

## Theory of giant magnetoresistance effects in Fe/Cr multilayers: Spin-dependent scattering from impurities

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Recent experiments have tested the assumption that a spin-dependent asymmetry in scattering is responsible for the giant magnetoresistance (GMR) in Fe/Cr multilayers by introducing additional impurities (with different spin-dependent scattering asymmetries) at the interfaces. This paper presents a theoretical calculation based on a Boltzmann transport equation approach that is appropriate for these recent experiments. We find that when impurities (Mn,V) are introduced that have a spin-dependent scattering asymmetry similar to that of Cr in Fe, the GMR is not substantially changed. When impurities (Al,Ir) with a spin-dependent scattering asymmetry opposite to that of Cr in Fe are introduced, there is a rapid degradation of the GMR. Our results are compared with experiment, and good agreement is found, provided that the magnitude of the scattering asymmetry in Al is reduced somewhat from low-temperature published values. It is argued that thermal effects could indeed provide such a reduction.

### I. INTRODUCTION

Recent experiments<sup>1,2</sup> have demonstrated that Fe/Cr multilayer structures with antiferromagnetic coupling between the Fe layers can exhibit giant magnetoresistance (GMR) effects, i.e., the resistivity of the structure changes markedly when an applied magnetic field is used to overcome the antiferromagnetic coupling, leaving the structure in a state where all the Fe spins are aligned. At low temperatures, the resistivity can change by 30–50%, and at room temperature changes of 10% have been measured.

Theoretical investigations of GMR have focused upon the effects of spin-dependent scattering at the interfaces and in the bulk Fe.<sup>3–5</sup> We can understand the basic idea behind these models by looking at the following simple picture. First, we note that in Fe with Cr impurities, spin-down electrons experience less scattering than spin-up electrons. We can then imagine that as a given electron passes from one Fe layer to the next, the amount of scattering that it will encounter depends upon the directions of the magnetizations in the Fe layers. For example, if all the Fe layers have their magnetizations in the same direction, a spin-down electron passes relatively easily through the entire structure, while a spin-up electron scatters strongly at each interface and in the bulk Fe. On the other hand, if the Fe layers are aligned antiparallel, then spin-down electrons leaving one layer will be strongly scattered at the next Fe layer, since their spins are now aligned with the magnetization (i.e., they are now locally spin up). The spin-up electrons are still strongly scattered in the bulk Fe and at the interfaces. Therefore, the resistivity of the structure should be greater in the antialigned state, since there is more overall scattering.

Recent experiments by Baumgart *et al.*<sup>6</sup>, demonstrate the effects of spin-dependent scattering on the GMR in Fe/Cr multilayers by introducing impurities at the Fe/Cr interfaces. These impurities, when alloyed with Fe, exhibit known asymmetries for scattering spin-up and spin-down electrons. The results of the experiments show that when the impurities have spin-dependent bulk scattering asymmetry ( $N_b$ ) similar to that of Cr in Fe, there is little effect on the GMR, but when the asymmetry is inverse ( $1/N_b$ ) to that of Cr in Fe, the GMR is rapidly degraded. Furthermore, these results are roughly independent of whether the impurity is added at only one Fe/Cr interface per unit cell, or whether the impurity is present at both Fe/Cr interfaces per unit cell. This supports the idea that it is the number (and type) of scattering centers which is the principal parameter influencing the GMR.

The purpose of the present paper is twofold. Our first goal is to extend the semiclassical model (Ref. 3) to give a more realistic picture of the physical processes which take place in the Fe/Cr multilayers. We then use this extended model to account theoretically for the results of Baumgart *et al.* The primary extensions employed in the present model are as follows: (1) Rather than assuming a sharp interface at the Fe/Cr boundaries as has been used previously, we assume that there are thin regions where the Fe and Cr are mixed. We will treat cases where the Fe has diffused into the Cr, the Cr has diffused into the Fe, and where there has been mutual diffusion. Given a region where the Fe and Cr are mixed, then, we assume that there is *bulk* asymmetric scattering in the mixing region, rather than asymmetric scattering at the interfaces. We therefore treat the scattering processes as bulk scattering in the films and in the mixing region at the interfaces. The transmission coefficients at the interfaces are assumed to be spin independent. (2) It is assumed

that the introduction of the impurity scatterers changes the composition of the mixing region, principally the (net) bulk scattering asymmetry and mean free path.

The model has many advantages. First, in the present semiclassical picture the bulk and interface scattering are treated in the same way (this advantage was first pointed out in the quantum mechanical models,<sup>5</sup> and in fact, the scattering properties in this model are obtainable from experimental data on the spin-dependent resistivity. Second, we are able to simultaneously account for *both* the magnetoresistance and the overall resistivity of the structure. In addition, this model agrees with recent experiments which demonstrate that the GMR effect increases with interfacial roughness,<sup>9</sup> which in our model leads to a larger mixing region. Finally, we are able to obtain a good match with experiment concerning the addition of spin-dependent scattering impurities at the interfaces.

## II. THEORY

In this section we present the theory for calculating the resistivity of a multilayer structure. We consider a unit cell composed of two films of Fe separated by a film of Cr, with thin regions of overlap at the interfaces. The geometry of a single-period structure is shown in Fig. 1. Physically, the mixing region  $m$  represents a layer in which Fe has penetrated into the Cr (or vice versa), creating a layer of mixed Fe and Cr. The addition of impurities at the interfaces then simply introduces a third material into the mixing region, provided the layer of added impurity is thin. We assume that a static electric field is applied along the  $x$  axis, parallel to the interfaces, as shown. A magnetic field will also be applied along the  $x$  axis, in order to overcome the antiferromagnetic coupling between the Fe layers. In the absence of a magnetic field and for antiferromagnetically coupled Fe layers, the Fe

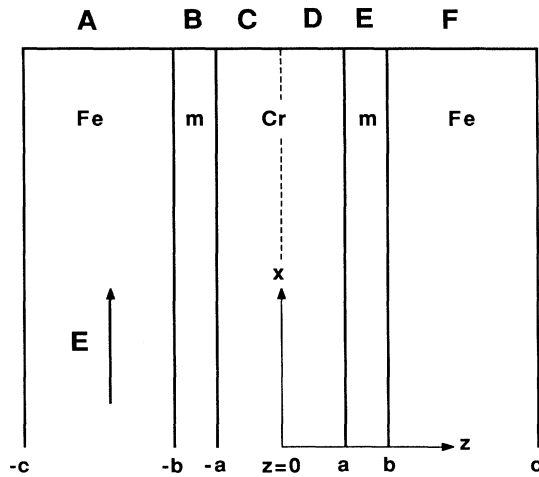


FIG. 1. The geometry of a single period of the Fe (15 Å)/m/Cr(12 Å)/m/Fe(15 Å) structure. The center of the structure is at  $z=0$ , and the boundaries of the mixing region are at  $z=\pm a$  and  $z=\pm b$ . An electric field is applied along the  $x$  axis, as shown.

magnetizations lie parallel or antiparallel to the  $x$  axis.

Following Ref. 4 we assume that the electron transport through the structure is governed by the Boltzmann equation, and that the electron distribution function  $f$  may be thought of as the Fermi-Dirac distribution plus corrections due to the interfaces and the electric field:

$$f^{\uparrow(\downarrow)}(\mathbf{z}, \mathbf{v}) = f_0^{\uparrow(\downarrow)}(\mathbf{v}) + g^{\uparrow(\downarrow)}(\mathbf{z}, \mathbf{v}), \quad (1)$$

where the arrows refer to the distributions for spin-up (spin-down) electrons,  $f_0$  is the Fermi-Dirac distribution, and  $g$  is the correction term. For brevity, we will suppress writing the functional dependence of  $g$  on  $\mathbf{z}$  and  $\mathbf{v}$  from now on. Substituting (1) into the Boltzmann equation and keeping only linear terms yields

$$\frac{\partial g^{\uparrow(\downarrow)}}{\partial z} + \frac{g^{\uparrow(\downarrow)}}{\tau^{\uparrow(\downarrow)} v_z} = \frac{eE}{m v_z} \frac{\partial f_0}{\partial v_x}, \quad (2)$$

where  $e$  is the electron charge,  $E$  is the applied electric field,  $\tau$  is the spin-dependent relaxation time, and  $m$  is the electron effective mass in each region. As usual, we assume that we may separate  $g$  into two parts,  $g_+$  for electrons with positive  $v_z$  and  $g_-$  for electrons with negative  $v_z$ . The general solution to (2) may then be written

$$g_{\pm}^{\uparrow(\downarrow)} = \frac{eE\tau^{\uparrow(\downarrow)}}{m} \frac{\partial f_0}{\partial v_x} \left[ 1 + F_{\pm}^{\uparrow(\downarrow)} \exp\left[\frac{-z}{\tau^{\uparrow(\downarrow)} v_z}\right] \right], \quad (3)$$

where  $F$  is an arbitrary function of  $\mathbf{v}$ , which is determined by the boundary conditions.

The boundary conditions for a single-period structure may be written as follows:

$$g_{A+}^{\uparrow(\downarrow)} = p g_{A-}^{\uparrow(\downarrow)} \quad \text{at } z = -c, \quad (4)$$

$$g_{F+}^{\uparrow(\downarrow)} = p g_{F-}^{\uparrow(\downarrow)} \quad \text{at } z = +c, \quad (5)$$

where  $p$  is the probability that nondiffusive scattering to occur, and the subscripts  $A, F$  refer to the individual films as labeled in Fig. 1. We note that the case of a superlattice can be treated by setting  $p=1$  in Eqs. (4) and (5) and fixing the interface at the position  $(c-b)/2$ . The rest of the boundary conditions within a unit cell are

$$g_{A-}^{\uparrow(\downarrow)} = T g_{B-}^{\uparrow(\downarrow)} \quad \text{at } z = -b, \quad (6)$$

$$g_{B+}^{\uparrow(\downarrow)} = T g_{A+}^{\uparrow(\downarrow)} \quad \text{at } z = -b, \quad (7)$$

$$g_{B-}^{\uparrow(\downarrow)} = T g_{C-}^{\uparrow(\downarrow)} \quad \text{at } z = -a, \quad (8)$$

$$g_{C+}^{\uparrow(\downarrow)} = T g_{B+}^{\uparrow(\downarrow)} \quad \text{at } z = -a, \quad (9)$$

$$g_{D-}^{\uparrow(\downarrow)} = T g_{E-}^{\uparrow(\downarrow)} \quad \text{at } z = a, \quad (10)$$

$$g_{E+}^{\uparrow(\downarrow)} = T g_{D+}^{\uparrow(\downarrow)} \quad \text{at } z = a, \quad (11)$$

$$g_{E-}^{\uparrow(\downarrow)} = T g_{F-}^{\uparrow(\downarrow)} \quad \text{at } z = b, \quad (12)$$

$$g_{F+}^{\uparrow(\downarrow)} = T g_{E+}^{\uparrow(\downarrow)} \quad \text{at } z = b, \quad (13)$$

where  $T$  is the probability for transmission of electrons across the interfaces. We assume that the electrons not transmitted are diffusively scattered (no reflection). To account for the possible change in the magnetization direction from one Fe film to another (the magnetization

axis defines the spin quantization direction), we assume an artificial boundary at  $z=0$  (the dashed line in Fig. 1), and write a boundary condition which changes the spin directions of electrons emerging from one of the Fe films into the proper spin direction for the adjacent Fe film. This gives

$$g_{C+}^{\uparrow(\downarrow)} = \cos^2 \left[ \frac{\theta}{2} \right] g_{C+}^{\uparrow(\downarrow)} + \sin^2 \left[ \frac{\theta}{2} \right] g_{C+}^{\downarrow(\uparrow)} \quad \text{at } z=0, \quad (14)$$

$$g_{C-}^{\uparrow(\downarrow)} = \cos^2 \left[ \frac{\theta}{2} \right] g_{C-}^{\uparrow(\downarrow)} + \sin^2 \left[ \frac{\theta}{2} \right] g_{C-}^{\downarrow(\uparrow)} \quad \text{at } z=0. \quad (15)$$

The set of equations (4)–(15) provides 24 equations in the 24 unknowns

$$F_{A\pm}^{\uparrow(\downarrow)} \dots F_{F\pm}^{\uparrow(\downarrow)}.$$

We solve numerically for the  $F$ 's. Once the  $F$ 's are known, and thus the  $g$ 's, the current density in each region may be written

$$J_x(z) = -2e \left[ \frac{m}{h} \right]^3 \int v_x f(v_z, z) d^3v, \quad (16)$$

where  $m$  is the effective mass in each region. The current in the whole structure may be easily calculated by integrating the current density over  $z$ , and thus the effective resistivity for the entire structure may easily be found.

In Sec. III, we present numerical solutions for the change in resistivity with applied magnetic field for Fe/Cr multilayers with impurities at the interfaces.

### III. RESULTS

In this section we present the results of numerical calculations for the resistivity of Fe/Cr multilayers. In order to compare with experimental results, we study the addition of Al and Mn to the interfaces of an Fe(15 Å)/Cr(12 Å) multilayer structure. We note that the scattering asymmetry for Mn in Fe is similar to that for Cr in Fe, and the asymmetry of Al in Fe is roughly the inverse of that for Cr in Fe, as discussed in Sec. I.

The input parameters for the problem are (1)  $\lambda_{Fe}$ , the arithmetic mean of the mean free paths for spin-up and spin-down electrons in the Fe; (2)  $N_{bFe}$ , the bulk scattering asymmetry ( $=\rho^\uparrow/\rho^\downarrow$ ) in Fe; (3)  $\lambda_m$ , the arithmetic mean of the mean free paths in the mixing region; (4)  $N_{bm}$ , the bulk scattering asymmetry in the mixing region; and (5)  $\lambda_{Cr}$ , the mean free path (spin independent) in Cr. The individual mean free paths for spin-up and spin-down electrons in the Fe and mixing layers may be calculated from the arithmetic mean of the mean free paths and the bulk scattering asymmetries. The other parameters are the thickness of the mixing region ( $t=b-a$  in Fig. 1), and the individual thicknesses of the Fe and Cr layers. A bit of algebra allows us to write the resistivity of the structure calculated in Sec. II entirely in terms of the above parameters. To fix the parameters, we use experimental values of the bulk scattering asymmetries, fix a value for  $t$ , and then choose reasonable values for the mean free paths such that the magnetoresistance and

overall resistivity of the pure Fe/Cr system are matched to experiment. The values of  $t$  are chosen to lie within the experimentally determined range of the interdiffusion, which are reported to be "mixed monolayers," i.e., a mixing region of roughly one atomic diameter,<sup>7</sup> to roughly 10 Å.<sup>8</sup>

As we pointed out earlier, in the absence of impurities there is a region of thickness  $t$  at the interfaces where the Fe and Cr are mixed. When the impurities are added, we assume that (i) they affect the mean free path and the scattering asymmetry in the mixing layer, (ii) the distance between Fe layers is increased by the thickness per period of added impurity, and (iii) that the thickness  $t=b-a$  of the mixing layer is constant. To arrive at the bulk scattering asymmetry and mean free path in the mixing region as a function of impurity thickness, we use the following averaging scheme. The net individual resistivities for spin-up ( $\rho^\uparrow$ ) and spin-down ( $\rho^\downarrow$ ) electrons in the mixing layer may be calculated from Matthiessen's rule (neglecting spin mixing), weighted by the thickness of impurity, and the asymmetry is then the ratio of the new resistivities  $N_{bm}=\rho^\uparrow/\rho^\downarrow$ . Explicitly,

$$N_{bm} = \frac{g_m \rho_m^\uparrow + g_{Cr} \rho_{Cr}^\uparrow}{g_m \rho_m^\downarrow + g_{Cr} \rho_{Cr}^\downarrow} = \frac{g_m N_m}{g_m + g_{Cr} K} + \frac{g_{Cr} N_{Cr}}{g_{Cr} + g_m (1/K)},$$

where  $N_m$  is the bulk asymmetry of the impurity  $m$  in Fe,  $N_{Cr}$  is the bulk asymmetry of Cr in Fe,  $K=\rho_{Cr}^\downarrow/\rho_m^\downarrow$ , and  $g_m$ , and  $g_{Cr}$  are the geometric weighting factors given by

$$g_m = \frac{M}{2}, \quad g_{Cr} = t - \frac{M}{2},$$

where  $M$  is the thickness/period of impurity (recall that the mixing layer is present at both interfaces in the unit cell and thus half the total thickness resides at each interface). In addition, the mean free path in the mixing region is affected by the inclusion of impurities as follows:

$$\lambda_m = \frac{\rho_m^0}{\rho_m} \lambda_m^0,$$

where

$$\frac{\rho_m^0}{\rho_m} = \frac{g_{Cr}(\rho_{Cr}^\uparrow + \rho_{Cr}^\downarrow)}{g_{Cr}(\rho_{Cr}^\uparrow + \rho_{Cr}^\downarrow) + g_m(\rho_m^\uparrow + \rho_m^\downarrow)}$$

is the ratio of the arithmetic means of the resistances in the mixing region with (numerator) and without (denominator) impurities, and  $\lambda_m^0$  is the mean free path in the mixing layer without impurities. Note that the subscripts Cr and  $m$  on the resistivities refer to the value of the resistivities of these elements when mixed with Fe.

Before we turn to the problem of the effect of impurities, we point out that this model properly reproduces all of the major features of the simple Fe/Cr system. To begin with, we note that room-temperature values for the GMR of 10% are achieved using experimental values for many of the input parameters. For the sets of parameters we chose, the model produces overall resistivities of the structure in the parallel configuration in the range 45–60  $\mu\Omega$  cm. These values are in very good agreement with the experimental range of 20–80  $\mu\Omega$  cm.<sup>5,8,9</sup> In addition,

although we have no room-temperature data concerning the dependence of magnetoresistance of the thickness of Fe and Cr for the structure we consider, we would like to point out that this model produces the behavior expected from low-temperature data (neglecting oscillations due to oscillations in the antiferromagnetic coupling). Using the same values as above for the asymmetries and mean free paths, we find that the magnetoresistance falls off very rapidly with increasing Cr thickness, while the reduction with increasing Fe thickness is much more gradual, in agreement with low-temperature results.

In Fig. 2 we plot the percentage change in the resistivity of the structure from the Fe-aligned state to the Fe-antiparallel state,  $(\rho^{\uparrow\uparrow} - \rho^{\uparrow\downarrow})/\rho^{\uparrow\downarrow}$ , as a function of the thickness per period of added impurity. The added impurities shown in Fig. 2 are Al and Mn, and the experimental points are shown as heavy dots (Al) and heavy squares (Mn). At zero added impurity (mixing region of Fe-Cr only), we achieve a fit assuming that the mean free path and bulk scattering asymmetry in Fe are  $\lambda_{\text{Fe}} = 40 \text{ \AA}$  and  $N_{b\text{Fe}} = 2.15$ , respectively, the mean free path and asymmetry in the mixing layer are  $\lambda_m = 18 \text{ \AA}$  and  $N_{\text{Cr}} = 4.6$ , respectively, the thickness of the mixing layer is  $t = 4 \text{ \AA}$ , and the mean free path in Cr is  $\lambda_{\text{Cr}} = 20 \text{ \AA}$ .

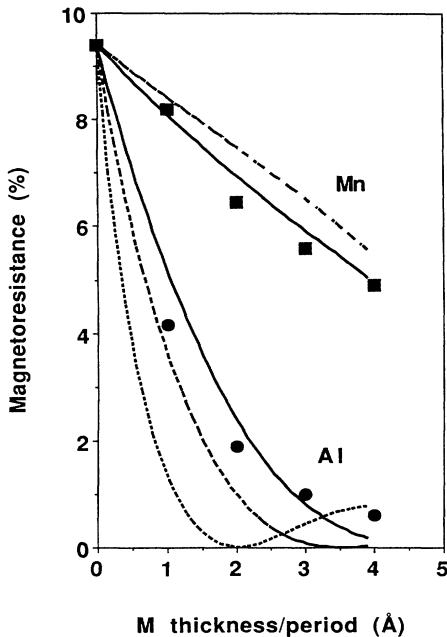


FIG. 2. The percent change in the magnetoresistance as a function of thickness per period of added impurity. The upper set of curves is for Mn impurities and the lower set is for Al impurities. The heavy squares are the experimental data for Mn, while the heavy dots are the experimental data for Al, both taken from Ref. 10. For Mn, the solid curve is calculated using the value for bulk scattering asymmetry  $N_m = 4$ , while the dashed curve is calculated using  $N_m = 6.5$ . For Al, the dashed line is obtained for  $N_m = 0.117$ , the dotted line for  $N_m = 0.281$ , and the solid line for  $N_m = 0.468$ . Note that 0.468 is a *smaller* asymmetry than 0.117, as explained in the text.

We have set the transmission probability  $T = 1$  since the effective interface scattering is taken into account in the thin mixing region. The plots for Mn agree quite well with experiment using the averaging scheme outlined above and the two published<sup>10</sup> values for the bulk asymmetry of Mn in Fe,  $N_m = 4$  (solid line) and  $N_m = 6.5$  (dashed line).

Theoretical curves for the addition of Al impurity are also shown in Fig. 2 for different values of bulk asymmetry. Here the dashed curve is obtained using the published value ( $N_m = 0.117$ ), the dotted curve is for  $2.4N_m$ , and the solid curve is for  $4N_m$ . For self-consistency, we note that the multiplying factors must also act on the parameter  $K$  above, i.e., we use  $K$ ,  $0.42K$ , and  $0.25K$ , respectively. The effect of the multiplying factor is to *reduce* the net bulk asymmetry of Al in the Fe-Cr mixing layer; i.e., 0.117 is a rather large asymmetry (compare the *magnitude*  $1/0.117 = 8.5$  to the value 4.4 for Cr), whereas four times 0.117 is a rather small asymmetry ( $1/0.468 \approx 2$ ). We note that since the latter produces the best fit, the experiment seems to show that the scattering asymmetry of Al in an Fe-Cr background is smaller than that for Al in Fe. We note that the values of  $\alpha (= 1/N_b)$  and  $\rho$  are taken from low-temperature data. The large impurity concentration of Cr in Fe and near the interfaces probably means that the values for Cr in Fe are still reasonable. However, at room temperature, spin-independent scattering due to phonons and other mechanisms will reduce the asymmetry of lower concentration impurities. Therefore, it is not unreasonable to expect a smaller asymmetry in the case of Al impurities, as the experiment seems to show. For the solid curves in Fig. 2, the calculation gives an overall resistivity in the parallel configuration of just over  $50 \mu\Omega \text{ cm}$ .

We note that for some values of parameters our calculations show that the GMR reaches a minimum and then begins to get larger as more impurity is added (see the dotted and dashed curves in Fig. 2). The reason for this is as follows. In the present model the GMR depends upon the magnitude of the bulk scattering asymmetry, and therefore as  $M$  gets larger, the magnitude of the asymmetry in the mixing region reaches a minimum when the asymmetries for the Cr and Al “cancel” one another, and then gets larger as the Al asymmetry begins to dominate. This upturn is not seen experimentally. One reason for the difference between experiment and theory is that our model neglects any changes in the antiferromagnetic coupling as  $M$  increases. Experiments have shown that the antiferromagnetic coupling between the Fe layers depends upon the thickness of the Cr layers,<sup>11</sup> i.e., the antiferromagnetic coupling disappears by the time  $d_{\text{Cr}} = 19 \text{ \AA}$ , and the present theoretical model does not account for the decay of the antiferromagnetic coupling.<sup>12</sup>

In addition, we note that the value of  $t = 4 \text{ \AA}$  we chose for Fig. 2 is a reasonable minimum, corresponding to the minimum penetration of roughly one atomic diameter as mentioned above. It is not the only possibility. We point out that the effect of larger  $t$  is to increase the GMR due to the increased number of scatterers, and therefore to fit the data we would need to reduce the bulk asymmetry.

For instance, if we let  $t=5 \text{ \AA}$ , then to fit the data we would need  $N_{\text{Cr}}=3.25$  (all other parameters the same) instead of 4.4. We could also adjust the mean free paths (increase the distance between scattering events to compensate for the increase in the number of scatterers), but since the effect of changing the mean free paths on the GMR is much smaller than the effect of the asymmetries, we get quickly out of the range of reasonable mean free paths at room temperature. For example, if  $t=5 \text{ \AA}$  and  $N_{\text{Cr}}=4.6$ , then to match the data we need to let  $\lambda_m=70 \text{ \AA}$ , which is very long for room temperature. The reason for the relative insensitivity of the GMR to mean free path comes from the bulk asymmetry in the Fe ( $N_{b\text{Fe}}=2$ ), which by itself accounts for roughly 35% of the GMR, i.e., if we let  $N_{b\text{Fe}}=1$ , so that there is no bulk asymmetry in the Fe, then with all other parameters the same, we find the GMR drops from 9.4% to 5.9%

When larger values of  $t$  are used in the calculation, with the corresponding lower values for the asymmetries, the major features seen in Fig. 2 are the same.

We may also investigate other geometries concerning the mixing region. For instance, we may study the effect of allowing the mixing region to penetrate into the Fe layers; this would correspond to a situation in which the Cr (and impurities) diffuses into the Fe. The other possibility involves allowing the materials to mutually diffuse into one another, so that the mixing region extends into both the Cr and Fe layers.

In Fig. 3, we present the results for the percent change

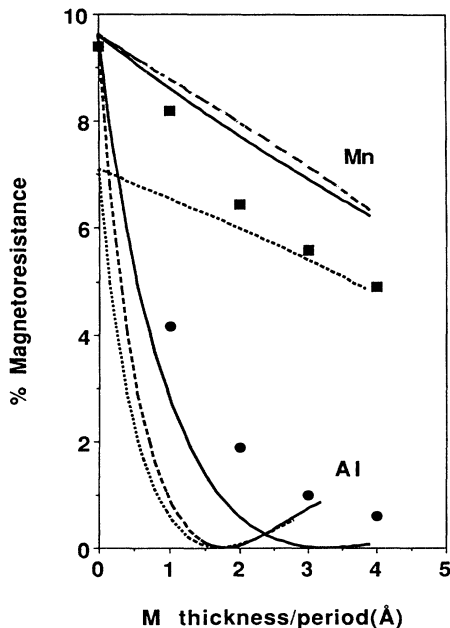


FIG. 3. Magnetoresistance as a function of impurity thickness for different geometries of the mixing region. The mixing region is situated as follows:  $4 \text{ \AA}$  into the Fe for the dotted curve,  $2 \text{ \AA}$  into both the Cr and the Fe for the dashed curve, and  $4 \text{ \AA}$  into both the Cr and the Fe for the solid curve. The published values for the asymmetries are used in all three curves, and the other parameters are given in the text.

in magnetoresistance from the Fe-aligned to the Fe-antialigned state as a function of added impurity for three different cases. In all curves, the above method for finding the bulk asymmetry in the mixing region is utilized, and we use the published values for the resistivities of the impurities in Fe everywhere. Once again, the experimental data for Al (dots) and Mn (squares) are shown. For the dotted curve, we assume that the mixing region extends  $4 \text{ \AA}$  into the Fe, with parameters  $\lambda_{\text{Fe}}=65 \text{ \AA}$ ,  $N_{b\text{Fe}}=2.15$ ,  $\lambda_m=18 \text{ \AA}$ ,  $N_{\text{Cr}}=4.6$ , and  $\lambda_{\text{Cr}}=35 \text{ \AA}$ . Even with these numbers, which have long mean free paths for room temperature, the dotted line does not represent the experimental values well. The reason for this is that with the mixing region completely within the Fe, the situation resembles that of pure Fe/Cr with no substantial interface scattering, and as we pointed out above, this scenario accounts for only 35% of the GMR with reasonable numbers for the input parameters. For the dashed line, we let the mixing region extend  $2 \text{ \AA}$  into the Fe and  $2 \text{ \AA}$  into the Cr, with the same parameters as those for the dotted curves. Lastly, for the solid line, we let the mixing region extend  $4 \text{ \AA}$  into the Fe and  $4 \text{ \AA}$  into the Cr. The best fit was obtained using  $\lambda_{\text{Fe}}=26 \text{ \AA}$ ,  $N_{b\text{Fe}}=2.15$ ,  $\lambda_m=18 \text{ \AA}$ ,  $N_{\text{Cr}}=4.6$ , and  $\lambda_{\text{Cr}}=20 \text{ \AA}$  (solid line). With these parameters we find a value of  $60 \mu\Omega \text{ cm}$  for the resistivity. This plot represents the best fit possible using only published (low-temperature) values for the resistivities of Al and Mn and the model outlined above.

#### IV. SUMMARY

We have calculated the GMR effect in Fe/Cr/Fe multilayer structures using a semiclassical model with thin regions at the interfaces where the materials are mixed. The interface scattering is therefore treated as bulk scattering within this mixing region. The model is capable of reproducing all of the major features of the Fe/Cr multilayer structures, including the values for the magnetoresistance and the saturated resistivities. We have then applied this model to calculate the magnetoresistance as a function of the amount of impurities added at the interfaces. Experiments have shown that the number and type of scattering impurities plays a major role in determining the size of the GMR; if the scattering asymmetry of the impurities in Fe ( $N_b$ ) is roughly equivalent to that for Cr, then the GMR is not rapidly degraded, whereas if the scattering asymmetry of the impurity is inverse to that for Cr then the GMR is rapidly degraded.

We assume that the resistivities in the mixing region may be calculated separately for spin-up and spin-down electrons using Mathiessen's rule, and we calculate the net scattering asymmetry between spin-up and spin-down electrons in the mixing region via  $N_{bm}=\rho^\uparrow/\rho^\downarrow$ . Furthermore, we assume that the mean free path is reduced in the mixing region as impurity is added.

When Mn is added to the interface region (Mn has a scattering asymmetry similar to that for Cr in Fe), using the experimental values for the bulk asymmetry of Mn in Fe, a very good agreement with experiment is obtained. When Al is added to the interface region (scattering

asymmetry inverse to that of Cr in Fe), a good fit with experiment is obtained if the scattering asymmetry is reduced slightly from the experimental value for Al in Fe. Since the experimental values of the asymmetries we use are low temperature, and since the experiments are at room temperature, the lower value of the scattering asymmetry for Al may be due to the effects of phonons and other related spin-independent high-temperature effects.

Finally, we note that the major parameters that affect the GMR in the present work are the magnitude of the scattering asymmetry, the thickness of the mixing region,

and to a lesser extent, the mean free path in the mixing region. All of these parameters are directly related to the number and type of scattering centers present at the interfaces. The reduced sensitivity of the GMR to the mean free path is due to the scattering asymmetry in bulk Fe itself, which maintains about 35% of the GMR effect.

#### ACKNOWLEDGMENTS

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