Effect of spin-flip scattering on the current-in-plane giant-magnetoresistance

Jian Chen and Selman Hershfield

Department of Physics and National High Magnetic Field Laboratory,

University of Florida, 215 Williamson Hall, Gainesville, FL 32611

(June 19, 1997)

Abstract

We use Boltzmann's equation to study the effect of spin-flip scattering on the current-in-plane giant-magnetoresistance (GMR). When the spin-flip scattering is in the paramagnetic spacer layer, the GMR is suppressed. When the spin-flip scattering is only in the ferromagnetic layers, the GMR due to bulk-spin-scattering anisotropy is suppressed, while the GMR due to surface-spin-scattering anisotropy is selectively enhanced and can actually lead to an increase in the GMR. For spin-diffusion lengths comparable to the mean-free path in the ferromagnetic layers, the GMR is due almost exclusively to surface scattering.

PACS Numbers: 75.70.Pa,73.61.-r

I. INTRODUCTION

The discovery[1,2] of the giant-magneto-resistance (GMR) in magnetic multilayers, e.g., Fe/Cr, Co/Cu, has led to extensive studies aimed at the understanding of its origin and its technical applications.[3] Although a quantitative microscopic theory still remains elusive at this stage, it has been proposed that the GMR arises from the difference in the scattering of spin-up and spin-down electrons in the magnetic multilayers.[3] There are two types of spin-dependent scattering: (1) bulk-scattering anisotropy inside the ferromagnetic layers[4] and (2) surface-scattering anisotropy at the interfaces of the ferromagnetic and paramagnetic layers.[5] As a result of the spin-dependent scattering, the resistance of magnetic multilayers can decrease by over 50% when an external magnetic field changes the ferromagnetic layers from antiparallel to parallel alignment.[1,2]

Since the GMR arises from spin-dependent scattering, it may be tempting to think that spin-flip scattering randomizes the spins and thereby reduces the GMR. Our calculation confirms this intuitive argument for spin-flip scattering in the paramagnetic spacer layers; however, we find that the GMR is not necessarily suppressed for spin-flip scattering in the ferromagnetic layers. In particular, when the spin-flip scattering is only in the ferromagnetic layers, the role of the surface scattering is selectively enhanced and the GMR can increase with smaller spin-diffusion length, L_{sf}. When L_{sf} becomes comparable to the mean-free paths in the ferromagnetic layers, the bulk-scattering anisotropy is effectively reduced. One may be able to use this property to single out the surface contribution to the GMR by introducing additional spin-flip scattering in the ferromagnetic layers. Recent experiments indicate that L_{sf} in permalloy ($Ni_{84}Fe_{16}$) is less than 100Å.[6] In this regime, the bulk-scattering anisotropy is suppressed and the GMR is dominated by surface-scattering anisotropy. In this paper, we confine our discussions to the current-in-plane geometry. The role of spin-flip scattering for the current-perpendicular-to-plane geometry has already been discussed by Valet and Fert.[7]

The rest of the paper is organized as follows. In section II, we give the theoretical model used to study the spin-flip scattering. The results are presented in section III, which is followed by the conclusions. In the Appendix, we use Fermi's golden rule to derive the spin-flip scattering rate in the case of magnetic impurities.

II. FORMALISM

We use the classical Boltzmann equation to study transport in the magnetic multilayers. The method was first used in the study of thin films by Fuchs[8] and Sondheimer,[9] who modeled the scattering at the surface by a diffusive scattering parameter. In our study of the magnetic multilayers, we follow previous practice[10] and model the up and down spin conduction electrons as free electrons with a common Fermi velocity v_F, but with different scattering times $\tau_{\sigma=\uparrow,\downarrow}$ and thus different mean-free paths $L_\sigma = v_F\tau_\sigma$. Spin-flip scattering is discussed in the specific context of scattering due to magnetic impurities that not only introduce spin mixing but also give rise to additional scattering within each spin channel. In the Appendix, we compute the scattering rates due to the magnetic impurities using Fermi's golden rule. The magnetic impurities are modeled as local magnetic fields. The orientation of these impurity fields is taken to be random within an angle θ_I with respect to the magnetization direction of the host material.

In the presence of an external electric field E, the linearized Boltzmann equation reads

$$\vec{v}\cdot\frac{\partial}{\partial\vec{r}}\begin{bmatrix} g_\uparrow(\vec{r},\vec{v}) \\ g_\downarrow(\vec{r},\vec{v}) \end{bmatrix} - \frac{e\vec{E}}{m}\cdot\frac{\partial}{\partial\vec{v}}\begin{bmatrix} f_\uparrow^0(\vec{v}) \\ f_\downarrow^0(\vec{v}) \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_\sigma}-\frac{3-x}{2\tau_{sf}}, & \frac{1-x}{2\tau_{sf}} \\ \frac{1-x}{2\tau_{sf}}, & -\frac{1}{\tau_\sigma}-\frac{3-x}{2\tau_{sf}} \end{bmatrix}\begin{bmatrix} g_\uparrow(\vec{r},\vec{v}) \\ g_\downarrow(\vec{r},\vec{v}) \end{bmatrix}, \quad (1)$$

where $g_\sigma(\vec{r},\vec{v})$ is the deviation of the distribution function from its equilibrium value $f_\sigma^0(\vec{v})$, x is defined as $\sin(2\theta_I)/2\theta_I$, and τ_{sf} is the spin-flip time, corresponding to a spin-diffusion length of $L_{sf} = v_F\tau_{sf}$. The effects of the magnetic impurities are included by the terms depending on τ_{sf} on the right-hand-side of Eq. (1). These terms, which are derived in the Appendix for the screened Coulomb potential, include both spin-flip and non-spin-flip scattering from the magnetic impurities. The term, $-(3-x)g_\sigma(\vec{r},\vec{v})/2\tau_{sf}$, includes the non-spin-flip scattering and the scattering-out for spin-flip pocesses. The term, $(1-x)g_{-\sigma}(\vec{r},\vec{v})/2\tau_{sf}$

contains the scattering-in for spin-flip processes. In the numerical calculations, we take $x = 0$ or $\theta_I = \pi$ for magnetic impurities in paramagnetic layers, which corresponds to completely random local field orientation. For magnetic impurities in ferromagnetic layers, the impurity fields should be aligned in the magnetization direction to a certain degree. Thus, as an example, we take $x \approx 2/3$, which corresponds to random fields within $\theta_I = 45^\circ$ of the magnetization direction.

To solve Eq. (1) we first consider the bulk case with only one material. There is then no spatial dependence to the distribution functions and the Boltzmann equation is easily solved:

$$g_\sigma(\vec{v}, bulk) = \frac{\frac{e\vec{E}}{m} \cdot \frac{\partial f_0(\vec{v})}{\partial \vec{v}} \left(\frac{1}{\tau_{-\sigma}} + \frac{1}{\tau_{sf}}\right)}{\left(\frac{1}{\tau_\uparrow} + \frac{3-x}{2\tau_{sf}}\right)\left(\frac{1}{\tau_\downarrow} + \frac{3-x}{2\tau_{sf}}\right) - \left(\frac{1-x}{2\tau_{sf}}\right)^2}. \tag{2}$$

In the magnetic multilayers, the distribution functions do have spatial dependence. In addition, the distribution functions for electrons going away from the top or bottom surface of a layer can be different because the neighboring layers can be different. We denote this directional dependence by a superscript $+/-$ on the velocity $\vec{v}$ for up/down going electrons. Within a given layer and for each $\vec{v}$, Eq. (1) is a coupled first order differential equation in space for a two component system. The solutions in layer i takes the form of the bulk value plus two exponentially decaying functions instead of one for the non-spin-flip case:[10]

$$\begin{aligned}
g^i_\uparrow(\vec{v}^+, z) &= g^i_\uparrow(\vec{v}, bulk) + A^i_\uparrow(\vec{v}^+)\exp\left[-z/|v_z|\tilde{\tau}^i_\uparrow\right] + B^i_\uparrow(\vec{v}^+)\exp\left[-z/|v_z|\tilde{\tau}^i_\downarrow\right] \\
g^i_\downarrow(\vec{v}^+, z) &= g^i_\downarrow(\vec{v}, bulk) + B^i_\downarrow(\vec{v}^+)\exp\left[-z/|v_z|\tilde{\tau}^i_\uparrow\right] + A^i_\downarrow(\vec{v}^+)\exp\left[-z/|v_z|\tilde{\tau}^i_\downarrow\right] \\
g^i_\uparrow(\vec{v}^-, z) &= g^i_\uparrow(\vec{v}, bulk) + A^i_\uparrow(\vec{v}^-)\exp\left[(z-d_i)/|v_z|\tilde{\tau}^i_\uparrow\right] + B^i_\uparrow(\vec{v}^-)\exp\left[(z-d_i)/|v_z|\tilde{\tau}^i_\downarrow\right] \\
g^i_\downarrow(\vec{v}^-, z) &= g^i_\downarrow(\vec{v}, bulk) + B^i_\downarrow(\vec{v}^-)\exp\left[(z-d_i)/|v_z|\tilde{\tau}^i_\uparrow\right] + A^i_\downarrow(\vec{v}^-)\exp\left[(z-d_i)/|v_z|\tilde{\tau}^i_\downarrow\right],
\end{aligned} \tag{3}$$

where the coordinate z is measured from the bottom of layer i with a thickness d_i. The two times, $\tilde{\tau}^i_\sigma$, which determine the rate of decay and the relation between the coefficients, $A^i_\sigma(\vec{v}^\pm)$ and $B^i_\sigma(\vec{v}^\pm)$, are obtained by diagonalizing the right-hand-side of Eq. (1):

$$\frac{1}{\tilde{\tau}^i_\sigma} = \frac{1}{2}\left[\frac{1}{\tau^i_\uparrow} + \frac{1}{\tau^i_\downarrow} + \frac{3-x}{\tau^i_{sf}} \pm \sqrt{\left(\frac{1}{\tau^i_\uparrow} - \frac{1}{\tau^i_\downarrow}\right)^2 + \left(\frac{1-x}{\tau^i_{sf}}\right)^2}\ \right], \tag{4a}$$

$$\frac{B^i_{-\sigma}(\vec{v}^{\pm})}{A^i_{\sigma}(\vec{v}^{\pm})} = \frac{2\tau^i_{sf}}{1-x}\left(\frac{1}{\tilde{\tau}^i_{\sigma}} - \frac{1}{\tau^i_{\sigma}} - \frac{3-x}{2\tau^i_{sf}}\right). \tag{4b}$$

In Eq. (4a), the $\pm$ signs are chosen so that in the limit where the spins are decoupled, $\tau^i_{sf} \to \infty$, the $\tilde{\tau}^i_{\sigma}$ reduce to the scattering times for spin-up and spin-down electrons, τ^i_{σ}. The coefficient $B^i_{\sigma}(\vec{v}^{\pm})$ gives the amount of mixing from the opposite spin-channel. When τ^i_{sf} approaches infinity, one can verify from Eq. (4b) that $B^i_{-\sigma}(\vec{v}^{\pm})/A^i_{\sigma}(\vec{v}^{\pm}) \to 0$. In a system with N layers, there are $4N$ independent variables $A^i_{\uparrow,\downarrow}(\vec{v}^{\pm})$ in Eq. (3), which are to be determined by the boundary conditions at the interfaces between the layers.

At the interfaces the scattering of electrons is modeled by spin-dependent transmission coefficients T_{σ} and a specularity factor S, which we take to be the same for both spins. The amount of diffusive scattering is thus $1-S$. This leads to the boundary conditions[10] for the distribution functions at the interface between layers i and $i+1$:

$$\begin{aligned} g^i_{\sigma}(\vec{v}^-, z=d_i) &= S\left[(1-T_{\sigma})g^i_{\sigma}(\vec{v}^+, z=d_i) + T_{\sigma}g^{i+1}_{\sigma}(\vec{v}^-, z=0)\right] \\ g^{i+1}_{\sigma}(\vec{v}^+, z=0) &= S\left[(1-T_{\sigma})g^{i+1}_{\sigma}(\vec{v}^-, z=0) + T_{\sigma}g^i_{\sigma}(\vec{v}^+, z=d_i)\right]. \end{aligned} \tag{5}$$

For N-layers, each of the $N-1$ interfaces provides 4 equations relating the $4N$ unknowns. The remaining four equations come from the two outer edges where we take $T_{\uparrow} = T_{\downarrow} = 0$.

For both ferromagnetic (F) and antiferromagnetic (A) alignments, the $4N \times 4N$ linear equation array is solved to obtain the distribution functions. With the distribution functions, the resistivity for each configuration is computed via

$$\frac{1}{R_{F,A}} = -\frac{en_e}{E}\left[\sum_{i=1}^{N}\sum_{\sigma=\uparrow,\downarrow}\sum_{\pm}\int_0^{d_i} dz \int d^3v\ v_x g^i_{\sigma}(\vec{v}^{\pm}, z)\right] \Big/ \sum_{i=1}^{N} d_i, \tag{6}$$

and hence the GMR is $1 - R_F/R_A$. In Eq. (6) the electron density, n_e, is taken to be uniform in the multilayers.

III. RESULTS AND DISCUSSIONS

Previous studies show that the GMR can arise from two different mechanisms: (1) spin-dependent bulk-scattering anisotropy $L_\uparrow \neq L_\downarrow$,[4] and (2) spin-dependent surface-scattering anisotropy $T_\uparrow \neq T_\downarrow$.[5] In this section, we discuss the effects of the spin-flip scattering on both of these mechanisms.

We first study the case with magnetic impurities in the paramagnetic spacer layers. The results shown in Fig. 1 include two extreme cases: the GMR arising from (1) purely bulk-scattering anisotropy and (2) surface-scattering anisotropy. In both cases, the GMR decreases as the spin-diffusion length L_{sf} decreases. Starting from large L_{sf}, the GMR is steadily reduced with decreasing L_{sf} and becomes half the original value when L_{sf} is comparable to the mean-free path L_{pm} in the paramagnet without the additional spin-flip scattering. This suppression of the GMR can be understood as follows. To obtain a large GMR, the paramagnetic spacer layer should preserve the spin and momentum of the electrons as they move from one magnetic layer to another. Otherwise, if the spin or momentum is lost in the paramagnet, the ferromagnetic layers become decoupled and there should be no difference in the parallel and anti-parallel alignments of the ferromagnetic layers. As Eq. (1) indicates, spin-flip scattering not only mixes the spins but also relaxes the momentum. Thus the GMR is reduced for smaller spin-diffusion length in the paramagnet. In Fig. 1, there is a second minimum in the curve for the case of purely surface scattering when the spin-diffusion length becomes close to the mean-free paths in the ferromagnet, $L_{sf} \sim L_\uparrow = L_\downarrow$. The GMR is very small for this particular case because the effective mean-free path in the paramagnet $\tilde{L}_{pm} = \tilde{\tau}_{pm} v_F$ [see Eq. (4a)] is very close to those in the ferromagnetic layers $L_\uparrow = L_\downarrow$.[11]

Next, we study the case with spin-flip scattering in the ferromagnetic layers. Fig. 2a shows that for purely bulk scattering the GMR decreases with decreasing L_{sf}. When L_{sf} becomes smaller, the effective scattering rates for up and down spins are drawn closer by the spin-flip scattering. Thus the spin-dependent scattering anisotropy is reduced and so is the GMR.

For the GMR arising from purely surface scattering, Fig. 2a shows that a smaller L_{sf} leads to an *increase* in the GMR. This is a rather surprising result as one would expect the spin-flip scattering to randomize the spins and hence to reduce the GMR. To understand this increase in the GMR with smaller L_{sf}, we look at the current density distribution in the supperlattice. Fig. (2b) shows that when L_{sf} becomes small, the currents densities carried by spin-up and spin-down electrons in the ferromagnetic layers do indeed become very close. However, since L_{sf} does not effect the surface scattering, the spin-up and spin-down electrons still have different transmission coefficients between the ferromagnetic layer and paramagnetic spacer layer. When the ferromagnetic layers are aligned parallel, the currents carried by electrons with up and down spins are different in the paramagnetic spacer layer because of the difference in the transmission coefficients. When the ferromagnetic layers are aligned antiparallel, the total currents carried by up and down spins are the same due to symmetry as shown in Fig. (2c). The total currents for the parallel and anti-parallel configurations can thus be different and this explains why the GMR remains finite for small L_{sf}. The reason the GMR increases is that the magnetic impurities also degrade the momentum and reduce the mean-free paths in the ferromagnet. For purely surface scattering, the GMR depends on the difference between the mean-free paths in the ferromagnetic and paramagnetic layers.[12] Decreasing the smaller one in the ferromagnetic layers leads to an increase in the GMR.

What we have discussed so far is either purely bulk-scattering or purely surface scattering. In reality, the two mechanisms coexist. What happens to the GMR in this more general case? We just showed in the previous paragraph that magnetic impurities in the ferromagnets suppress bulk-scattering anisotropy and enhance the relative role of surface-scattering anisotropy. For the case when bulk- and surface-scattering anisotropies coexist, this conclusion still holds. Fig. 3 shows that at fixed surface scattering anisotropy, the GMR changes rapidly with the spin-up and spin-down mean-free paths when L_{sf} is large. When L_{sf} becomes smaller, the GMR becomes relatively insensitive to the changes in the mean-free paths thus demonstrating the suppression of the bulk-scattering anisotropy. It has been established that nonmagnetic impurities in ferromagnets can lead to different scattering rates for the up and down spins.[4] By fixing the magnetic impurity concentration and varying the nonmagnetic impurity concentration, or vice versa, one may be able to change $L_\uparrow/L_\downarrow$ and $L_{sf}/L_\downarrow$ independently. Thus the parameter space in Fig. (3) may be reached experimentally with different combinations of magnetic and nonmagnetic impurities.

IV. CONCLUSIONS

We have studied the effect of spin-flip scattering on the current-in-plane GMR in magnetic multilayers using the classical Boltzmann equation. We find that spin-flip scattering in the paramagnetic spacer layers suppresses the GMR arising from both the bulk- and surface-scattering anisotropies of the spin-up and spin-down electrons. More interestingly, spin-flip scattering in the ferromagnetic layers selectively suppresses the bulk-scattering anisotropy and enhances the relative role of the surface-scattering anisotropy. When the spin-diffusion length is short, such as in permalloy,[6] the GMR is dominated by the surface-scattering anisotropy. In experiments, bulk- and surface-scattering is usually entangled, and it is difficult to separate the contributions from the two. Our calculation shows that spin-flip scattering in the ferromagnetic layers can effectively suppress the anisotropy from bulk-scattering and thereby single out the contribution to GMR from surface-scattering. To achieve this, the spin-diffusion length should be made comparable to the mean-free paths in the ferromagnetic layers.

ACKNOWLEDGMENTS

This work is supported by DOD/AFOSR F49620-96-1-0026 and NSF grant DMR9357474. We thank J. Bass, T.S. Choy, K. Majumdar, and X. Wang for useful discussions.

APPENDIX A: APPENDIX

In this appendix, we derive the form of the scattering from magnetic impurities by using Fermi's golden rule. We model the magnetic impurities by a local magnetic field at the site of the impurities. The interaction between a conduction electron with spin $\vec{S}_{el}$ and the magnetic impurities located at $\vec{R}_i$ takes the form

$$V_I = \sum_{\vec{R}_i} v_i(\vec{r} - \vec{R}_i) \hat{H} \cdot \vec{S}_{el}, \tag{A1}$$

where $v_i(\vec{r} - \vec{R}_i)$ is the impurity potential and $\hat{H}$ is a unit vector denoting the direction of the local magnetic field. With randomly distributed impurities at a density n_I, Fermi's golden rule gives the collision integral for the Boltzmann equation

$$\begin{aligned} \Delta \left(\frac{df_\sigma(\vec{k})}{dt} \right)_{coll} &= -\frac{2\pi}{\hbar} n_I \sum_{\sigma'} \int \frac{d^3k'}{(2\pi)^3} |v_i(\vec{k} - \vec{k}')|^2 \delta(\epsilon_{\vec{k}'\sigma'} - \epsilon_{\vec{k}\sigma}) \\ &\times \overline{|\langle \sigma' | \hat{H} \cdot \vec{S}_{el} | \sigma \rangle|^2} [f_\sigma(\vec{k}) - f_{\sigma'}(\vec{k}')], \end{aligned} \tag{A2}$$

where the overbar denotes the average over impurity field directions and $v_i(\vec{k})$ is the Fourier transform of $v_i(\vec{r})$. If the impurity magnetic field on different sites are randomly oriented within an angle θ_I from the $\hat{z}$ direction, the directional average in Eq. (A2) can be evaluated to give,

$$\overline{|\langle \sigma' | \hat{H} \cdot \vec{S}_{el} | \sigma \rangle|^2} = \delta_{\sigma - \sigma'} (1 + x)/4 + \delta_{\sigma + \sigma'} (1 - x)/4, \tag{A3}$$

where $x \equiv \sin(2\theta_I)/2\theta_I$. Using Eq. (A3) and assuming a spherical Fermi surface, Eq. (A2) can be reduced to

$$\begin{aligned} \Delta \left(\frac{df_\sigma(\vec{k})}{dt} \right)_{coll} &= -\frac{\pi}{2\hbar} n_I \sum_{\sigma'} \int \frac{d^3k'}{(2\pi)^3} |v_i(\vec{k} - \vec{k}')|^2 \\ &\times \left\{ (1+x) g_\sigma(\vec{k})(1 - \hat{k} \cdot \hat{k}') + (1-x) \left[g_\sigma(\vec{k}) - g_{-\sigma}(\vec{k}) \hat{k} \cdot \hat{k}' \right] \right\} \\ &= -\left[\frac{(1+x)}{\tau_2} + \frac{(1-x)}{\tau_1} \right] g_\sigma(\vec{k}) + (1-x) \left[\frac{1}{\tau_1} - \frac{1}{\tau_2} \right] g_{-\sigma}(\vec{k}), \end{aligned} \tag{A4}$$

where

$$\frac{1}{\tau_1}\equiv \frac{\pi}{2\hbar}n_I\int \frac{d^3k'}{(2\pi)^3}|v_i(\vec{k}-\vec{k}')|^2\delta(\epsilon_{\vec{k}'}-\epsilon_{\vec{k}}),$$
$$\frac{1}{\tau_2}\equiv \frac{\pi}{2\hbar}n_I\int \frac{d^3k'}{(2\pi)^3}|v_i(\vec{k}-\vec{k}')|^2\delta(\epsilon_{\vec{k}'}-\epsilon_{\vec{k}})(1-\hat{k}'\cdot\hat{k}). \tag{A5}$$

The difference between τ_1 and τ_2 is the factor $(1-\hat{k}'\cdot\hat{k})$ in the integral. τ_1 is the usual relaxation time and τ_2 is the relaxation time associated with transport. For screened Coulomb potential with the Fermi vector k_F as the inverse screening length, i.e., $v_i(\delta\vec{k}) = 1/(\delta k^2+k_F^2)$, carrying out the integrations in Eq. (A5) yields $\tau_2 = 1.98\tau_1 \approx 2\tau_1$. In this case, the collision integral can be further simplified

$$\Delta\left(\frac{df_\sigma(\vec{k})}{dt}\right)_{coll} \approx -(3-x)\frac{g_\sigma(\vec{k})}{2\tau_1}+(1-x)\frac{g_{-\sigma}(\vec{k})}{2\tau_1}. \tag{A6}$$

When the magnetic impurities are in the paramagnetic spacer layer, we take the orientation of the local magnetic field to be completely random, $\theta_I = \pi$. When the magnetic impurities are in the ferromagnetic layer, we take, as an example, the orientation to be randomly distributed within $\theta_I = \pi/4$ of the magnetization direction of the host magnet. Eq. (A6) is used in the Boltzmann equation of Eq. (1) with $\tau_1 = \tau_{sf}$ to model the scattering due to magnetic impurities.

REFERENCES

[1] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).

[2] S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).

[3] For a review, see P. M. Levy, Solid State Physics, **47**, 367 (1994).

[4] I. A. Campbell and A. Fert, *Ferromagnetic Materials*, ed. E. P. Wohlfrath, (North-Holland, Amsterdam 1982), chap. 9.

[5] M. D. Stiles, J. Appl. Phys. **79**, 5805 (1996).

[6] W.-C. Chiang, Q. Yang, W. P. Pratt, Jr., R. Loloee, and J. Bass, J. Appl. Phys. **81**, 4570 (1997).

[7] T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).

[8] K. Fuchs, Proc. Cambridge Philos. Soc. **34**, 100 (1938).

[9] E. H. Sondheimer, Adv. Phys. **1**, 1 (1952).

[10] J. Barnas, A. Fuss, R.E. Camley, P. Grünberg, and W. Zinn, Phys. Rev. B **42**, 8110 (1990).

[11] When the specular scattering at the interface is identical for the up and down spins, $S_\uparrow = S_\downarrow = S$, the GMR is zero when $\tilde{L}_{pm} = L_\uparrow = L_\downarrow$. This is because the paramagnet has become identical with the ferromagnet and the conductance of the multilayer no longer depends on the transmission coefficients, which are the only spin-dependent scattering factors. More generally when $S_\uparrow \neq S_\downarrow$, spin-up and spin-down electrons have different surface resistances and the GMR is not zero when $\tilde{L}_{pm} = L_\uparrow = L_\downarrow$. The existence and the size of this second minimum then depends on the relative sizes of $S_\uparrow$, $S_\downarrow$, $T_\uparrow$, and $T_\downarrow$.

[12] For the particular case when $L_\uparrow = L_\downarrow$, $S = 1$, $T_\uparrow = 1$, and $T_\downarrow = 0$, it can be shown that GMR $\sim (L_{pm} - L_\uparrow)^2 L_{pm}/(L_{pm} + L_\uparrow)(L_{pm}^2 + 7L_{pm}L_\uparrow + L_\uparrow^2)$.

FIGURES

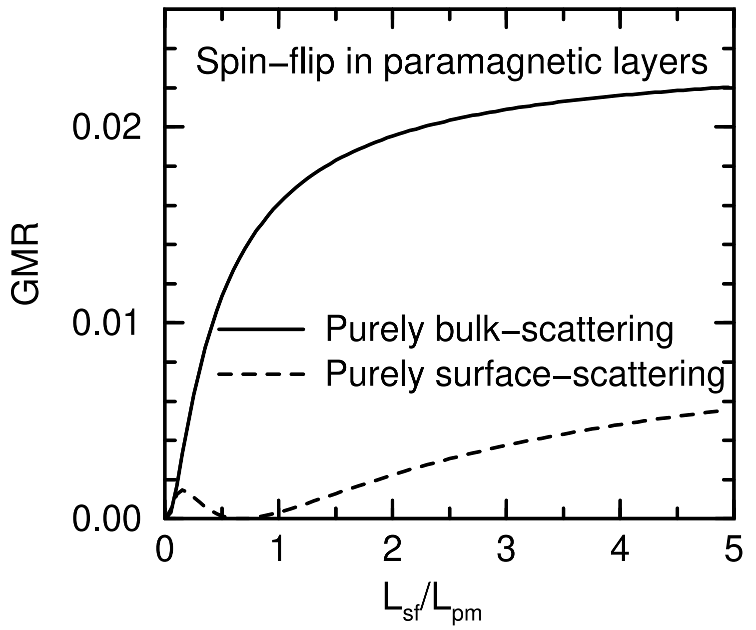

FIG. 1. Dependence of the GMR on the ratio of spin-diffusion length L_{sf} in the paramagnetic layers. L_{pm} is the mean-free path in the paramagnet without the additional spin-flip scattering. The spin-flip scattering in the paramagnet suppress the GMR from both the bulk and surface scattering. When L_{sf} becomes small, electrons emerging from one ferromagnetic layer lose their spin memory before reaching the neighboring ferromagnetic layer and hence cannot distinguish between parallel and antiparallel alignments. Thus the GMR is strongly suppressed. For surface-scattering, the GMR has an additional minimum when L_{sf} becomes close to the mean-free paths in the ferromagnetic layers $L_\uparrow = L_\downarrow$. In this particular case, the effective mean-free path in the paramagnetic layers becomes close to those in the ferromagnetic layers and the GMR is zero for this particular case.[11] The parameters chosen for purely bulk-scattering are: $L_\uparrow = 8d$, $L_\downarrow = 2d$, $L_{pm} = 20d$, $S = 0.5$, $T_\uparrow = T_\downarrow = 0.5$; d is the film thickness for each layer. The parameters chosen for purely surface scattering are: $L_\uparrow = L_\downarrow = 5d$, $L_{pm} = 20d$, $S = 0.5$, $T_\uparrow = 0.8$, and $T_\downarrow = 0.2$.

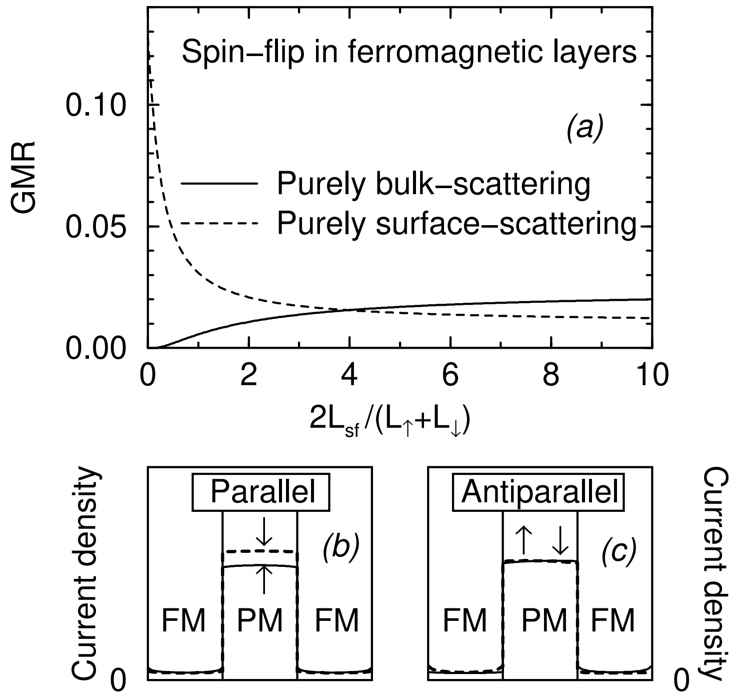

FIG. 2. *(a)* Dependence of the GMR on the spin-diffusion length L_{sf} in the ferromagnetic layers. $L_{\uparrow,\downarrow}$ are the mean-free paths for spin-up and spin-down electrons in the ferromagnets without the additional spin-flip scattering. For purely bulk-scattering, the GMR decreases with decreasing L_{sf}. For purely surface scattering, the GMR increases with decreasing L_{sf}. The parameters chosen for bulk- and surface-scattering are the same as in Fig. (1). For purely surface scattering, *(b)* and *(c)* give the current densities for the parallel and antiparallel alignments, respectively. For the parallel alignment in *(b)*, although the current densities in the ferromagnetic layers for spin-up (solid lines) and spin-down (dashed lines) are very similar, the difference in the transmission coefficients leads to different current densities in the paramagnetic spacer layer. For the antiparallel alignment in *(c)*, the total currents for up and down spins are the same because the spin-up current density is the mirror image of the spin-down current density with respect to the center of the paramagnetic spacer layer. For purely bulk scattering, both the parallel and antiparallel alignments see similar current densities as in *(c)*. Figures *(b)* and *(c)* are both obtained with $L_{sf} = L_{\uparrow} = L_{\downarrow}$.

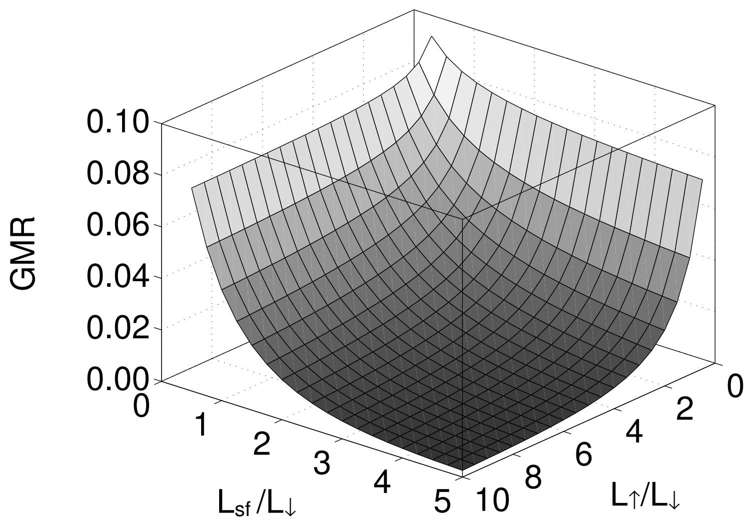

FIG. 3. Dependence of the GMR on the ratios $L_{sf}/L_{\downarrow}$ and $L_{\uparrow}/L_{\downarrow}$ for fixed interface scattering with magnetic impurities in the ferromagnetic layers. At large L_{sf}, the GMR depends sensitively on the bulk-scattering anisotropy $L_{\uparrow}/L_{\downarrow}$. At smaller L_{sf}, the bulk scattering anisotropy is suppressed and the GMR depends weakly on $L_{\uparrow}/L_{\downarrow}$. Parameters used in this plot are: $L_{pm} = 20d$, $L_{\downarrow} = 2d$, $S = 0.5$, $T_{\uparrow} = 0.8$, and $T_{\downarrow} = 0.2$.