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Effects of interchannel transitions in the current-in-plane giant magnetoresistance

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Abstract. Transport in magnetic multilayers is considered theoretically within a quasi classical approach based on the Boltzmann kinetic equation. The case of an in-plane electric current is analysed within the two-current model with spin mixing processes taken into account. Such processes decrease the resistance change at the transition from antiparallel to parallel alignment of the film magnetizations. Scattering by interfaces and surfaces is taken into account by appropriate spin-dependent boundary conditions.

1. Introduction

The giant magnetoresistance (GMR) effect found in transition metal magnetic multilayers [1, 2] results from a redistribution of the local spin-dependent electron scattering probability when the sublayer magnetizations rotate from the antiparallel to parallel alignment (or vice versa). The effect is usually described within a two-current model introduced to describe transport properties of ferromagnetic transition metals [3, 4]. The model assumes two well defined spin channels for electronic transport. The channels are more or less independent and in first approximation one simply assumes no inter-channel transitions. This approximation can be justified at low temperatures. At higher temperatures, however, the approximation is no longer valid and one has to take into account spin mixing processes. In magnetic sublayers such processes result, for example, from electron scattering on the long-wavelength spinwave excitations [5].

Most theoretical descriptions of the GMR effect are based on the assumption of independent spin channels [6–11], which considerably simplifies the problem. However, to describe properly the temperature behaviour of the GMR effect in both current-in-plane (CIP) and current-perpendicular to-plane (CPP) geometries one has to include those spin mixing processes which conserve the electron momentum [12]. Spin flip processes of diffuse type are simply included in the spin-dependent relaxation times. Spin mixing processes are particularly important in the case when the electric current flows perpendicularly to the sublayers, as discussed by Valet and Fert [13] in their classical model of perpendicular transport.

In this paper we analyse theoretically the role of spin mixing processes in the CIP transport within the quasi classical approach based on the Boltzmann kinetic equation. Considerations are restricted to a symmetrical sandwich consisting of two ferromagnetic

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films separated by a nonmagnetic spacer. In the limit of perfectly reflecting outer surfaces they apply also to infinite superlattices. The electronic properties of the system are described within the jellium model with a uniform and spin-independent electron potential across the sample. Further details of the model as well as the Boltzmann equation and some symmetry relations are described in section 2. The solution of the Boltzmann equation is presented in section 3, whereas a final expression for the magnetoresistance is derived in section 4. Some numerical results are presented and discussed in section 5.

2. Boltzmann equation

For simplicity, we consider a symmetrical sandwich structure in which two ferromagnetic films of thickness d_m are separated by a nonmagnetic spacer of thickness d_n as shown schematically in figure 1. The periodic part of the electronic potential is assumed constant across the structure and independent of the electron spin orientation. The probability of electron scattering from impurities located inside the films and from surface and interface roughness is assumed to be spin dependent and is taken into account respectively by appropriate relaxation times, surface specularity factors and interface transmission coefficients. Inside the ferromagnetic films the relaxation times τ_{m+} and τ_{m-}, respectively for spin majority and spin minority electrons, are generally different in contrast to the nonmagnetic spacer where they are assumed equal for both spin directions, $\tau_{n\sigma} = \tau_n$. We use the notation according to which the electron spin projection onto the local quantization axis (opposite to the sublayer magnetization) is denoted as '+' for majority electrons and '−' for minority electrons, whereas the projection onto the global quantization axis is denoted as $\sigma = \uparrow$ and $\sigma = \downarrow$.

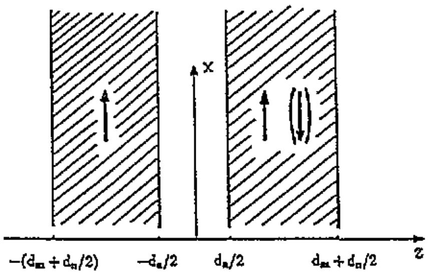

Figure 1. Schematic illustration of the sandwich structure and the coordinate system used in this paper.

It was shown for bulk systems [5] that those electron scattering processes which transfer the electron momentum between the two spin channels can be taken into account by an additional term in the Boltzmann equation. For systems with broken translational symmetry along the axis z (as in the case under consideration) this equation may be written in the form

$$\frac{\partial g_\sigma(z, v)}{\partial z} + \frac{g_\sigma(z, v)}{v_z \tau_\sigma(z)} + \frac{g_\sigma(z, v) - g_{-\sigma}(z, v)}{v_z \tau_{+-}(z)} = \frac{|e|E}{m v_z} \frac{\partial f^0(v)}{\partial v_x}. \tag{1}$$

Here $\tau_{\sigma,-\sigma} = \tau_{-\sigma,\sigma} \equiv \tau_{+-}$ is the spin mixing relaxation time [5], $g_\sigma(z, v)$ is the deviation of the Fermi–Dirac distribution function $f_\sigma(z, v)$ from the equilibrium distribution $f^0(v)$,

$$g_\sigma(z, v) = f_\sigma(z, v) - f^0(v) \tag{2}$$

and it is indicated explicitly that the relaxation times depend on z. In the case considered here this dependence is step like. One should note at this point that spin flip scattering processes contribute in general to τ_+ and τ_- (diffuse scattering processes) as well as to τ_{+-} (electron momentum conserving scattering processes).

Let us now apply equation (1) to the structure under consideration. Due to a discontinuity of the relaxation times at the interfaces, this equation has to be applied separately to each sublayer and the appropriate solutions have to be joined using relevant boundary conditions. Before doing this let us analyse first some symmetry properties of the function $g_\sigma(z, v)$. It is convenient to decompose the distribution function $g_\sigma(z, v)$ into two parts, $g_\sigma^+(z)$ and $g_\sigma^-(z)$, respectively for positive and negative v_z (the dependence of $g_\sigma^\pm(z)$ on the electron velocity is not indicated explicitly). For a symmetrical sandwich with the $z = 0$ plane being in the middle of the structure (see figure 1), the functions $g_\sigma^\pm(z)$ obey the relation

$$g_\sigma^\pm(z) = g_\sigma^\mp(-z) \tag{3}$$

for the parallel alignment and

$$g_\sigma^\pm(z) = g_{-\sigma}^\mp(-z) \tag{4}$$

for the antiparallel one. It is sufficient then to calculate the distribution function only for a half of the structure, say for $z < 0$.

3. Distribution function

According to what we stated above it is sufficient to calculate the distribution function for one of the two ferromagnetic films, say for the left one. By applying the symmetry relations one can then obtain the distribution function in the second film. In the following we will distinguish both parallel and antiparallel orientations of the film magnetizations. Consider first the parallel configuration. In this geometry the local quantization axes coincide with the global one. Inside the left magnetic layer, i.e., for $-(d_m + d_n/2) \leqslant z \leqslant (-d_n/2)$, the solutions $g_{m\uparrow}^\pm(z)$ and $g_{m\downarrow}^\pm(z)$ of equations (1) can be written in the form

$$g_{m\uparrow}^\pm(z) = A_m\left[1 + F_m'^\pm e^{\mp\alpha_m' z} + F_m''^\pm e^{\mp\alpha_m'' z}\right] \tag{5}$$

$$g_{m\downarrow}^\pm(z) = A_m\left[D_m + C_m' F_m'^\pm e^{\mp\alpha_m' z} + C_m'' F_m''^\pm e^{\mp\alpha_m'' z}\right] \tag{6}$$

where A_m and D_m are defined as

$$A_m = \frac{|e|E}{m}\frac{\partial f^0(v)}{\partial v_x}\frac{\tau_{m+}(\tau_{m+-} + 2\tau_{m-})}{\tau_{m+-} + \tau_{m+} + \tau_{m-}} \tag{7}$$

and

$$D_m = \frac{2 + \tau_{m+-}/\tau_{m+}}{2 + \tau_{m+-}/\tau_{m-}} \tag{8}$$

whereas the parameters $\alpha_m'^{('')}$ and $C_m'^{('')}$ are given by

$$\alpha_m'^{('')} = \frac{1}{|v_z|}\left[\frac{\tau_{m-} + \tau_{m+}}{2\tau_{m+}\tau_{m-}} + \frac{1}{\tau_{m+-}} \pm \sqrt{\left(\frac{\tau_{m-} - \tau_{m+}}{2\tau_{m+}\tau_{m-}}\right)^2 + \left(\frac{1}{\tau_{m+-}}\right)^2}\right] \tag{9}$$

and

$$C_m'^{('')} = \tau_{m+-}\left[\frac{\tau_{m-} - \tau_{m+}}{2\tau_{m+}\tau_{m-}} \mp \sqrt{\left(\frac{\tau_{m-} - \tau_{m+}}{2\tau_{m+}\tau_{m-}}\right)^2 + \left(\frac{1}{\tau_{m+-}}\right)^2}\right]. \tag{10}$$

The functions $F_{\mathrm{m}}^{\prime\pm}$ and $F_{\mathrm{m}}^{\prime\prime\pm}$ in (5) and (6) (their velocity dependence is not indicated explicitly here) will be determined later.

Inside the nonmagnetic spacer the solution of equations (1) can be written in the form analogous to (5) and (6), i.e.,

$$g_{\mathrm{n}\uparrow}^{\pm}(z) = A_{\mathrm{n}}\left[1 + F_{\mathrm{n}}^{\prime\pm}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime}z} + F_{\mathrm{n}}^{\prime\prime\pm}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime\prime}z}\right] \tag{11}$$

$$g_{\mathrm{n}\downarrow}^{\pm}(z) = A_{\mathrm{n}}\left[D_{\mathrm{n}} + C_{\mathrm{n}}^{\prime}F_{\mathrm{n}}^{\prime\pm}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime}z} + C_{\mathrm{n}}^{\prime\prime}F_{\mathrm{n}}^{\prime\prime\pm}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime\prime}z}\right]. \tag{12}$$

Owing to the lack of spin asymmetry in relaxation times the parameters A_{n}, D_{n}, $\alpha_{\mathrm{n}}^{\prime(\prime\prime)}$ and $C_{\mathrm{n}}^{\prime(\prime\prime)}$ are now of the forms

$$A_{\mathrm{n}} = \frac{|e|E}{m}\frac{\partial f^{0}(v)}{\partial v_{x}}\tau_{\mathrm{n}} \tag{13}$$

$$D_{\mathrm{n}} = 1, \tag{14}$$

$$\alpha_{\mathrm{n}}^{\prime} = \frac{1}{|v_{z}|}\left(\frac{1}{\tau_{\mathrm{n}}} + \frac{2}{\tau_{\mathrm{n}+-}}\right) \tag{15}$$

$$\alpha_{\mathrm{n}}^{\prime\prime} = \frac{1}{|v_{z}|\tau_{\mathrm{n}}} \tag{16}$$

and

$$C_{\mathrm{n}}^{\prime} = -1 \qquad C_{\mathrm{n}}^{\prime\prime} = 1. \tag{17}$$

Additionally, the symmetry condition (3) together with (17) gives

$$F_{\mathrm{n}}^{\prime+} = F_{\mathrm{n}}^{\prime-} \equiv F_{\mathrm{n}}^{\prime} \tag{18}$$

$$F_{\mathrm{n}}^{\prime\prime+} = F_{\mathrm{n}}^{\prime\prime-} \equiv F_{\mathrm{n}}^{\prime\prime}. \tag{19}$$

Taking this into account we may rewrite the distribution function inside the nonmagnetic spacer in the form

$$g_{\mathrm{n}\uparrow}^{\pm}(z) = A_{\mathrm{n}}\left[1 + F_{\mathrm{n}}^{\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime}z} + F_{\mathrm{n}}^{\prime\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime\prime}z}\right] \tag{20}$$

$$g_{\mathrm{n}\downarrow}^{\pm}(z) = A_{\mathrm{n}}\left[1 - F_{\mathrm{n}}^{\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime}z} + F_{\mathrm{n}}^{\prime\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime\prime}z}\right]. \tag{21}$$

Consider now the antiparallel orientation of the film magnetizations with the magnetization of the right film reversed (figure 1). The distribution function in the left ferromagnetic film is still given by (5) and (6). The distribution function in the right ferromagnetic film follows then from the symmetry relation (4). The general expressions (11) and (12) for the distribution function in the nonmagnetic spacer are also valid, but now the symmetry condition (4) leads to the relations

$$F_{\mathrm{n}}^{\prime+} = -F_{\mathrm{n}}^{\prime-} \equiv F_{\mathrm{n}}^{\prime} \tag{22}$$

$$F_{\mathrm{n}}^{\prime\prime+} = F_{\mathrm{n}}^{\prime\prime-} \equiv F_{\mathrm{n}}^{\prime\prime}. \tag{23}$$

Thus, in the antiparallel alignment the distribution function in the nonmagnetic film is given by

$$g_{\mathrm{n}\uparrow}^{\pm}(z) = A_{\mathrm{n}}\left[1 \pm F_{\mathrm{n}}^{\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime}z} + F_{\mathrm{n}}^{\prime\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime\prime}z}\right] \tag{24}$$

$$g_{\mathrm{n}\downarrow}^{\pm}(z) = A_{\mathrm{n}}\left[1 \mp F_{\mathrm{n}}^{\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime}z} + F_{\mathrm{n}}^{\prime\prime}\mathrm{e}^{\mp\alpha_{\mathrm{n}}^{\prime\prime}z}\right]. \tag{25}$$

For both configurations the constants $F_{\mathrm{m}}^{\prime\pm}$, $F_{\mathrm{m}}^{\prime\prime\pm}$, $F_{\mathrm{n}}^{\prime}$ and $F_{\mathrm{n}}^{\prime\prime}$ can be found from the boundary conditions

$$g_{\mathrm{m}\sigma}^{+}(z_{\mathrm{s}}) = p_{\sigma}g_{\mathrm{m}\sigma}^{-}(z_{\mathrm{s}}) + p_{\sigma,-\sigma}g_{\mathrm{m}-\sigma}^{-}(z_{\mathrm{s}}) \tag{26}$$

for the surface at $z = z_s = -(d_m + d_n/2)$, and

$$g^{+}_{n\sigma}(z_i) = T_\sigma g^{+}_{m\sigma}(z_i) + T_{\sigma,-\sigma} g^{+}_{m-\sigma}(z_i) \tag{27}$$

$$g^{-}_{m\sigma}(z_i) = T_\sigma g^{-}_{n\sigma}(z_i) + T_{\sigma,-\sigma} g^{-}_{n-\sigma}(z_i) \tag{28}$$

for the interface at $z = z_i = -d_n/2$. In the above formula p_σ and T_σ are coefficients which describe the spin conserving specular reflection from the surface and transmission across the interface. $p_{\sigma,-\sigma}$ and $T_{\sigma,-\sigma}$, on the other hand, describe similar electron reflection and transmission but with simultaneous reversal of the electron spin. Physical processes which contribute to $p_{\sigma,-\sigma}$, and $T_{\sigma,-\sigma}$ are similar to those which contribute to τ_{+-}—for example electron scattering on surface or interface spin waves. Such processes leave the in-plane electron momentum almost unchanged. In the following we will assume $p_{\sigma,-\sigma} = p_{-\sigma,\sigma} \equiv p_{+-}$ and $T_{\sigma,-\sigma} = T_{-\sigma,\sigma} \equiv T_{+-}$ and by the mixing processes we will mean only those which contribute to τ_{+-}, p_{+-} and T_{+-}. In equations (27) and (28) we assume no specular reflection at the interfaces and the same transmission coefficients for electrons incident from both sides.

Taking into account the solutions (5, 6) and (20, 21) for the parallel configuration or (5, 6) and (24, 25) for the antiparallel one, we arrive at the following set of equations for the unknown parameters $F'^{\pm}_m$, $F''^{\pm}_m$, F'_n and F''_n:

$$\begin{aligned} &e^{\alpha'_m(d_n/2+d_m)}F'^{+}_m + e^{\alpha''_m(d_n/2+d_m)}F''^{+}_m - (p_+ + C'_m p_{+-})e^{-\alpha'_m(d_n/2+d_m)}F'^{-}_m \\ &\quad -(p_+ + C''_m p_{+-})e^{-\alpha''_m(d_n/2+d_m)}F''^{-}_m \\ &\quad = p_+ + p_{+-}D_m - 1 \end{aligned} \tag{29}$$

$$\begin{aligned} &C'_m e^{\alpha'_m(d_n/2+d_m)}F'^{+}_m + C''_m e^{\alpha''_m(d_n/2+d_m)}F''^{+}_m - (p_- C'_m + p_{+-})e^{-\alpha'_m(d_n/2+d_m)}F'^{-}_m \\ &\quad -(p_- C''_m + p_{+-})e^{-\alpha''_m(d_n/2+d_m)}F''^{-}_m \\ &\quad = (p_- - 1)D_m + p_{+-} \end{aligned} \tag{30}$$

$$\begin{aligned} &-(T_+ + C'_m T_{+-})e^{\alpha'_m d_n/2}F'^{+}_m - (T_+ + C''_m T_{+-})e^{\alpha''_m d_n/2}F''^{+}_m + Ke^{\alpha'_n d_n/2}F'_n + Ke^{\alpha''_n d_n/2}F''_n \\ &\quad = T_+ + T_{+-}D_m - K \end{aligned} \tag{31}$$

$$\begin{aligned} &-(C'_m T_- + T_{+-})e^{\alpha'_m d_n/2}F'^{+}_m - (C''_m T_- + T_{+-})e^{\alpha''_m d_n/2}F''^{+}_m - Ke^{\alpha'_n d_n/2}F'_n + Ke^{\alpha''_n d_n/2}F''_n \\ &\quad = T_- D_m + T_{+-} - K \end{aligned} \tag{32}$$

$$\begin{aligned} &e^{-\alpha'_m d_n/2}F'^{-}_m + e^{-\alpha''_m d_n/2}F''^{-}_m \mp (T_+ - T_{+-})Ke^{-\alpha'_n d_n/2}F'_n - (T_+ + T_{+-})Ke^{-\alpha''_n d_n/2}F''_n \\ &\quad = (T_+ + T_{+-})K - 1 \end{aligned} \tag{33}$$

$$\begin{aligned} &C'_m e^{-\alpha'_m d_n/2}F'^{-}_m + C''_m e^{-\alpha''_m d_n/2}F''^{-}_m \pm (T_- - T_{+-})Ke^{-\alpha'_n d_n/2}F'_n - (T_- + T_{+-})Ke^{-\alpha''_n d_n/2}F''_n \\ &\quad = (T_- + T_{+-})K - D_m \end{aligned} \tag{34}$$

where we introduced a parameter K defined as

$$K = \tau_n \frac{\tau_{m+-} + \tau_{m+} + \tau_{m-}}{\tau_{m+}(\tau_{m+-} + 2\tau_{m-})} \tag{35}$$

and the upper and lower signs in (33) and (34) refer respectively to the parallel and antiparallel configurations. The above set of equations can be solved either analytically or numerically to give $F'^{\pm}_m$, $F''^{\pm}_m$, F'_n and F''_n for the two magnetization orientations.

4. Magnetoresistance

Having found the distribution function one can calculate the current density from the general formula

$$j_{x\sigma}(z) = -e\left(\frac{m}{h}\right)^3 \int v_x g_\sigma(v, z)\, dv \tag{36}$$

and consequently the resistance and magnetoresistance. On performing analytical integration over $v = |v|$ and z one arrives at the following formula for the relative resistance change.

$$\frac{\Delta R}{R_0} \equiv \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{\kappa_{\uparrow\uparrow} - \kappa_{\uparrow\downarrow}}{\kappa_{\uparrow\downarrow}}. \tag{37}$$

Here $R_{\uparrow\uparrow}$ and $R_{\uparrow\downarrow}$ are respectively the resistances in the parallel and antiparallel configurations, and

$$\kappa_\mu = \frac{8}{3}d_n + \frac{8}{3}d_m(1 + D_m)\frac{\lambda_{m+}}{\lambda_n}\frac{\lambda_{m+-} + 2\lambda_{m-}}{\lambda_{m+-} + \lambda_{m+} + \lambda_{m-}} + 2I_\mu \tag{38}$$

for $\mu = \uparrow\uparrow, \uparrow\downarrow$, where

$$\begin{aligned} I_\mu = \int_0^1 dx\ (1 - x^2)x\Bigg[\frac{\lambda_{m+}}{\lambda_n}\frac{\lambda_{m+-} + 2\lambda_{m-}}{\lambda_{m+-} + \lambda_{m+} + \lambda_{m-}} \\ \times\bigg[F_m^{\prime +}(1 + C_m^\prime)\frac{1}{\beta_m^\prime}\left(e^{\beta_m^\prime(d_m + d_n/2)/x} - e^{\beta_m^\prime d_n/2x}\right) \\ +F_m^{\prime -}(1 + C_m^\prime)\frac{1}{\beta_m^\prime}\left(e^{-\beta_m^\prime d_n/2x} - e^{-\beta_m^\prime(d_m + d_n/2)/x}\right) \\ +F_m^{\prime\prime +}(1 + C_m^{\prime\prime})\frac{1}{\beta_m^{\prime\prime}}\left(e^{\beta_m^{\prime\prime}(d_m + d_n/2)/x} - e^{\beta_m^{\prime\prime} d_n/2x}\right) \\ +F_m^{\prime\prime -}(1 + C_m^{\prime\prime})\frac{1}{\beta_m^{\prime\prime}}\left(e^{-\beta_m^{\prime\prime} d_n/2x} - e^{-\beta_m^{\prime\prime}(d_m + d_n/2)/x}\right)\bigg] \\ +2F_n^{\prime\prime}\frac{1}{\beta_n^{\prime\prime}}\left(e^{\beta_n^{\prime\prime} d_n/2x} - e^{-\beta_n^{\prime\prime} d_n/2x}\right)\Bigg]. \end{aligned} \tag{39}$$

The index μ distinguishes two different magnetization orientations and for clarity of notation it has been omitted on the right-hand side of equations (39). However, one has to bear in mind that for different μ we have different sets of the parameters $F_m^{\prime\pm}$, $F_m^{\prime\prime\pm}$, $F_n^\prime$ and $F_n^{\prime\prime}$. We have also introduced here several mean free paths according to the definitions

$$\lambda_n = v_F\tau_n \tag{40}$$

$$\lambda_{m\pm} = v_F\tau_{m\pm} \tag{41}$$

and

$$\lambda_{m+-} = v_F\tau_{m+-}. \tag{42}$$

The parameters $\beta_m^\prime$, $\beta_m^{\prime\prime}$ and $\beta_n^{\prime\prime}$ which occur in equations (39) are defined similarly to the corresponding parameters $\alpha_m^\prime$, $\alpha_m^{\prime\prime}$ and $\alpha_n^{\prime\prime}$, but with $|v_z|$ replaced by v_F, i.e.,

$$\beta_m^{\prime(\prime\prime)} = \frac{\lambda_{m-} + \lambda_{m+}}{2\lambda_{m+}\lambda_{m-}} + \frac{1}{\lambda_{m+-}} \pm \sqrt{\left(\frac{\lambda_{m-} - \lambda_{m+}}{2\lambda_{m+}\lambda_{m-}}\right)^2 + \left(\frac{1}{\lambda_{m+-}}\right)^2} \tag{43}$$

and

$$\beta_n^{\prime\prime} = \frac{1}{\lambda_n}. \tag{44}$$

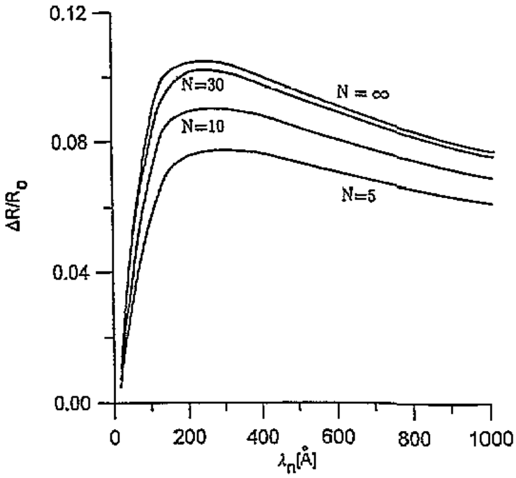

Figure 2. The influence of bulk spin mixing processes on the relative resistance change. The ratio $\Delta R/R_0$ is shown against electron mean free path λ_n in the nonmagnetic spacer. The following parameters have been assumed: $d_m = d_n = 20$ Å, $p_+ = p_- = T_+ = T_- = 0.9$, $p_{+-} = T_{+-} = 0$, $N_b = 5$, $\kappa = 1$ and $N_m = N_n = N$ with N as indicated.

5. Numerical results

Equations (29–34) determine the unknown parameters which enter equations (37–39) for the magnetoresistance. From the phenomenological point of view the following spin-dependent scattering processes can contribute to the magnetoresistance under consideration: (i) electron scattering on impurities and defects located inside the sublayers (so-called bulk scattering), (ii) diffuse scattering from rough interfaces and (iii) diffuse scattering from rough outer surfaces. Those scattering processes are described respectively by the following phenomenological parameters: $\lambda_{m\pm}$, $T_\pm$ and $p_\pm$. In a general case, the magnetoresistance is a superposition of all the three different terms. Similarly, one may also state that there are three possible spin mixing scattering processes (i) the bulk ones described by λ_{m+-} and λ_{n+-}, (ii) the interface mixing processes described phenomenologically by T_{+-} and the surface ones described by the parameters p_{+-}. In the following discussion we will analyse all those possibilities in more detail.

5.1. Magnetoresistance of bulk origin

Suppose first that $T_+ = T_-$ and $p_+ = p_-$, but $\lambda_{m+} \neq \lambda_{m-}$. In that case the GMR effect is due to spin-dependent scattering from scattering centres distributed inside the films and is determined by a bulk spin asymmetry factor defined as

$$N_b = \frac{\lambda_-}{\lambda_+}. \tag{45}$$

The two different electric subcurrents are mixed, in general, by all the mixing processes described above. Figure 2 shows the relative resistance change $\Delta R/R_0$ in the presence of bulk mixing processes only (which are described by λ_{m+-} and λ_{n+-}). $\Delta R/R_0$ is plotted there against electron mean free path in the nonmagnetic spacer λ_n with the other mean free paths assumed proportional to λ_n,

$$\bar{\lambda}_m = \kappa\lambda_n \tag{46}$$

$$\lambda_{m+-} = N_m \overline{\lambda}_m = N_m \kappa \lambda_n \tag{47}$$

$$\lambda_{n+-} = N_n \lambda_n \tag{48}$$

where $\overline{\lambda}_m$ is the average mean free path in the magnetic material,

$$\overline{\lambda}_m = \tfrac{1}{2}(\lambda_{m+} + \lambda_{m-}). \tag{49}$$

In figure 2 we assumed $N_m = N_n = N$ and different curves correspond to different values of N. The case $N = \infty$ corresponds to the limit of independent spin channels. It is evident that the mixing processes lower the GMR effect. For the parameters assumed in figure 2 the spin mixing mean free paths in the magnetic and nonmagnetic films are the same. In a general case, however, $\lambda_{m+-} \neq \lambda_{n+-}$ and one may expect that λ_{n+-} is much longer than λ_{m+-}. The dependence of the GMR effect on both N_m and N_n is presented in more detail in figure 3.

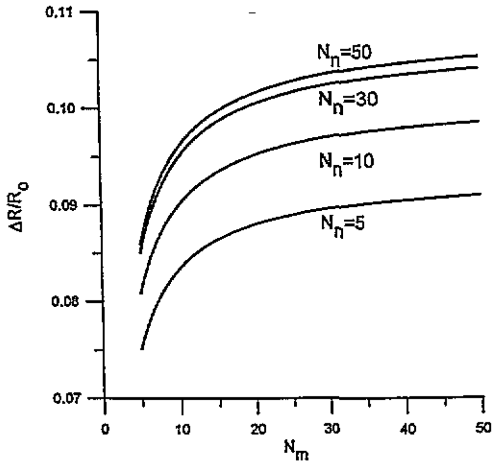

Figure 3. The ratio $\Delta R/R_0$ in the presence of bulk spin mixing processes shown against N_m. Different curves correspond to indicated values of N_n and the other parameters are $\lambda_n = \overline{\lambda}_m = 200$ Å, $N_b = 5$, $d_m = d_n = 20$ Å, $p_+ = p_- = T_+ = T_- = 0.9$ and $p_{+-} = T_{+-} = 0$.

The mixing processes may also result from coherent interface spin flip transitions described phenomenologically by the parameter T_{+-}. The role of those processes in the GMR effect is similar to the role of bulk spin mixing processes discussed above. In figure 4 the ratio $\Delta R/R_0$ is shown against λ_n for indicated values of the parameter T_{+-} and no bulk or interface mixing transitions. For each curve the transmission coefficients T_+ and T_- were adjusted so as to keep the same probability of diffuse interface scattering. Similar behaviour for the surface spin mixing transitions is shown in figure 5, where $T_{+-} = 0$ and $N_m = N_n = \infty$ have been assumed.

5.2. *Magnetoresistance due to spin-dependent interface scattering*

Consider now the case when the GMR originates from the spin-dependent scattering by rough interfaces and analyse the role of various mixing processes. The relevant factor characterizing the GMR effect is now the spin asymmetry ratio for the probabilities of diffuse electron scattering from the interfaces, which can be defined as

$$N_i = \frac{1 - T_- - T_{+-}}{1 - T_+ - T_{+-}}. \tag{50}$$

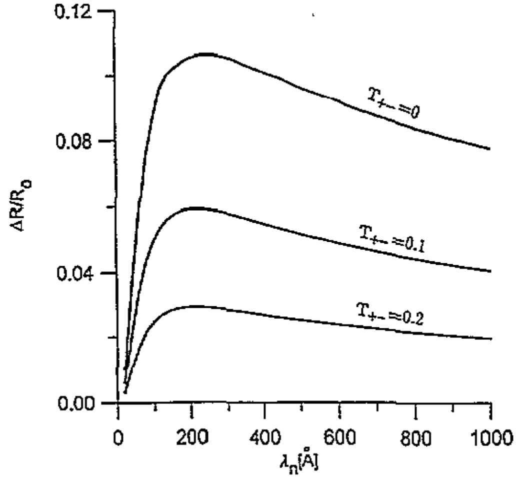

Figure 4. The influence of interface spin mixing processes on the GMR effect. The ratio $\Delta R/R_0$ is shown against λ_n for $d_m = d_n = 20$ Å, $p_+ = p_- = 0.9$, $p_{+-} = 0$. Different curves correspond to indicated values of T_{+-} and for each curve T_+ and T_- are taken as $T_\pm = 0.9 - T_{+-}$. The other parameters are $N_b = 5$, $\kappa = 1$ and $N_m = N_n = \infty$.

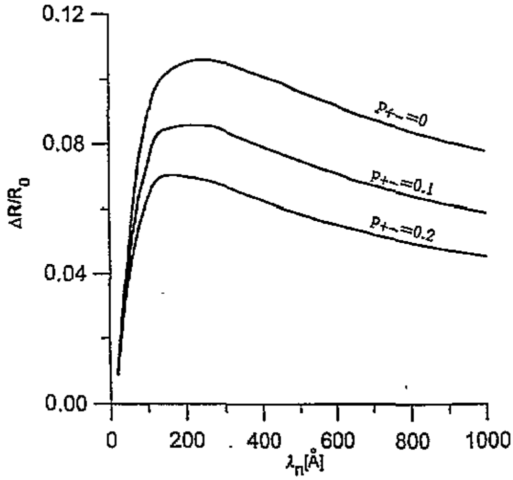

Figure 5. Role of surface spin mixing processes in the GMR effect. $\Delta R/R_0$ is shown against λ_n for $d_m = d_n = 20$ Å, $T_+ = T_- = 0.9$, $T_{+-} = 0$. Different curves correspond to indicated values of p_{+-} and for each curve p_+ and p_- are taken as $p_\pm = 0.9 - p_{+-}$. The other parameters are $N_b = 5$, $\kappa = 1$ and $N_m = N_n = \infty$.

The GMR effect occurs now for $N_i \neq 1$.

In figure 6 we show the influence of the bulk mixing processes on the ratio $\Delta R/R_0$. Different curves correspond to different values of $N = N_m = N_n$ and it is evident that the bulk spin mixing processes lower the GMR effect. The same is also true for the spin mixing processes occuring at interfaces as well as surfaces, as is shown in figure 7. Different curves in this figure correspond to different values of the interface and surface mixing parameters. The other parameters are adjusted so as to have the same probability of diffuse scattering at the interfaces as well as surfaces (and consequently the same factors N_i and N_s for all curves).

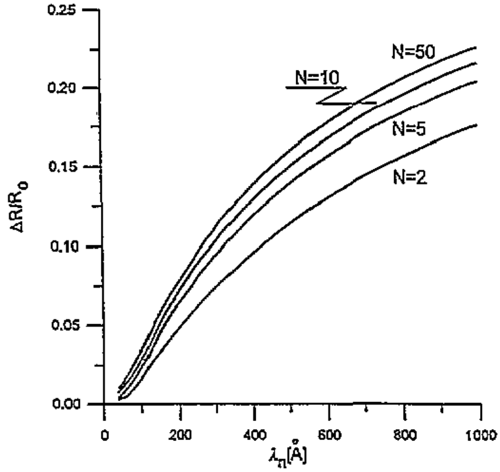

Figure 6. Relative resistance change $\Delta R/R_0$ in the presence of bulk spin mixing processes shown against mean free path λ_n for $d_m = d_n = 20$ Å, $p_+ = p_- = 0.9$, $p_{+-} = T_{+-} = 0$ $T_+ = 0.5$, $T_- = 0.9$ ($N_i = 0.2$), $\kappa = 1$ and $N_b = 1$. Different curves correspond to different $N_m = N_n = N$ with N as indicated.

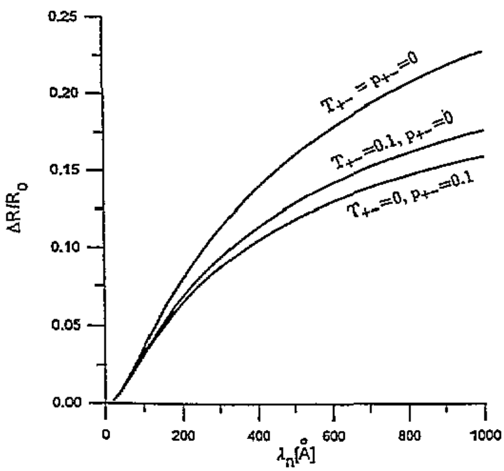

Figure 7. Relative resistance change against λ_n for $d_m = d_n = 20$ Å, $p_+ = p_- = 0.9 - p_{+-}$, $T_+ = 0.5 - T_{+-}$, $T_- = 0.9 - T_{+-}$ with p_{+-} and T_{+-} as indicated. The other parameters are $\kappa = 1$, $N_b = 1$ and $N_m = N_n = \infty$.

5.3. Magnetoresistance due to surface spin-dependent scattering

The GMR effect can also occur when there is no spin asymmetry in bulk scattering processes and no spin asymmetry in diffuse scattering by interface roughness (or no interface roughness), but there is instead some spin asymmetry in the probability of diffuse scattering by surface roughness. Since real structures are grown on substrates and are usually covered by protecting layers, the origin of this spin asymmetry is similar to that for interface scattering.

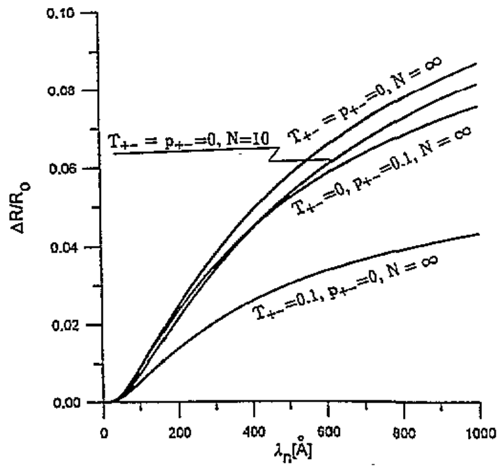

Figure 8. Magnetoresistance due to surface spin-dependent scattering. The four curves represent the relative resistance change $\Delta R/R_0$ against mean free path λ_n respectively for no spin mixing processes (the upper curve), for bulk spin mixing processes (the curve for $p_{+-} = T_{+-} = 0$, $N = 10$), for interface spin mixing processes (the curve for $p_{+-} = 0$, $T_{+-} = 0.1$, $N = \infty$) and for surface mixing scattering (the curve for $p_{+-} = 0.1$, $T_{+-} = 0$, $N = \infty$). N is defined as $N = N_m = N_n$. The other parameters assumed here are $d_m = d_n = 20$ Å, $p_+ = 0.9 - p_{+-}$, $p_- = 0.5 - p_{+-}$, $T_+ = T_- = 0.9 - T_{+-}$, $\kappa = 1$ and $N_b = 1$.

The relevant factor describing the GMR effect can now be defined as

$$N_s = \frac{1 - p_- - p_{+-}}{1 - p_+ - p_{+-}}. \tag{51}$$

If $N_s \neq 1$, the GMR occurs also when $N_i = N_b = 1$. In figure 8 we present some numerical data showing the influence of various spin mixing processes on the GMR effect induced by the surface spin-dependent scattering. Different curves correspond to different values of the bulk, interface and surface spin mixing parameters. However, the other parameters have been adjusted so as to keep the same probabilities of diffuse scattering.

6. Summary

We have analysed in detail the role of various electron momentum conserving spin mixing processes in the GMR effect induced by spin-dependent probabilities of electron scattering by impurities in the bulk as well as by interface and surface roughness. Independently of where the mixing processes occur (in the bulk, at interfaces or at surfaces) they lead to a decrease of the GMR effect. The model used here assumes the same lattice potential for both spin directions and for all sublayers. In the future work we will use a more realistic model, with different lattice potentials in different sublayers and with more realistic boundary conditions. Such a model will be applied to available [14] as well as new experimental results. Despite the simplifications introduced here the model presents properly the general trends in the behaviour of the GMR effect and the role of various mixing processes. Our results show that the spin mixing processes influence the GMR effect considerably and that theoretical descriptions of the temperature dependence of the effect have to take those processes into account.

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