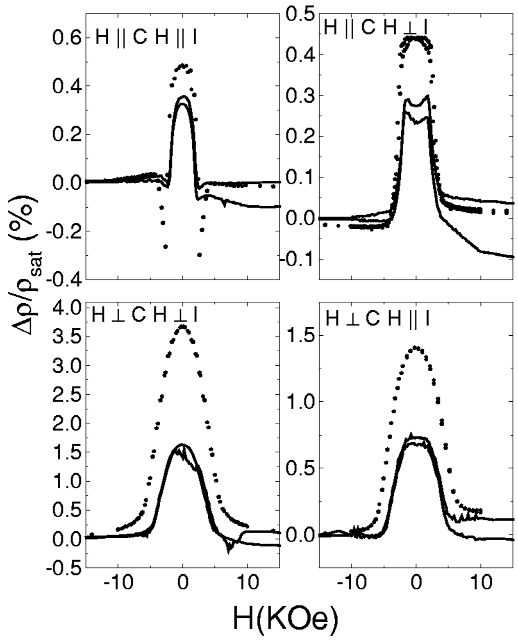

FIG. 2. The magnetoresistance as a function of magnetic field at $T=5$ K (dotted) and $T=250$ K (solid) for four separate geometries. The data were obtained measuring from positive to negative and negative to positive fields. The difference in the values at high positive fields are due to small differences in the temperature.

In Fig. 2 the MR dips at $H=1.5$ KOe in the $H\|c/H\|I$ geometry and dips at $H=0$ KOe in the $H\|c/H\perp I$ geometry at high temperature. The MR also evolves differently as a function of temperature. We assume that the magnetization $\vec{M}_1$(H) and $\vec{M}_2$(H) do not significantly depend on temperature since the dips in the MR remain at approximately the same field at all temperatures. This leaves all of the temperature dependence in the coefficient A and the ratio $(\rho_{\perp}/\rho_{\|})$. By simulating the MR=AMR+GMR with the above equations, and using A and resistivity ratio $(\rho_{\perp}/\rho_{\|})$ as adjustable parameters, the data are qualitatively reproduced as shown in Fig. 3 for the 5 K data set. Note that in this approach the AMR and GMR effects are assumed to be independent and thus their contributions to the MR are added up independently. This assumption is reasonable because the GMR depends on the amount of spin polarization occurring either inside of each ferromagnetic layer or at the interfaces, whereas the AMR depends on the anisotropic s-d scattering described above. It is especially true if the GMR spin-dependent scattering occurs preferentially at the interfaces, in which case the AMR and GMR could depend differently on temperature. Only one physical constraint was placed on the adjustable parameters in the simulation: that the ratio $(\rho_{\perp}/\rho_{\|})$ must be the same for the current flowing along a given crystallographic direction. This is reasonable because $\rho_{\perp}/\rho_{\|}$ is proportional to the ratio of the spin up and spin

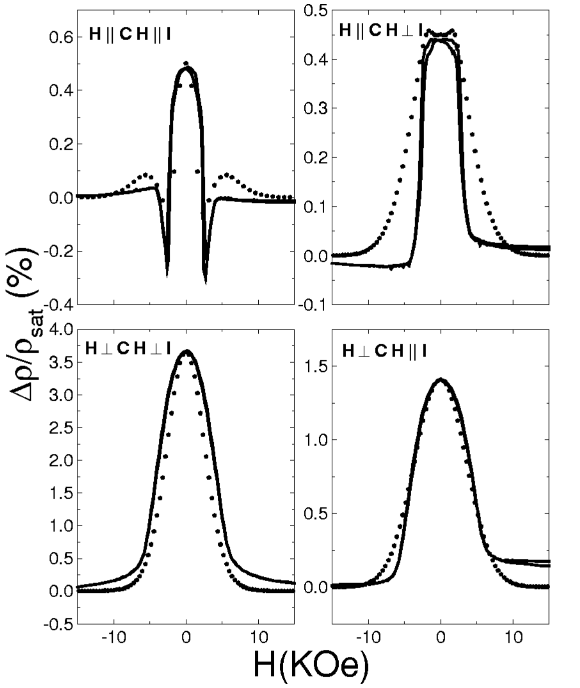

FIG. 3. Magnetoresistance measurements (solid) and simulation (dotted) at 5 K. The simulation qualitatively matches the data.

down resistivities, which only depends on the crystallographic direction in which the current is flowing.[15,16] Figure 4 shows the simulation broken down into its AMR and GMR components. Notice that the interesting dips in the MR are only due to AMR.

At this point it is useful to compare our results with previous work. Studies on cobalt films have found the magnitude of the AMR to be 2.5% at 4.2 K,[17] which is more than

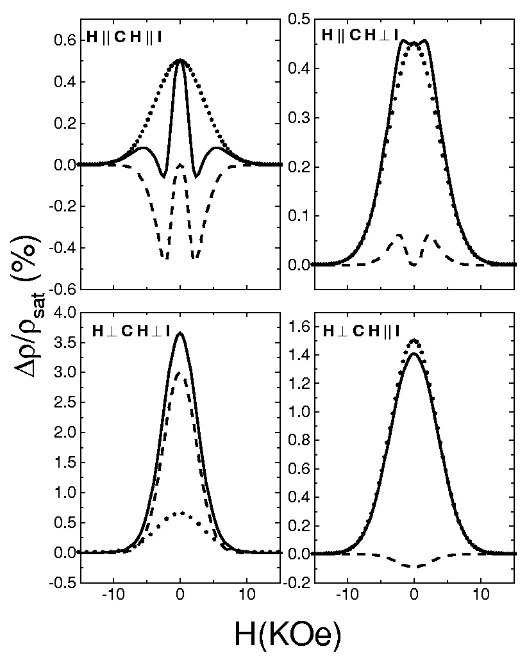

FIG. 4. Simulation broken down into total MR (solid), AMR (dashed), and GMR (dotted) contributions.

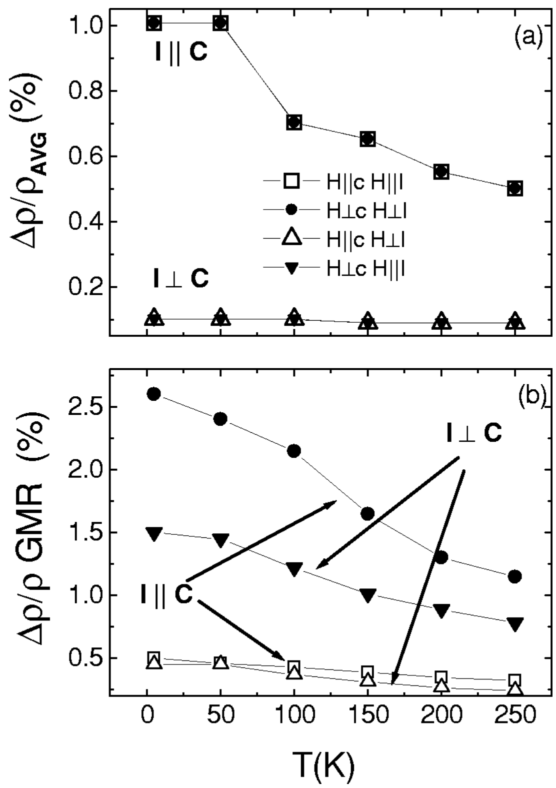

FIG. 5. Magnitude of the AMR $\Delta\rho_{AMR}/\rho_{avg}[=2(\rho_{\parallel}-\rho_{\perp})/(\rho_{\parallel}+\rho_{\perp})]$ (a) and magnitude of the GMR $\Delta\rho_{GMR}\,/\,\rho_{sat}$ (b), plotted as a function of temperature for the $H\|c/H\|I$, $H\|c/H\perp I$, $H\perp c/H\|I$, and $H\perp c/H\perp I$ geometries.

twice the value [$\sim 1\%$ -see Fig. 5(a)] we find in our superlattices at similar temperatures. When comparing to pure cobalt films,[17] $\rho = 14.0\ \mu\Omega\,\mathrm{cm}$, the residual resistivity of the superlattice is greater, with $\rho_{\|} = 39.5\ \mu\Omega\,\mathrm{cm}$ for $I\|c$ and $\rho_{\perp} = 32.0\ \mu\Omega\,\mathrm{cm}$ for $I\perp c$ at 5 K (see inset in Fig. 6) . Single crystal cobalt also shows a large difference between $\rho_{\|} = 10.28\ \mu\Omega\,\mathrm{cm}$ and $\rho_{\perp} = 5.544\ \mu\Omega\,\mathrm{cm}$.[18] The large resistivity in our samples could be due to the relatively large resistivity of Re (18.6 vs 5.8 $\mu\Omega\,\mathrm{cm}$ for Co in bulk),[19] perhaps resulting from the high density of states at the Re Fermi energy,[20] in addition to interface and defect scattering. The magnetoresistance of hcp(0001) oriented Co/Re multilayers has been found by other authors to be less than 2% at 18 K,[21] while our hcp $(10\bar{1}0)$ oriented superlattices have a MR larger than 3.5% at 5 K in certain geometries. In contrast to this previous Co/Re multilayer work, our samples are epitaxial, and therefore the AMR is more noticeable.

The existence of GMR in magnetic multilayer systems has been attributed to the matching of the band structure of the non-magnetic layer with either the spin up or spin down bands of the magnetic layer.[22] The small GMR value in Co/Ir superlattices has been blamed on the failure of the Ir bands to match with either the majority or minority spin bands of Co.[23] In the case of Co/Re, the bands of Re are similar to the spin down bands of Co.[20] This means that the GMR for Co/Re should be large, but we only find a GMR of about 2.5% at 5 K. The low value of the GMR can be attributed to the large resistivity of the Re spacer. In other words, rela-

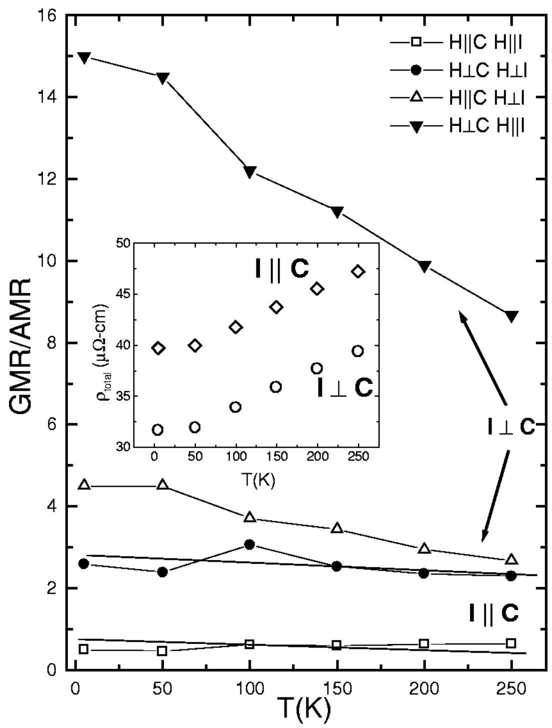

FIG. 6. The ratio $\Delta\rho_{GMR}/\Delta\rho_{AMR}$ plotted as a function of temperature. Inset is the total resistivity at zero applied field (○, ◇), ρ_{total}, as a function of temperature for the $I\|c$ and $I\perp c$ geometries.

tively few electrons traverse the Re spacer to the next Co-Re interface with out being scattered.

Notice in Fig. 5(a) that the temperature dependence of the AMR depends on what crystallographic direction the current flows along. The GMR is usually thought to be isotropic, but Fig. 5(b) shows that it is anisotropic with respect to both the field and current directions in our sample. Other authors[24] have also found the GMR to be anisotropic and to depend on the asymmetry in the spin-dependent resistivity ratios ($\rho_\uparrow/\rho_\downarrow$) parallel and perpendicular to the current.

The AMR depends only on the direction of the magnetization with respect to the sensing current and depends on the transport through the ferromagnetic layers.[15] On the other hand, experimentally the GMR has been shown to depend on interface scattering,[10] and in other studies[12] bulk scattering has been shown to be important. By comparing the temperature dependence of the GMR to the AMR (Fig. 6), one can determine whether the nature of the electron scattering is the same for the AMR and GMR. Since the AMR is known to be a result of scattering within the magnetic layers, differences between the AMR and the GMR must be due to differences in the electron scattering mechanism responsible for the two effects. In Fig. 6 the $I\|c$ geometry the curves are flat indicating the AMR and the GMR have a similar temperature dependence. This implies that when $I\|c$, bulk scattering is more important, while if $I\perp c$, the temperature dependences are different, meaning that interface scattering is more important. Our simple empirical model, relying on $\vec{M}_1$ and $\vec{M}_2$ determined from neutron reflectivity, does not take into account possible domain formation within the Co layers, which could alter the magnetoresistance.[24,25] This could explain why the model only reproduces the qualitative features of the data, such as the dips near $H=0$.

IV. CONCLUSIONS

In summary, we have measured the temperature-dependent magnetoresistance on a patterned, epitaxial Co/Re superlattice. We simulated the magnetoresistance and separated the AMR and the GMR effects for several temperatures. By comparing the temperature dependence of the AMR and the GMR, we find that in the $I\|c$ geometry the AMR and the GMR have the same temperature dependence, which implies that there is predominantly bulk scattering. In the $I\perp c$ geometry, the AMR and the GMR vary quite differently with temperature, implying that interface scattering dominates. Additionally, the GMR contribution is also found to be anisotropic. Finally, we note that other work, most notably in NiFe/Cu superlattices,[26] has revealed similar behavior in terms of dips near $H=0$ KOe with $H\|c/H\perp I$. We propose that the behavior observed in that instance is also due to the competition between the AMR and the GMR.

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