Theory of Giant Magnetoresistance Effects in Magnetic Layered Structures with Antiferromagnetic Coupling

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We present a simple theoretical description of recently measured giant magnetoresistance effects in Fe/Cr layered structures. The resistivity is calculated by solving the Boltzmann transport equation with spin-dependent scattering at the interfaces. The magnitude of the effect depends on the ratio of the layer thickness to the mean free path and on the asymmetry in scattering from spin-up and spin-down electrons. Good agreement with experiment is found for both sandwich structures and superlattices.

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The study of magnetic layered structures has resulted in the discovery of a fascinating variety of behaviors.[1-5] Recently there have been some very exciting reports of giant magnetoresistance effects in magnetic layered structures with antiferromagnetic couplings.[6,7] Baibich *et al.*[7] have suggested that spin-dependent scattering at the interfaces is responsible for the magnetoresistance effect, but there have been no theoretical calculations investigating if this mechanism is consistent with the experimental results. Furthermore, the general behavior (magnetic field dependence, temperature dependence, and structural influences) has not previously been addressed theoretically. Here we present a simple theoretical model which reproduces all the major features of the data qualitatively and quantitatively. Furthermore, the parameters obtained from the model give some support to the suggestion of Baibich *et al.*

In the Fe/Cr multilayers which were studied, there is an effective antiferromagnetic coupling between Fe films due to the intervening Cr films. As a result, the magnetic moments of neighboring Fe films are antiparallel to each other in zero field. With a strong enough external field, the antiferromagnetic coupling may be overcome, and the magnetic moments of the Fe films can be forced to all lie in the same direction.

The experimental results for the magnetoresistance on epitaxial samples can be summarized as follows: (1) The resistance of the structure is largest when the magnetic moments in neighboring Fe films are antiparallel and smallest when they are parallel. (2) Multilayer structures with thin Fe films have a much larger magnetoresistance effect than a single sandwich structure of Fe/Cr/Fe. A magnetoresistance effect of 50% at liquid He temperatures was reported for a multilayer structure, while the largest number reported for a sandwich is 1.5% at room temperatures. (3) Changing from room temperature to that of liquid He increases the magnetoresistance effect by about a factor of 2 to 3.

The problem considered here is similar, to some extent, to that of electron scattering from domain walls which was discussed by Cabrera and Falicov.[8] Their results, however, cannot explain the present experimental data. The mechanisms explored in Ref. 8 show no change in resistivity in a geometry where the current flows parallel to the domain wall and parallel (or antiparallel) to the magnetizations. Experimentally it has been shown that the large magnetoresistance effect in layered systems is nearly the same for the current flowing parallel or perpendicular to the magnetizations[6,7] (the small differences can be attributed to the magnetoresistivity anisotropy effect). To explain all the basic features of the magnetoresistance in layered structures one has to take into account the diffusive scattering of electrons due to interface roughness. Such scattering, of course, does not occur in the domain-wall problem.

Point (1) above suggests that a spin-dependent scattering mechanism is responsible for the effect. Points (2) and (3) suggest that the effect also depends on the relative lengths of the mean free path compared to the thickness of the various films. Our model, an extension of the Fuchs-Sondheimer theory,[9] uses these ideas by introducing spin-dependent coefficients for specular reflection, transmission, and diffuse scattering at the Fe/Cr boundaries.

We compute the conductivity of the structure through use of the Boltzmann equation. Consider first a simple sandwich structure as illustrated in the inset of Fig. 1. The dashed line in the center of the Cr film is not a true boundary; it is the position at which the change in axis of quantization for the electron spin is calculated. In each region the Boltzmann equation reduces to a differential equation which depends on the coordinate z only:

$$\frac{\partial g}{\partial z}+\frac{g}{\tau v_z}=\frac{eE}{mv_z}\frac{\partial f_0}{\partial v_x}. \qquad (1)$$

Here f_0 is the equilibrium distribution function and g is the correction to the distribution function due to scattering and the external electric field E in the x direction. We neglect terms in the Boltzmann equation which arise due to magnetic fields since, for the size of the fields involved here, the resulting effects are much smaller than that discussed here. It is convenient to divide g into four

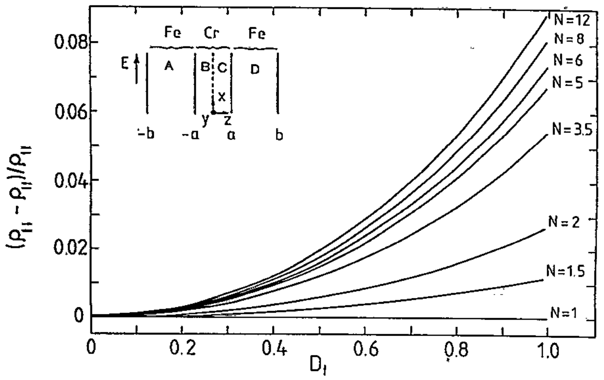

FIG. 1. The maximum normalized change in resistance, as a function of the diffusive scattering constant $D_\uparrow$ and N. $\rho_{\uparrow\downarrow}$ is the resistivity when the magnetizations in the two Fe films are antiparallel and $\rho_{\uparrow\uparrow}$ is the resistivity for the case where the magnetizations are parallel. The inset shows the geometry.

separate portions in each region of space. We calculate separately the contributions to g for spin-up or spin-down electrons moving to the right (positive v_z) or left (negative v_z). Thus g for electrons with positive v_z in region A is given by

$$g = g_{A+\uparrow}(v_z,z) + g_{A+\downarrow}(v_z,z) . \tag{2}$$

Similarly g for electrons with negative v_z in region A is

$$g = g_{A-\uparrow}(v_z,z) + g_{A-\downarrow}(v_z,z) . \tag{3}$$

The solutions for $g_{A\pm\uparrow}$ are given by

$$g_{A\pm\uparrow}(v_z,z) = \frac{eE\tau}{m}\frac{\partial f_0}{\partial v_x}\left[1 + A_{\pm\uparrow}\exp\left(\frac{\mp z}{\tau|v_z|}\right)\right] . \tag{4}$$

The solutions for $g_{A\pm\downarrow}$ are the same except with $\uparrow$ replaced by $\downarrow$ everywhere. The solutions in the other regions will have similar forms.

The coefficients $A_{\pm\uparrow(\downarrow)}$ and similar coefficients for the solutions in the remaining regions B, C, and D are as yet unknown parameters which are to be determined through the boundary conditions. At the outer surfaces of the sandwich, the distribution function g for an electron leaving the surface is equal to the distribution function g for an electron of the same spin striking the surface multipled by the probability of a specular scattering event, R_0. Thus we have

$$g_{A+\uparrow} = R_0 g_{A-\uparrow} \quad \text{at } z = -b , \tag{5}$$

$$g_{D-\uparrow} = R_0 g_{D+\uparrow} \quad \text{at } z = +b . \tag{6}$$

Similar equations hold for the down spins. At the Fe/Cr interface, the distribution function g for an electron with a given spin leaving the interface contains terms from a possible reflection event (with a probability $R_\uparrow$ for up spins and a probability $R_\downarrow$ for down spins) and a possible transmission event (with a probability $T_\uparrow$ for up spins and $T_\downarrow$ for down spins). We obtain for up spins at $z = -a$,

$$G_{A-\uparrow} = T_\uparrow g_{B-\uparrow} + R_\uparrow g_{A+\uparrow} , \tag{7}$$

$$g_{B+\uparrow} = T_\uparrow g_{A+\uparrow} + R_\uparrow g_{B-\uparrow} . \tag{8}$$

Similar equations hold for the down spins at $z = -a$, and a similar set of equations holds for the $z = +a$ interface.

Finally, an electron in film A with spin up which enters film D will have a certain probability to be an up or down spin in film D because the magnetic moments in the two films are in different directions. We take this into account by introducing a change in quantization axis at $z = 0$. Thus

$$g_{B-\uparrow} = T_{\uparrow\uparrow} g_{C-\uparrow} + T_{\uparrow\downarrow} g_{C-\downarrow} , \tag{9}$$

$$g_{B-\downarrow} = T_{\downarrow\downarrow} g_{C-\downarrow} + T_{\downarrow\uparrow} g_{C-\uparrow} , \tag{10}$$

$$g_{C+\uparrow} = T_{\uparrow\uparrow} g_{B+\uparrow} + T_{\uparrow\downarrow} g_{B+\downarrow} , \tag{11}$$

$$g_{C+\downarrow} = T_{\downarrow\downarrow} g_{B+\downarrow} + T_{\downarrow\uparrow} g_{B+\uparrow} , \tag{12}$$

where $T_{\downarrow\uparrow}$ is the probability for an electron of spin up (with respect to the magnetization in layer A) at $z = -0$ to continue as a spin down (with respect to the magnetization direction in layer D) at $z = +0$ and the other symbols are defined similarly. The transmission coefficients are given by

$$T_{\uparrow\uparrow} = T_{\downarrow\downarrow} = \cos^2(\theta/2) , \tag{13}$$

$$T_{\uparrow\downarrow} = T_{\downarrow\uparrow} = \sin^2(\theta/2) , \tag{14}$$

where θ is the angle between the magnetization vectors in the two Fe films.

Having found the various g's, we can find the current density in the direction of the field by using

$$J(z) = \int v_x g(v_z,z) d^3v . \tag{15}$$

The current in the entire structure is then found by integrating $J(z)$ over the coordinate z. It is then simple to find the effective resistivity of the entire structure.

The resistivity for an infinite superlattice can be calculated similarly. One simply replaces the true outer boundaries of the Fe film with perfectly reflective boundaries at the midpoints of the Fe films.

There are still a large number of unknown parameters. We make some simplifying assumptions in order to concentrate on the most important factors: (1) We assume a model system of two equivalent simple metals, i.e., they have the same Fermi energies, same mean-free-path values, etc. In this case it is appropriate to neglect angular dependence[10] of scattering at the Fe/Cr interfaces. Also, it is natural to then assume that there is only transmission or diffusive scattering[11] at the Fe/Cr interfaces, i.e., $R_\uparrow = R_\downarrow = 0$. (2) We assume that the scattering at the outer boundaries is purely diffusive.

Despite the simplicity of these assumptions, our model nonetheless gives a good account of the magnetic depen-

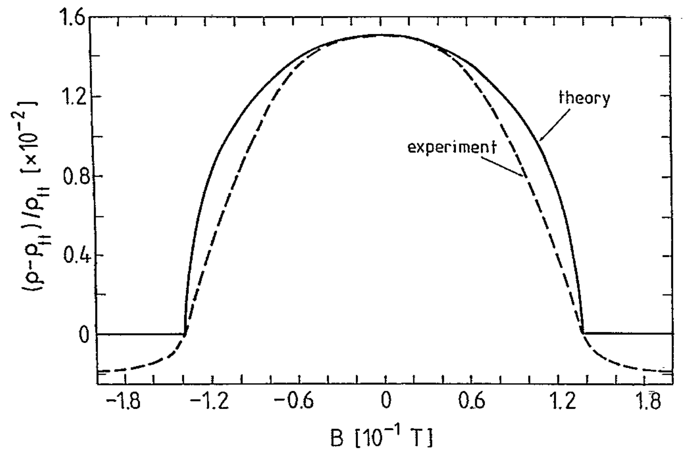

FIG. 2. The percentage change in resistance as a function of applied field. The deviation of the experimental data from zero at high field is a measure of the size of the magnetoresistance anisotropy effect, neglected in the theory. The parameters for the figure are $N=6$ and $D_{\uparrow}=0.48$.

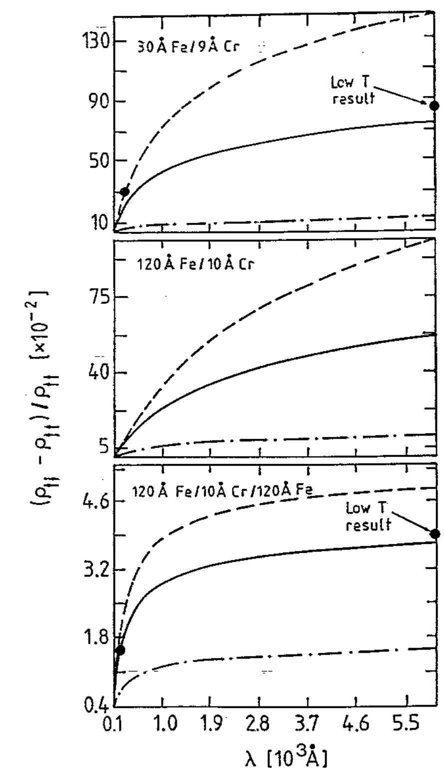

FIG. 3. Maximum percent change in resistance as a function of mean free path λ for different structures and different parameters $D_{\uparrow}$ and N. (---) $D_{\uparrow}=0.5$, $N=12$; (——) $D_{\uparrow}=0.48$, $N=6$; (-·-·) $D_{\uparrow}=0.5$, $N=0.2$. The upper two sets of curves are infinite superlattices with units cells as shown. The lower set of curves is for the sandwich structure. Also included are experimental results (●) from Ref. 6 and those estimated from Ref. 7. The low-temperature results are placed at the side of the figure as we do not have sufficient data to accurately estimate the low-temperature mean free path.

dence of the resistivity. We are now able to characterize the resistivity of magnetic layered systems with just two parameters—the diffusive scattering parameter $1-T_{\uparrow}=D_{\uparrow}$, and $N=D_{\uparrow}/D_{\downarrow}$. $D_{\uparrow}$ should be a measure of the roughness of the interface. For a perfect interface there is translational invariance parallel to the layers and the wave vector parallel to the layers must be conserved. In this case the resistivity would not be changed due to scattering of electrons at the interfaces, and there would be no magnetoresistance effect. As interface roughness increases, $D_{\uparrow}$ should also increase. N determines the asymmetry in up-spin and down-spin scattering. If the suggestion of Baibich *et al.*[7] is correct then $N=6$, a value obtained from measurements of Fe samples with Cr impurities.[12]

We now turn to the results of the theoretical calculations. Figure 1 shows how the magnetoresistance effect depends on the diffusive scattering parameter and on N. These calculations are for a (120-Å Fe)/(10-Å Cr)/(120-Å Fe) structure with a mean free path $\lambda=180$ Å. As $D_{\uparrow}$ increases or as N increases the magnetoresistance effect also increases. Since the experimental results show approximately a 1.5% effect for this case, we can put a lower limit on the value of N at 1.6.

Figure 2 shows resistivity versus applied field for a (120-Å Fe)/(10-Å Cr)/(120-Å Fe) sandwich structure. The theoretical curve is produced with parameters $\lambda=180$ Å, appropriate to room temperature, $N=6$, and $D_{\uparrow}=0.48$. The angle θ between the magnetizations in the two Fe films is calculated by minimizing the sum of the exchange, anisotropy, and Zeeman energies for this structure. The parameters for the calculation were as follows: interface exchange constant $A_{12}=-8.0\times10^{4}$ J/m^2, $K=3.8\times10^{4}$ J/m^3, and the surface is a (110) plane. The experimental results are those from Ref. 6. We see here that the theory is in reasonable agreement with experimental results. One reason for the differences may be that the theoretical calculations did not include magnetoresistance anisotropy. In comparison to the effect discussed here in Fe, the contributions of the magnetoresistance anisotropy is small; however, in other materials it may be considerably larger.[13,14]

In Fig. 3 we explore the behavior of the magnetoresistance effect as a function of mean free path and as dependent on the number of layers. We also show experimental results on the sandwich structure of Ref. 6 and the multilayer structure of Ref. 7. As the mean free path increases (a decrease in temperature) the magnetoresistance effect grows larger. For the sandwich structure a change in mean free path from 180 to 6000 Å (change from room temperature to impurity-dominated scattering at low temperatures) gives an enhancement of the magnetoresistance effect by a factor of 2.5 in good agreement with experiments. The theoretical results show that the infinite superlattices have a significantly larger magnetoresistance effect (a factor of 10–30 times larger depending on the mean free path and N) than the single sandwich, again in agreement with the experimental results. This simply reflects the increased role of spin-dependent interface scattering in the multilayered systems with a large mean free path.

We stress that a determination of N cannot be made from a single sandwich structure alone. For example, the $N=6$, $D_{\uparrow}=0.48$ curve for the sandwich structure shown in Fig. 3 is very similar to one calculated using parameters $N=12$, $D_{\uparrow}=0.44$. However, in the superlattice structure the $N=12$ case would give $(\rho_{\uparrow\downarrow}-\rho_{\uparrow\uparrow})/\rho_{\uparrow\uparrow}=137\%$ at $\lambda=6000$ Å, a value much too high to agree with the data. The fact that we obtain a reasonable fit to both the sandwich and the superlattice results with a *single set of parameters (with $N=6$)* gives considerable support to the case $N=6$. A conclusive determination of N would require detailed experimental results, particularly on many-layered structures.

In conclusion, we have demonstrated that our model correctly describes all the major features of the experimental data. In particular, we have seen that increasing the number of layers and increasing the ratio of mean free path to thickness both significantly increase the size of the magnetoresistance effect.

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