

Influence of interface spin-flip processes on spin accumulation and spin currents in magnetic multilayers

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Macroscopic description of electronic transport in magnetic layered structures has been extended by including effects due to spin-flip scattering at interfaces. Such processes lead to spin-memory losses at the interfaces and therefore play a significant role in giant magnetoresistance and spin switching phenomena. They also modify distribution of spin currents, electric fields and spin accumulation in the vicinity of interfaces. A system consisting of two oppositely magnetized semi-infinite ferromagnets, and the case of magnetic/nonmagnetic superlattices in parallel and anti-parallel magnetic configurations are analysed in detail.

Key words: *magnetic multilayers; spin accumulation; spin-flip scattering*

1. Introduction

Since the discovery of the giant magnetoresistance (GMR) effect in magnetic multilayers, electronic transport in artificially layered structures has been extensively studied, both experimentally and theoretically. The GMR effect was first observed in the current-in-plane (CIP) geometry [1, 2], but later it was also found for electric currents flowing perpendicularly to the layers (current-perpendicular-to-plane (CPP) geometry) [3]. In the latter case, the effect was even larger. The electronic transport along the axis normal to the layers leads to some non-equilibrium phenomena, for instance spin-splitting of the chemical potential (spin accumulation) at interfaces.

One of the theoretical descriptions commonly used to interpret such experimental data is the macroscopic description proposed by Valet and Fert [4]. Owing to its simplicity, this description allows basic parameters (for instance spin diffusion lengths)

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to be easily extracted from the experimental data on CPP GMR [5, 6]. The macroscopic description takes into account spin accumulation at the interfaces and its relaxation in the bulk due to spin-flip scattering. However, the description ignores spin-flip scattering at the very contact between different layers. Some experimental data cannot be described properly by this simplified description and one should take into account the fact that electrons can partially lose their spin memory when crossing the interface between magnetic and nonmagnetic films [7, 8]. This problem is addressed in the present paper, where we extend the Valet–Fert model by including the influence of spin-flip scattering processes at the interfaces. These processes are effectively included into the boundary conditions via the corresponding spin-mixing interfacial resistance.

We consider a layered structure and assume that electric current flows along the axis z normal to the interfaces. At the beginning we consider a simplified situation, where two semi-infinite ferromagnetic systems are in direct contact at the plane $z = 0$. Then, we analyse a magnetic superlattice, in which magnetic layers are separated by nonmagnetic metallic films. In both cases, we neglect interfacial spin-conserving scattering and take into account only spin-flip processes.

2. Macroscopic description of Fert and Valet

Starting from the kinetic Boltzmann equation, Valet and Fert [4] showed that when the spin diffusion length l_s (for both spin orientations) is much longer than the corresponding mean free path, electronic transport is well described by the macroscopic equations:

$$\frac{e}{\sigma_s} \frac{\partial J_s(z)}{\partial z} = \frac{\bar{\mu}_s(z) - \bar{\mu}_{-s}(z)}{l_s^2} \quad (1)$$

$$J_s(z) = \frac{\sigma_s}{e} \frac{\partial \bar{\mu}_s(z)}{\partial z} \quad (2)$$

where e is the electron charge ($e > 0$), σ_s and $J_s(z)$ are the conductivity and current density for the spin s , respectively, whereas $\bar{\mu}_s = \mu_s(z) - eV(z)$ is the electrochemical potential. As the local spin quantization axis we assume, following Ref. [4], the one determined by the local spin polarization (opposite to the local magnetization), with $s = \uparrow$ corresponding to the spin-majority electrons and $s = \downarrow$ corresponding to the spin-minority ones. Spin projection onto the global quantization axis will be denoted as $s = +$ and $s = -$. When the local and global axes coincide, then $s = \uparrow$ ($s = \downarrow$) is equivalent to $s = +$ ($s = -$).

The above equations may be rewritten in a more suitable form as:

$$\frac{e}{\sigma_{\pm}} \frac{\partial J_{\pm}(z)}{\partial z} = \pm 2 \frac{\Delta\mu(z)}{l_{\pm}^2} \quad (3)$$

$$J_{\pm} = \sigma_{\pm} \left[F(z) \pm \frac{1}{e} \frac{\partial \Delta\mu(z)}{\partial z} \right] \quad (4)$$

where the spin accumulation $\Delta\mu(z)$ is introduced explicitly via the formula $\bar{\mu}_s(z) = \bar{\mu}(z) \pm \Delta\mu(z)$, and the driving electric field $F(z)$ is determined by the derivative of the spin-independent part of the electrochemical potential:

$$F(z) = \frac{1}{e} \frac{\partial \bar{\mu}(z)}{\partial z} \quad (5)$$

Equations (3) and (4) lead to the following two second-order differential equations:

$$\frac{\partial^2 \Delta\mu(z)}{\partial z^2} = \frac{\Delta\mu(z)}{l_{sf}^2} \quad (6)$$

$$\frac{\partial^2}{\partial z^2} [\sigma_+ \bar{\mu}_+(z) + \sigma_- \bar{\mu}_-(z)] = 0 \quad (7)$$

where l_{sf} is defined as $1/l_{sf}^2 = 1/l_+^2 + 1/l_-^2$. The general solutions of the above equations have the form:

$$\Delta\mu(z) = C_1 \exp(z/l_{sf}) + C_2 \exp(-z/l_{sf}) \quad (8)$$

$$[\sigma_+ \bar{\mu}_+(z) + \sigma_- \bar{\mu}_-(z)] = C_3 z + C_4 \quad (9)$$

where the constants C_1 – C_4 are to be determined from the appropriate boundary conditions. From the solutions of (8) and (9) one can obtain the general expressions for the spin accumulation $\Delta\mu(z)$, electric field $F(z)$, and current density $J_s(z)$ inside each layer of any multilayer structure [4].

3. Ferromagnetic semi-infinite systems in direct contact

Consider a structure consisting of two equivalent semi-infinite parts, which are magnetized in opposite directions, e.g., the left one is magnetized along the positive axis x while the right one along the axis $-x$. Let the global spin quantization axis coincide with the axis x (it also coincides with the local spin quantization axis in the right part) and let the interface between the two semi-infinite systems be in the plane $z = 0$ (axis z is normal to the interface). It is convenient to introduce the bulk spin asymmetry coefficient β by writing the bulk resistivity of the ferromagnetic material in the form [4]:

$$\rho_{\uparrow(\downarrow)} = 1/\sigma_{\uparrow(\downarrow)} = 2\rho(1 \mp \beta) \quad (10)$$

where ρ_{\uparrow} and ρ_{\downarrow} denote bulk resistivities in the spin-majority and spin-minority channels, respectively, and the upper (lower) sign corresponds to \uparrow (\downarrow).

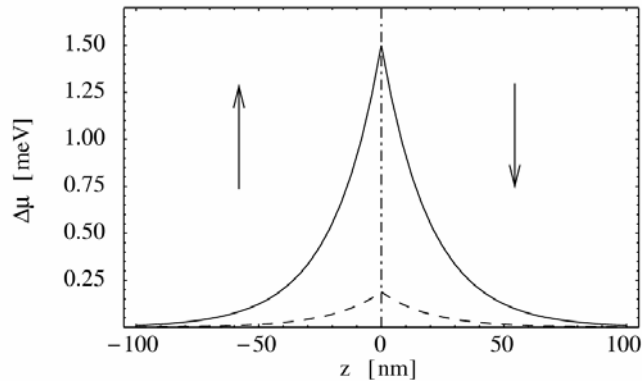


Fig. 1. Spin accumulation at the interface between two semi-infinite ferromagnets, calculated for $\rho = 100 \, \Omega \cdot \text{nm}$, $l_{sf} = 20 \, \text{nm}$, $\beta = 0.5$, $J = 1.5 \times 10^{-6} \, \text{A/nm}^2$, $R_{sf} = 0.5 \times 10^3 \, \Omega \cdot \text{nm}^2$ (dashed line), and $1/R_{sf} = 0$ (solid line)

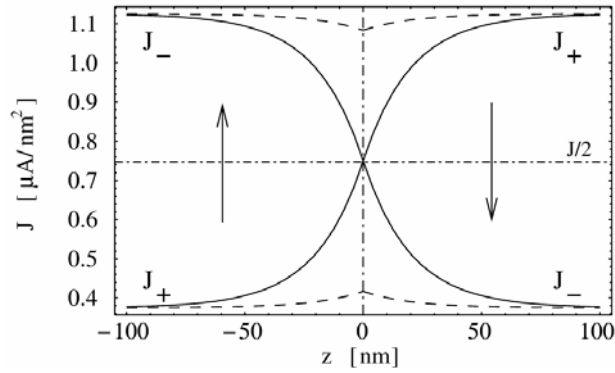


Fig. 2. Spin currents at the interface between two semi-infinite ferromagnets, calculated for the same situation as in Fig. 1

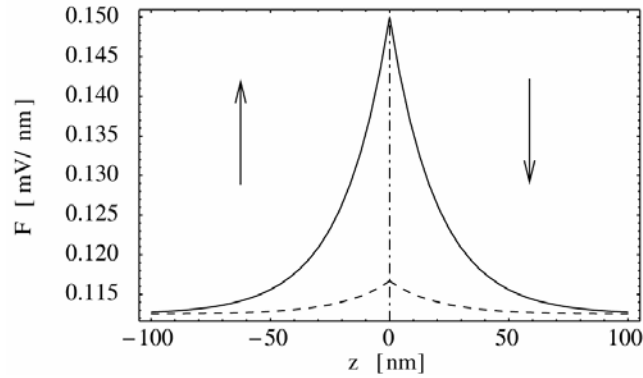


Fig. 3. Electric field at the interface between two semi-infinite ferromagnets, calculated for the same situation as in Fig. 1. The dashed-dotted line represents the field E_0

In the limit of vanishing interface resistance and in the absence of spin-flip scattering at the interface, the solutions for spin accumulation, electric current, and effective field have been discussed in Ref. [4], and are presented in Figs. 1, 2, and 3 by solid lines. The main objective of this paper is to answer the question how interface spin-flip scattering modifies spin accumulation and spin currents. To answer this, we include interface spin-flip scattering effectively by a certain interfacial spin-mixing resistance R_{sf} per unit square. The interface boundary conditions are then given by the following expressions:

$$R_{sf} [J_+(z=0^-) - J_+(z=0^+)] = -\frac{1}{e} [\bar{\mu}_+(z=0^+) - \bar{\mu}_-(z=0^+)] \quad (11)$$

$$\bar{\mu}_+(z=0^+) - \bar{\mu}_+(z=0^-) = 0 \quad (12)$$

$$\bar{\mu}_-(z=0^+) - \bar{\mu}_-(z=0^-) = 0 \quad (13)$$

Since spin-flip processes allow spin transfer between the two spin channels, the spin current density is generally discontinuous across the boundary at $z = 0$. On the other hand, the electrochemical potentials are continuous across the interface in the absence of spin-conserving interface scattering.

Using the general solutions (8) and (9) together with the boundary conditions (11)–(13), one can obtain the exact solutions for spin accumulation, electric field, and current density in both the left and right parts of the structure. These solutions for the left part ($z < 0$) read:

$$\Delta\mu(z) = \beta J l_{sf} e \rho \frac{\tilde{R}_{sf}}{\tilde{R}_{sf} + 1} \exp(z/l_{sf}) \quad (14)$$

$$J_{\pm}(z) = (1 \mp \beta) \frac{J}{2} \pm \frac{\beta J}{2} \frac{\tilde{R}_{sf}}{\tilde{R}_{sf} + 1} \exp(z/l_{sf}) \quad (15)$$

$$F(z) = J \rho (1 - \beta^2) + \beta^2 J \rho \frac{\tilde{R}_{sf}}{\tilde{R}_{sf} + 1} \exp(z/l_{sf}) \quad (16)$$

where $\tilde{R}_{sf} = R_{sf}/(2l_{sf}\rho)$ is a dimensionless spin-flip resistance, and J is the charge current density. The solutions for the right part ($z > 0$) are also given by Eqs. (14)–(16), but with $\exp(z/l_{sf})$ replaced by $\exp(-z/l_{sf})$, and β replaced by $-\beta$ in Eqs. (15) and (14).

As shown in Ref. [4], the interface gives rise to an additional interfacial resistance r_I due to the spin-bottle-neck effect. The additional voltage drop can be calculated as

$$V_I = \int_{-\infty}^{+\infty} (F(z) - E_0) dz, \text{ where } E_0 = J \rho (1 - \beta^2) \text{ is the electric field far away from the}$$

interface (see Eq. (16)). This voltage drop can be related *via* Ohm's law to the additional interface resistance, finally yielding:

$$r_I = 2\beta^2 \rho l_{sf} J \frac{\tilde{R}_{sf}}{1 + \tilde{R}_{sf}} \quad (17)$$

One should note that the absence of spin-flip processes corresponds to an infinite value of R_{sf} . The resistance r_I reduces then to the value $r_I = 2\beta^2 \rho l_{sf} J$, derived in Ref. [4]. It follows from the above formula that the presence of interfacial spin-flip scattering reduces the magnitude of r_I by a factor of $\tilde{R}_{sf} [1 + \tilde{R}_{sf}]$.

The influence of interfacial spin-flip scattering on spin accumulation, electric current and electric field is shown in Figs. 1, 2, and 3 by dashed lines. Spin accumulation is significantly reduced in comparison to that in the case without spin-flip scattering (the solid line in Fig. 1). According to Eq. (14), the suppression is described by the factor $\tilde{R}_{sf} / [1 + \tilde{R}_{sf}]$. The same factor also describes the suppression of the additional electric field, $F(z) - E_0$, near the interface. There is also a visible discontinuity of the spin currents at $z = 0$, $\Delta J_\sigma = J_\sigma(z = 0^+) - J_\sigma(z = 0^-)$, which follows from the presence of interfacial spin-flip processes (see Fig. 2). This discontinuity is equal to:

$$\Delta J_+ = -\Delta J_- = \beta J \frac{1}{1 + \tilde{R}_{sf}} \quad (18)$$

and disappears in the absence of interfacial spin-flip scattering.

4. Magnetic/nonmagnetic superlattice structure

Let us now consider an infinite superlattice structure of nonmagnetic layers alternating with ferromagnetic ones. Two configurations are studied in detail – anti-parallel (AP) and parallel (P). The magnetic and nonmagnetic layers are characterized by the same parameters as before, but we attach indices F and N to distinguish parameters characterizing ferromagnetic (F) material from those describing nonmagnetic (N) material. Accordingly, the ferromagnetic layers are characterized by β , ρ_F , and l_{sf}^F , whereas the nonmagnetic ones by ρ_N and l_{sf}^N . Note that the spin asymmetry vanishes for nonmagnetic layers (the corresponding parameter β is equal to zero), hence $\rho_N = \rho_F/2 = \rho_l/2$ (we therefore did not attach the index F to the parameter β , as this makes no confusion).

Taking into account the superlattice periodicity and the boundary conditions (11)–(13), we calculated numerically the influence of the finite value of R_{sf} on spin accumulation, spin currents, and the electric field. Figure 4 shows spin accumulation in the AP configuration. The solid line there corresponds to the absence of interface spin-flip scattering, whereas the dashed line represents the solution with a finite spin-mixing interface resistance. As previously, the reduction of spin accumulation is clearly visible.

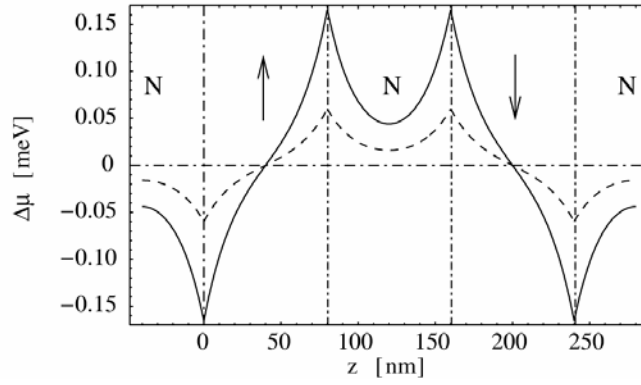


Fig. 4. Spin accumulation in a superlattice composed of magnetic and nonmagnetic metals in an antiparallel configuration. The parameters used for the numerical calculations were:

$\rho_F = 100 \text{ } \Omega \cdot \text{nm}$, $l_{sf}^F = 20 \text{ nm}$, $\beta = 0.5$, nm (for the ferromagnetic metal), $\rho_N = 12 \text{ } \Omega \cdot \text{nm}$,

and $l_{sf}^N = 20 \text{ nm}$ (for the nonmagnetic metal). The other parameters were

$J = 1.5 \times 10^{-6} \text{ A/nm}^2$, $R_{sf} = 0.5 \times 10^3 \text{ } \Omega \cdot \text{nm}^2$ (dashed line), and $1/R_{sf} = 0$ (solid line)

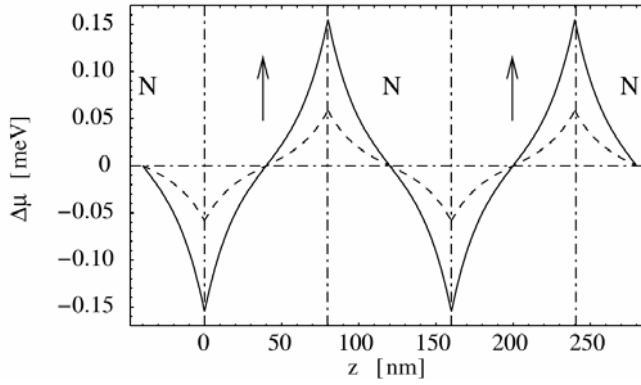


Fig. 5. The same as in Fig. 4, but for parallel magnetic configuration

Spin accumulation for the P configuration is shown in Fig. 5, where again the solid (dashed) line corresponds to the case with vanishing (non-vanishing) interface spin-flip scattering. The influence of spin-mixing resistance on the spin currents and electric field is qualitatively similar to that in the case of two semi-infinite systems in direct contact.

5. Conclusions

The presence of spin-flip scattering at the interfaces in a multilayer structure significantly reduces spin accumulation as well as other features that follow from spin accumulation. The suppression of spin accumulation is described by the factor

$\tilde{R}_{sf}/[1 + \tilde{R}_{sf}]$. A finite spin-mixing interfacial resistance R_{sf} introduces sharp jumps in the spin current densities at the interfaces. Spin-memory loss at the interface has a significant impact on other transport characteristics, for instance on CPP GMR and spin switching phenomena. This is because these two phenomena rely on electron spin coherence at distances larger than the thickness of the nonmagnetic films separating the ferromagnetic ones. The loss of spin coherence at interfaces leads to a suppression of the CPP GMR and also to a suppression of the spin torque due to spin transfer.

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