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Classical theory of giant magnetoresistance in spin-valve multilayers: influence of thicknesses, number of periods, bulk and interfacial spin-dependent scattering

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Abstract. Using the same approach as Camley and Barnas, we study theoretically the magnetotransport properties of spin-valve multilayers. We emphasize that the absolute change in sheet conductance (ΔG) between parallel and antiparallel alignment of the magnetizations of successive ferromagnetic layers is the most relevant macroscopic quantity to represent and compare the magnetoresistance in these structures. We present results on the influence of the thicknesses of the ferromagnetic and non-magnetic layers on the magnetoresistance for the two cases most studied experimentally: sandwiches and multilayers with a large number of periods. We also investigate the influence of the number of periods on the magnetoresistance and discuss the similarities and differences obtained in the respective cases of bulk or interfacial spin-dependent scattering.

1. Introduction

Electrical transport properties of multilayers comprising ferromagnetic layers separated by non-magnetic metallic layers have been studied experimentally by many groups (see, for instance [1]). Very large or even giant magnetoresistance (MR) has been obtained in these structures (spin-valve multilayers) in which the relative orientation of the magnetizations in successive ferromagnetic layers can be changed due either to the existence of an antiferromagnetic coupling through the spacer layer (as in Fe/Cr [2], Co/Ru [3], Co/Cu [4, 5]...), or because of different pinning forces acting on the magnetization of the ferromagnetic layers (different coercivities [6, 7] or exchange anisotropy [8–11]). Qualitatively, it is now widely admitted that this particular MR effect results from a coherent interplay between the successive ferromagnetic layers of spin-dependent scattering (SDS) phenomena occurring at the interfaces and/or in the bulk of the ferromagnetic layers.

In this paper we use the same approach as Camley and Barnas [12, 13] to investigate theoretically the longitudinal magnetotransport properties of these spin-valve multilayers. This approach is an extension of the Fuchs–Sondheimer theory which assumes parallel conductivity of the two species of conduction electrons (with spin ↑ or spin ↓); (two current model) and takes into account SDS rates at the ferromagnetic/non-magnetic interfaces and/or spin-dependent mean-free paths in the ferromagnetic layers. It has been developed by different groups [14–16] especially in the case of interfacial spin-dependent scattering [14]. In this paper we describe the longitudinal (current in the plane of the layers) magnetoresistance of spin-valve

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structures in terms of absolute change in sheet conductance (ΔG) rather than relative or absolute change of resistivity. As we show below, ΔG is the measurable quantity most directly related to the MR while other quantities such as $\Delta R/R$ or ΔR are influenced both by the magnetoresistance and the resistance of the structures. We begin by recalling the main points of the classical theory. We proceed to investigate the influence on ΔG of the thicknesses of the ferromagnetic and non-magnetic layers for the two extreme cases of sandwiches and multilayers with infinite numbers of periods. We then study intermediate situations by looking at the influence of the number of periods. Finally we compare the similarities and differences in the MR properties in the two cases of interfacial or bulk SDS.

We consider a multilayered structure consisting of alternating ferromagnetic (F) and non-magnetic (NM) layers: substrate/$F_1 t_1$/$NM_2 t_2$/$F_3 t_3$/…/$NM_n t_n$/vacuum, where the t_i's are the thicknesses of the various layers, $D = \sum_{i=1}^{n} t_i$ is the total thickness of the structure, and n is the total number of layers. The current flows in the plane of the layers (electric field E parallel to the x-axis), while the z-axis is normal to the film plane. A detailed description of the theory can be found in [13]. Therefore we just recall here the main points: our first goal is to calculate the perturbation $g^\sigma(z,v)$ induced by the electric field on the Fermi distribution of conduction electrons $f_0^\sigma(z,v)$ for the configurations of parallel and antiparallel alignment of the magnetizations (σ refers to the spin of the electron while v is its velocity). We then integrate $g^\sigma(z,v)$ over z and v to obtain the current and sheet conductance for the two configurations. To first order $g^\sigma(z,v)$ is solution of the Boltzmann equation:

$$\frac{\partial g^\sigma(z,v)}{\partial z} + \frac{g^\sigma(z,v)}{\tau^\sigma v_z} = \frac{eE}{mv_z}\frac{\partial f_0(v)}{\partial v_x} \tag{1}$$

where e and m denote the charge and effective mass of the electrons and τ^σ are the relaxation times for spin $\uparrow$ or $\downarrow$ electrons ($\tau^\sigma = \lambda^\sigma/v_F$, λ^σ mean-free path, v_F Fermi velocity). In the general case, we assume different mean-free paths for the two species of electrons in the ferromagnetic layers (hypothesis of bulk SDS, $\lambda^\uparrow \neq \lambda^\downarrow$, equivalent to $\tau^\uparrow \neq \tau^\downarrow$). For convenience $g^\sigma(z,v)$ is divided into two parts: one for electrons with positive $v_z(g_+^\sigma(z,v))$, another for negative $v_z(g_-^\sigma(z,v))$. The local solution of (1) can be calculated in each layer i:

$$g_{i(\pm)}^\sigma(z,v) = \frac{eE\tau_i^\sigma \partial f_0}{m\partial v_x}(v)G_{i(\pm)}^\sigma(z,v_z) \tag{2}$$

with

$$G_{i(\pm)}^\sigma(z,v_z) = 1 - A_{i(\pm)}^\sigma \exp\left(\mp\frac{z}{\tau_i^\sigma |v_z|}\right). \tag{3}$$

In our definition of the coefficients $A_{i(\pm)}^\sigma$, we assume that within each layer i the origin of the z axis is taken at the interface between layer i and $i-1$ for $v_z > 0$ and between layer i and $i+1$ for $v_z < 0$.

Assuming the free electron gas (spherical Fermi surface): $\partial f_0/\partial v_x = mv_x \partial f_0/\partial \epsilon$, where ϵ is the electron energy.

In order to completely determine the perturbation $g^\sigma(z,v)$, all the coefficients A_i must be calculated. This is done by using boundary conditions at outer surfaces and at each inner interface. In the present study we assume perfectly diffuse scattering on the outer interfaces. This implies

$$g^{\sigma}_{1+}(z=0, v_z) = 0 \tag{4}$$

at the substrate/F_1 interface and

$$g^{\sigma}_{n-}(z=D, v_z) = 0 \tag{5}$$

at the NM_n/vacuum surface. These two equations lead to the determination of A^{σ}_{1+} and A^{σ}_{n-}. At inner interfaces, we assume that the Fermi energies of the different metals are sufficiently close to neglect refraction. An incident electron is assumed to have a probability T^{σ}_i of coherent transmission through the interface between layer i and $i+1$ and a probability $(1-T^{\sigma}_i)$ of diffuse scattering. In the general case, the T^{σ}_i's are spin-dependent at the interfaces between ferromagnetic and non-magnetic metals. The boundary condition at the interface between layer i and $i+1$ is:

$$T^{\sigma}_i g^{\sigma}_{i+}(z^-_i, v_z) = g^{\sigma}_{i+1_+}(z^+_i, v_z) \tag{6}$$

for electron with a positive component of velocity along the z-axis, and

$$g^{\sigma}_{i-}(z^-_i, v_z) = T^{\sigma}_i g^{\sigma}_{i+1_-}(z^+_i, v_z) \tag{7}$$

for electrons with a negative component of velocity v_z (z^+_i and z^-_i refer to the two sides of the interface located at abscissa z_i).

All coefficients can be calculated numerically by recurrence using equations (2)–(7) leading to a complete determination of the perturbation $g^{\sigma}(z, v)$. The current induced by the applied electric field is then obtained by integrating

$$J = e \sum_{\sigma=\uparrow\downarrow} \int v_x \, \mathrm{d}^3 v \int g^{\sigma}(v_z, z) \, \mathrm{d}z \tag{8}$$

which yields for the conductance:

$$G = e^2 \sum_{\uparrow\downarrow, i, (\pm)} \int v_x^2 \left(\frac{\partial f_0}{\partial \epsilon}\right) \left(1 - A^{\sigma}_{i(\pm)} \exp\left(\mp \frac{z}{\tau^{\sigma}_i |v_z|}\right)\right) \tau^{\sigma}_i \, \mathrm{d}^3 v \, \mathrm{d}z. \tag{9}$$

Since $\partial f_0/\partial\epsilon$ is a delta function at 0° K, the integration over v is performed over the Fermi surface. The integration leads to two terms:

$$G = G_0 - G_1 \text{ with } G_0 = e^2 \sum_{i=1,\uparrow\downarrow}^{n} \frac{\tau^{\sigma}_i n^{\sigma}_i t_i}{m_i} \tag{10}$$

and

$$G_1 = \frac{3}{4} e^2 \sum_{i,\sigma} \frac{n_i}{m_i} \left\{ \int_0^1 (1-\mu^2)\mu A^{\sigma}_{i+} (\tau^{\sigma}_i)^2 v_{\mathrm{F}} \left(1 - \exp\left(\frac{-t_i}{\tau^{\sigma}_i v_{\mathrm{F}} \mu}\right)\right) \mathrm{d}\mu \right.$$
$$\left. + \int_{-1}^{0} (1-\mu^2)\mu A^{\sigma}_{i-} (\tau^{\sigma}_i)^2 v_{\mathrm{F}} \left(1 - \exp\left(\frac{-t_i}{\tau^{\sigma}_i v_{\mathrm{F}} \mu}\right)\right) \mathrm{d}\mu \right\}. \tag{11}$$

In this formula the variable μ refers to the incidence of the elecrons with respect to the plane of the layers. The first term (G_0) gives the same conductance as if the various layers were carrying the current in parallel. The second term (G_1) contains all finite size effects. It must be calculated both in parallel and antiparallel alignment of the magnetizations of the successive ferromagnetic layers. The magnetoresistance is then given by:

$$\begin{aligned}\Delta G &= G_{\text{parallel}} - G_{\text{antiparallel}} \\ &= G_{1\,\text{antiparallel}} - G_{1\,\text{parallel}}.\end{aligned} \tag{12}$$

At this stage we point out that the current and therefore the conductance are linearly related (formula (8)) to the perturbation $g^{\sigma}(z,v)$ of the distribution of conduction electrons induced by the electric field. Similarly ΔG is linearly related to the change in this perturbation induced by a change in the relative orientation of the magnetizations of the successive ferromagnetic layers. Therefore ΔG is the macroscopic quantity most directly related to the MR of these spin-valve structures. Other quantities such as $\Delta G/G$ or $\Delta R/R$ or ΔR are influenced both by the MR of the structure and by its overall conductance. These quantities are related to each other through the following relations:

$$\frac{\Delta G}{G_{\text{parallel}}} = \frac{\Delta R}{R_{\text{antiparallel}}} \tag{13}$$

$$\frac{\Delta G}{G_{\text{antiparallel}}} = \frac{\Delta R}{R_{\text{parallel}}} \tag{14}$$

$$\Delta R = \frac{\Delta G}{G_{\text{parallel}} G_{\text{antiparallel}}}. \tag{15}$$

In this paper therefore, we mostly discuss our results on the behaviour of the MR in terms of ΔG rather than $\Delta R/R$. Experimentally, the determination of ΔG requires the measurements of both the sheet resistance R of the structure and $\Delta R/R$.

In the following, we first consider the case with only bulk SDS in the ferromagnetic layers ($\lambda^{\uparrow} \neq \lambda^{\downarrow}$ and $T^{\uparrow} = T^{\downarrow} = 1$). We discuss the variation of ΔG for infinite multilayers and sandwiches with diffuse scattering on the outer interfaces, then investigate in more detail the influence of the number of periods constituting the multilayers. Secondly we consider the case with only interfacial SDS ($T^{\uparrow} \neq T^{\downarrow}$ and $\lambda^{\uparrow} = \lambda^{\downarrow}$) for infinite multilayers and sandwiches and compare the results with the previous case. The case of infinite multilayers is treated by considering the four layers structure: $Ft_{\text{F}}/\text{NM}t_{\text{NM}}/Ft_{\text{F}}/\text{NM}t_{\text{NM}}$ with periodic boundary conditions analogous to relations (6) and (7) [14]. In this case the coefficients $A^{\sigma}_{i(\pm)}$ are calculated self-consistently (with an accuracy of 10^{-5}) to ensure a periodic behaviour of $g(z, v_z)$.

2. Bulk spin-dependent scattering only

To illustrate the case with only bulk SDS, we choose a set of parameters found to be close to those for $Ni_{80}Fe_{20}$ and Cu at 0° K: $\lambda^{\uparrow}_{\text{NiFe}} = 114$ Å, $\lambda^{\downarrow}_{\text{NiFe}} = 12$ Å,

$\lambda_{Cu}^{\uparrow} = \lambda_{Cu}^{\downarrow} = 205$ Å [19]. These values correspond to the following resistivities measured experimentally on spin-valve sandwiches at 1.5° K, $\rho_{NiFe} = 15.4\,\mu\Omega$ cm and $\rho_{Cu} = 4.5\,\mu\Omega$ cm. The correspondence between ρ and λ has been established using bulk Fe as a reference ($\rho_{Fe} = 9.7\,\mu\Omega$ cm for $(\lambda^{\uparrow} + \lambda^{\downarrow}) = 200$ Å) and assuming the product $\rho(\lambda^{\uparrow} + \lambda^{\downarrow})$ constant for elements close to Fe [13].

2.1. *Infinite multilayers*

Figures 1 and 2(*a*) represent the variation of absolute change in sheet conductance per period versus the thicknesses of the non-magnetic spacer layer (figure 1) and magnetic layers (figure 2(*a*)) in infinite multilayers of the form $\infty(Ft_F/\text{NM}t_{NM}/Ft_F/\text{NM}t_{NM})$. The decrease of ΔG in figure 1 for large t_{NM} thickness is physically related to the decrease in the flow of electrons exchanged between the ferromagnetic layers caused by the increasing scattering in the non-magnetic spacer layer [9]. Asymptotically, the decrease of ΔG has an exponential form characterized by a decay length equal to the mean-free path in the spacer layer. However, since ΔG is given by an exponential integral of the form $\int_0^1 f(\mu)\exp(-t_{NM}/\lambda_{NM}\mu)\mathrm{d}\mu$, this asymptotic regime is in general reached only for $t_{NM} \geqslant 10\lambda_{NM} \cong 2000$ Å in Cu which is not in the usual experimental range. At lower thicknesses (t_{NM} of the order of 1 to $10\lambda_{NM}$), ΔG has a steeper decrease than in the asymptotic regime. The existence of a maximum in ΔG versus t_{NM} in the range of thicknesses $t_{NM} \cong 30$ Å to 50 Å and $t_F \leqslant 50$ Å is surprising. We do not have a simple explanation for it. However, a detailed examination of the behaviour of the perturbations $g^{\sigma}(z, v)$ at low t_{NM} and t_F values shows that increasing t_{NM} leads to a larger increase of the average conductivity of spin ↑ electrons in the parallel configuration of magnetizations than of the average conductivity of both species of electrons in the antiparallel configuration. This results in the observed increase of ΔG.

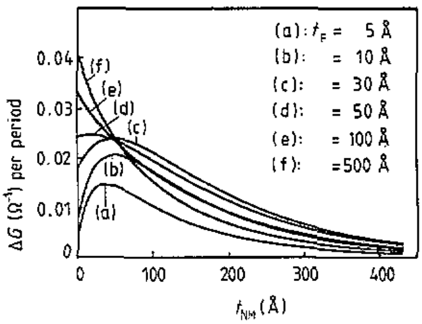

Figure 1. Magnetoresistance (absolute change of sheet conductance ΔG per period) versus the thickness of the non-magnetic spacer layer of an infinite multilayer ∞ ($Ft_F/\text{NM}t_{NM}/Ft_F/\text{NM}t_{NM}$) for different values of the thickness of the magnetic layers $\lambda_F^{\uparrow} = 114$ Å, $\lambda_F^{\downarrow}12$ Å, $\lambda_{NM} = 205$ Å, $T^{\uparrow} = T^{\downarrow} = 1$ (only bulk spin-dependent scattering).

Regarding the variation of ΔG versus t_F (figure 2(*a*)), we find that ΔG saturates above a thickness of the order of the larger of the two mean-free paths $\lambda_F^{\uparrow}$ or $\lambda_F^{\downarrow}$. This saturation also exists in the case of sandwiches (see below and [15]) and has been observed experimentally in various spin-valve structures of the form F/Cu/NiFe/FeMn with F = (NiFe, Co, Fe) [15, 18]. The sharp increase of ΔG at low t_F thickness is related to the improvement in the stopping of spin ↓ electrons in the ferromagnetic layers when t_F is increased between 0 Å and $\lambda_F^{\downarrow}$. Again the maximum observed in ΔG for large t_{NM} values has no simple explanation and requires a detailed examination of the behaviour of $g^{\sigma}(z, v)$ to be understood. In figure 2(*b*), we plotted for comparison the same results as in figure 2(*a*) but in a way which is more

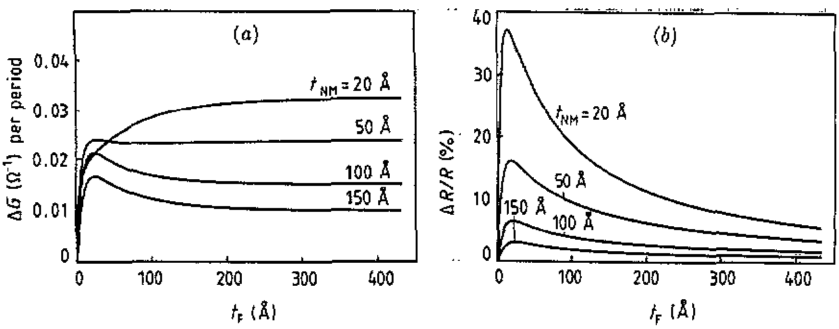

Figure 2. (*a*) Magnetoresistance (absolute change of sheet conductance ΔG per period) versus thickness of the magnetic layer of an infinite multilayer ∞ (Ft_F/NMt_{NM}/Ft_F/NM) for different values of the thickness of the non-magnetic layers. Same parameters as for figure 1. (*b*) Same data as in figure 2(*a*) but the magnetoresistance is represented by $\Delta R/R_{\text{parallel}}$ instead of ΔG.

frequently used experimentally: $\Delta R/R_{\text{parallel}}$ versus t_F. This relative change of sheet resistance shows a sharp maximum at low thickness as observed in (Co/Cu) [4, 5] or (Fe/Cr) [2] multilayers. Above the maximum, $\Delta R/R$ decreases monotonically. Using relation (14), it can easily be shown that this decrease follows a $1/(t_F + \text{constant})$ law as observed experimentally [11]. Note that because of its wider variety of behaviour ΔG gives more detailed insights into the MR than does $\Delta R/R$.

2.2. *Sandwiches*

Let us now consider the case of spin-valve sandwich structures of the form F/NM/F/FeMn where F and NM have the same mean-free paths as above (simulating the case of NiFe and Cu). FeMn is a highly resistive layer ($\rho_{\text{FeMn}} = 95\,\mu\Omega$ cm) used experimentally [8–10] to pin the magnetization of one of the ferromagnetic layers through exchange anisotropy. As already mentioned, we assume perfectly diffuse scattering on the outer surfaces. Figures 3 and 4 show the variation of ΔG versus the thicknesses of non-magnetic and ferromagnetic layers. In comparison with the case of infinite multilayers, these variations are simpler; they have been discussed in [15]. These differences from the multilayer case come from the strong boundary conditions imposed here through the assumption of diffuse scattering on the outer surfaces (relations (4) and (5)). Discussions of the influence of the scattering on the outer boundaries can be found in [13] and [19].

2.3. *Finite multilayers*

We next investigate the intermediate case of finite multilayers of the form $n\,(Ft_F/\text{NM}t_{NM}/Ft_F/\text{NM}t_{NM})$ and in particular the influence of the number of periods n on the MR of these structures. Figures 5 and 6(*a*) represent the variation of ΔG per period versus t_F for two values of t_{NM} (t_{NM} = 10 Å for which $\Delta G(t_F)$ is monotonic both for sandwiches and infinite multilayers, and t_{NM} = 100 Å for which a maximum has been observed on $\Delta G(t_F)$ in the multilayer case—figure 2). An overall increase of ΔG per period is observed as the number of periods is increased e.g. as the diffuse scattering at outer surfaces is progressively removed. On $\Delta R/R$, we have already shown [15] that increasing the number of periods leads to a very significant

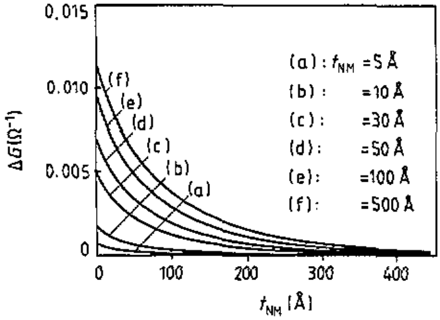

Figure 3. Magnetoresistance (absolute change of sheet conductance ΔG) versus thickness of the non-magnetic spacer layer of a spin-valve sandwich Ft_F/NMt_{NM}/F50 Å/FeMn 90 Å for different values of the thickness of the unpinned magnetic layer. $\lambda_F^\uparrow = 114$ Å, $\lambda_F^\downarrow = 12$ Å, $\lambda_{NM} = 205$ Å, $T^\uparrow = T^\downarrow = 1$.

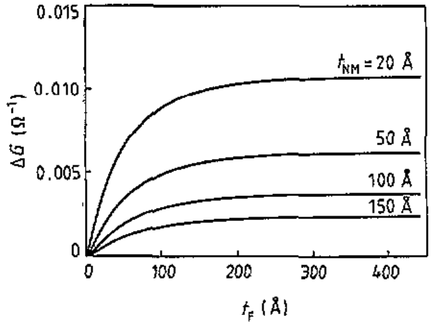

Figure 4. Magnetoresistance (absolute change of sheet conductance ΔG) versus thickness of the unpinned magnetic layer of a spin-valve sandwich Ft_F/NMt_{NM}/F50 Å/FeMn 90 Å for different values of the thickness of the non-magnetic layer. Same parameters as in figure 3.

enhancement of the maximum amplitude of $\Delta R/R$ together with a shift of the position of the maximum towards lower t_F thickness. For $t_{NM} = 100$ Å figure 6(*a*) illustrates the progressive change of $\Delta G(t_F)$ from the situation of a sandwich to that of an infinite multilayer. Note that the same type of behaviour of $\Delta G(t_F)$ versus n would be obtained on a sandwich structure by progressively changing the condition of scattering on the outer surfaces from perfectly diffuse scattering (present case, $n = 1$) to perfectly specular reflection (equivalent to an infinite multilayer with double thickness of the ferromagnetic layers). Figure 6(*b*) represents the variation of the conductance per period of the multilayer versus t_F in the configuraiton of parallel alignment of the magnetizations. As already discussed in previous papers [9, 15], to the lowest order of approximation, we can assume that the current is carried in parallel in the various layers. A linear increase of the conductance versus t_F is then expected with a slope equal to $1/\rho_F$ (ρ_F = *resistivity of the ferromagnetic metal* F). Such a linear behaviour is observed in figure 6(*b*) at large t_F thicknesses with a slope corresponding to $\rho_F = 15.4\,\mu\Omega$ cm as expected from our choice of $(\lambda^\uparrow + \lambda^\downarrow)_F$. Furthermore, when n is increased, we observe a global rise of the conductance due to the decreasing relative role of the diffuse scattering on the outer surfaces. In the low t_F regime, a minimum of conductance is observed versus t_F which is at first sight quite surprising. It is a striking feature that the conductance of a metallic multilayer may decrease while the thicknesses of the layers are increased. In fact we found that this behaviour is a quite general phenomenon in metallic multilayers (even for non-magnetic materials) comprising alternating layers of two materials of significantly different resistivities (e.g. Cu/Ta/Cu/Ta). The origin of this minimum of conductance is the following: let us consider a multilayer of the form (Ht_H/Lt_L/Ht_H/Lt_L) where H is a highly resistive layer, L a low resistive layer. When t_H is increased from $t_H \ll \lambda_H$ to $t_H \gg \lambda_H$, for $t_H < \lambda_H$ (λ_H *is the mean-free path in material* H) the conduction electrons can traverse the H layers without undergoing many scattering events. Therefore the average mean-free paths of conduction electrons is close to that in metal L. The infinite multilayer almost behaves like the bulk metal L. As the thickness t_H becomes of the order of λ_H, more and more scattering events occur in the H layers limiting the average mean-free paths of conduction electrons to a value of the order of t_L. This results in a decrease of the conductance of the L layers which is larger than the increase of the conductance in the H layers. In other words, this minimum of conductance of the multilayer is due to a confinement of the conduction electrons in the layers with lower resistivity induced by the scattering in the layers with higher ρ when t_H becomes of the order of λ_H. This effect is illustrated in figure 7 for which we chose H and L materials with the same resistivities as before but removed all spin-dependence of the mean-free paths or of the transmission through the interfaces (simulating non-magnetic metals). We point out, however, that the L layers must be thick enough ($t_L \geqslant \lambda_L/10$) to give rise to this minimum in $G(t_H)$. Note also that this effect of a minimum of conductance versus t_H can be recovered within Garcia and Suna's theory [17] but has never been explicitly pointed out before.

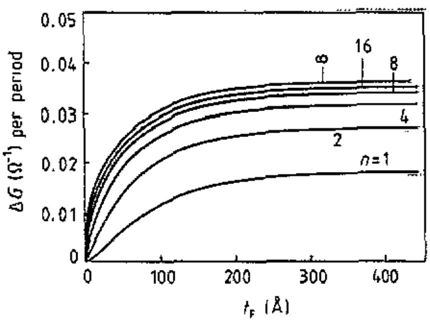

Figure 5. Magnetoresistance (absolute change of sheet conductance ΔG per period) versus thickness of the magnetic layer of a finite multilayer n (Ft_F/NM 10 Å/Ft_F/NM 10 Å) for different values of the number of periods n. Same parameters as for figure 1.

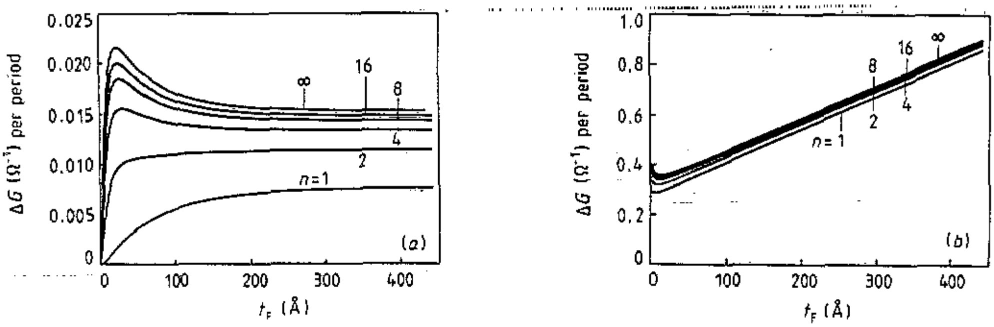

Figure 6. (*a*) Magnetoresistance (absolute change of sheet conductance ΔG per period) versus thickness of the magnetic layer of a finite multilayer n (Ft_F/NM 100 Å/Ft_F/NM 100 Å) for different values of the number of periods n. Same parameters as for figure 5 but larger thickness of the spacer layer. (*b*) Conductance versus thickness of the magnetic layer for the same structures as in figure 6(*a*).

3. Interfacial spin-dependent scattering only

In the following, we no longer consider the contribution to the MR due to bulk SDS in the F layer but assume only interfacial SDS at the F/NM interfaces. Our purpose is to compare the behaviour of the MR in these two extreme hypotheses and propose an experimental way to distinguish between bulk and interfacial SDS.

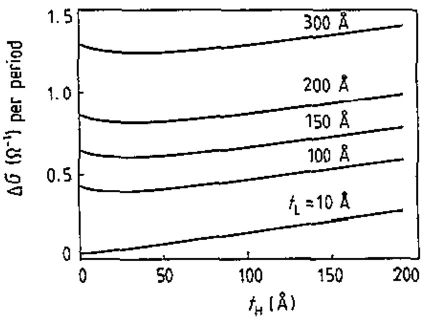

Figure 7. Conductance per period of an infinite metallic multilayer ∞ (H t_H/L t_L/H t_H/L t_L) comprising two different metals (H has a high resistivity $\lambda_H^\uparrow = \lambda_H^\downarrow = 63$ Å, L a low resistivity $\lambda_L^\uparrow = \lambda_L^\downarrow = 205$ Å) versus thickness t_H of the highly resistive layer for different thicknesses of the L layers. The period that we considered is H t_H/L t_L/H t_H/L t_L as in the case of magnetic multilayers.

3.1. *Infinite multilayers*

Figures 8(*a*) and (*b*) show the variation of the MR of an infinite multilayer ∞(Ft_F/NM 10 Å/Ft_F/NM 10 Å) with spin-dependent transmission at the F/NM interfaces and equal mean-free paths for both species of electrons in the F and NM layers. The mean-free paths are chosen so that the sums $(\lambda^\uparrow + \lambda^\downarrow)_F$ and $(\lambda^\uparrow + \lambda^\downarrow)_{NM}$ (and therefore the resistivities) are equal to those of the previous case. The ratio $T^\uparrow/T^\downarrow$ is chosen to be equal to the ratio $(\lambda^\uparrow/\lambda^\downarrow)_F$ used in the case of bulk SDS ($T^\uparrow = 1$; $T^\downarrow = 0.105$). ΔG per period (figure 8(*a*)) saturates at large t_F thickness as for bulk SDS (see figure 2(*a*)) but decreases monotonically at low t_F thickness. However, in realistic systems, the electronic properties of the interfaces which give rise to the spin-dependent character of the transmission cannot remain unchanged down to $t_F = 0$ Å. This is not taken into account in our model in which the transmission coefficients are assumed independent of t_F for $t_F > 0$ Å. As a result, a steep decrease of $\Delta G(t_F)$ down to 0 for $t_F = 0$ Å is expected experimentally for thicknesses t_F below say 2 or 3 monolayers due for instance to an incomplete coverage of the interfaces. With this additional feature, figure 8(*a*) would be more similar to figure 2(*a*) with, however, a steeper maximum of $\Delta G(t_F)$ (if observed) than in the case of bulk SDS. On $\Delta R/R$ (figure 8(*b*)), a monotonic decrease is obtained. However, as for $\Delta G(t_F)$ a drop of the MR is expected at low t_F thickness due to the change in the electronic properties of the interfaces for very thin F layers. The variation of ΔG versus the thickness of the non-magnetic spacer layer t_{NM} (not shown) is very similar to the case of bulk SDS. For large t_F thickness, a monotonic decrease of $\Delta G(t_{NM})$ is observed with an exponential asymptotic form. For low t_F thickness, a maximum occurs as for bulk SDS (figure 6 for $t_F \leqslant 50$ Å).

3.2. *Sandwiches*

Figure 9 represents the variation of the MR versus t_F in the case of a spin-valve sandwich similar to that of figure 4 but with only interfacial SDS ($\lambda_F^\uparrow = 63$ Å, $\lambda_F^\downarrow = 63$ Å, $\lambda_{NM} = 205$ Å, $T^\uparrow = 1$, $T^\downarrow = 0.105$). We note the similarity in the shape of $\Delta G(t_F)$ between figure 9 (interfacial SDS) and figure 4 (bulk SDS) with, however, a saturation of $\Delta G(t_F)$ reached at lower t_F thickness for interfacial SDS than bulk SDS (for the same ratios $T^\uparrow/T^\downarrow$ and $\lambda^\uparrow/\lambda^\downarrow$).

3.3. *Finite multilayers*

Figures 10(*a*) and 10(*b*) illustrate the effect of the number of periods on the conductance and MR (ΔG) per period of a multilayer of composition n (Ft_F/NM

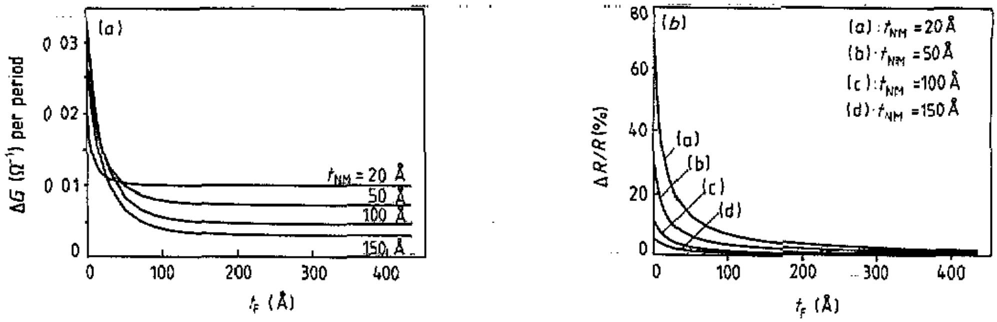

Figure 8. (*a*) Magnetoresistance (absolute change of sheet conductance ΔG per period) versus thickness of the magnetic layer, of an infinite multilayer ∞ (Ft_F/NM t_{MN}/Ft_F/NM t_{NM}) for different values of the thickness of the non-magnetic layers. $\lambda_F^{\uparrow} = 63$ Å, $\lambda_F^{\downarrow} = 63$ Å, $\lambda_{NM} = 205$ Å, $T^{\uparrow} = 1$, $T^{\downarrow} = 0.105$ (interfacial spin-dependent scattering only). (*b*) Same data as in figure 2(*a*) but the magnetoresistance is represented by $\Delta R/R_{\text{parallel}}$ instead of ΔG.

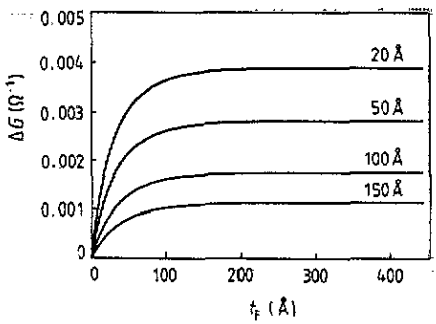

Figure 9. Magnetoresistance (absolute change of sheet conductance ΔG) versus thickness of the magnetic spacer layer of a spin-valve sandwich F t_F/NM t_{NM}/F 50 Å/FeMn 90 Å for different values of the thickness of the non-magnetic magnetic layer. $\lambda_F^{\uparrow} = 63$ Å, $\lambda_F^{\downarrow} = 63$ Å, $\lambda_{NM} = 205$ Å, $T^{\uparrow} = 1$, $T^{\downarrow} = 0.105$ (interfacial spin-dependent scattering only).

10 Å/Ft_F/NM 10 Å) with interfacial SDS. The mean-free paths and transmission coefficients are the same as before. As for the bulk SDS case (figure 6(*b*)), the conductance (figure 10(*a*)) increases almost linearly with t_F with some deviations characteristic of finite size effects for $t_F \leqslant \lambda$. A slight global rise of the conductance is observed with n (due to the decreasing role of diffuse scattering on outer boundaries). No minimum is found here at low t_F in contrast to figure 6(*b*). However, this is not due to the interfacial character of the SDS but to the low value of the t_{NM} thickness used here ($t_{NM} = 10$ Å). For thicker NM layers, a minimum is actually observed as on figure 6(*b*). The MR (figure 10(*b*)) progressively increases with n from the characteristic shape for spin-valve sandwiches ($n = 1$) [15] to a more complicated behaviour for large n. As discussed before, in realistic systems, we expect $\Delta G(t_F)$ to go progressively to 0 for $t_F \rightarrow 0$ Å because of the thickness dependence of the transmission through the interfaces for thin F layers. This should lead to an MR behaviour somewhat similar to that found for bulk SDS (figure 5) but with more rapid saturation of $\Delta G(t_F)$.

4. Summary and conclusion

In summary, this comparison of the MR behaviour of multilayers in the two extreme situations of bulk and interfacial SDS has shown that many differences should exist in

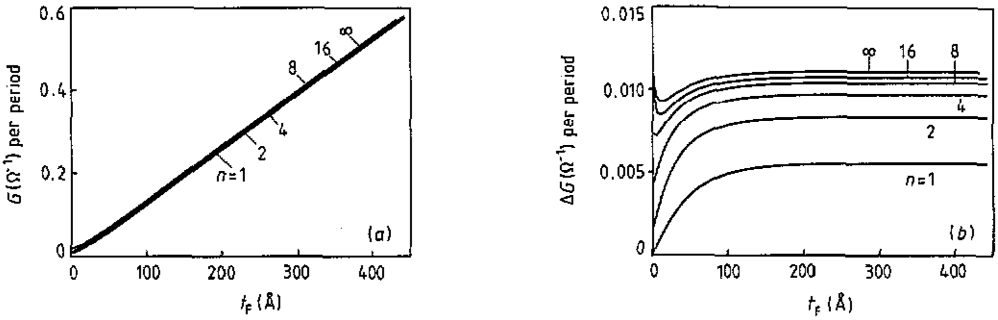

Figure 10. (*a*) Conductance per period versus thickness of the magnetic layer of a finite multilayer n (Ft_F/NM 10 Å/Ft_F/NM 10 Å) for different values of the number of periods n. Same parameters as for figure 9. (*b*) Magnetoresistance (absolute change of sheet conductance ΔG per period) versus thickness of the magnetic layer for the same structures as in figure 10(*a*).

principle in the variation of $\Delta G(t_F)$ between these two cases, especially at low t_F thicknesses. However, as discussed above, the spin-dependent electronic properties of the NM/F interfaces in realistic systems are expected to change when t_F becomes smaller than 2 or 3 monolayers. Consequently it may be difficult to use experimental data at low t_F to distinguish between interfacial or bulk SDS. In contrast, at large t_F thicknesses, it is clear that $\Delta G(t_F)$ saturates faster in the case of interfacial SDS than for bulk SDS for the same conductivity of the ferromagnetic layers e.g. same sum $(\lambda^{\uparrow} + \lambda^{\downarrow})_F$.

In the following, we demonstrate that the measurements of both $G(t_F)$ and $\Delta G(t_F)$ in spin-valve sandwiches can provide a way to distinguish between bulk and interfacial SDS. Indeed the slope of $G(t_F)$ for large t_F thicknesses leads to the determination of the resistivity ρ_F of the ferromagnetic metal and therefore of the sum $(\lambda^{\uparrow}+\lambda^{\downarrow})_F$. Furthermore, as discussed above, the rate at which $\Delta G(t_F)$ saturates provides a value for the longer of the two mean-free paths $\lambda^{\uparrow}$ or $\lambda^{\downarrow}$. It is then possible to separately determine $\lambda^{\uparrow}$ and $\lambda^{\downarrow}$, then calculate the contribution to the MR from the bulk part of the SDS. If the experimental MR is larger than this calculated contribution from bulk SDS, some interfacial SDS must be added by introducing spin-dependent transmission coefficients $T^{\uparrow}$ and $T^{\downarrow}$ at the F/NM interfaces. Using this method, we have quantitatively analysed transport data obtained on three series of NiFe, Co and Fe-based spin-valves. We found that the spin-dependent scattering is mostly bulk with NiFe, partly bulk and partly interfacial with Co and mainly interfacial with Fe [20].

In conclusion, in this paper, we used an extended Fuchs–Sondheimer theory (similar to the model of Camley and Barnas) including bulk and/or interfacial spin-dependent scattering to interpret or predict the MR properties of spin-valve sandwiches and multilayers. We underlined that the absolute change of sheet conductance (ΔG) between the two configurations of parallel and antiparallel alignment of the magnetizations in the successive ferromagnetic layers is the most appropriate measurable quantity to describe the spin-valve MR from a fundamental point of view. We showed that the variation of ΔG versus the thicknesses of the various layers provides more detailed information on the MR than other quantities such as $\Delta R/R$ do. Some surprising results have been obtained in this study such as an increase of ΔG versus the thickness of the non-magnetic spacer layer in spin-valve multilayers, or a decrease in the conductance G of a metallic multilayer when the thicknesses of some of its metallic layers are increased. Recently, within the quantum theory of [19], we calculated the magnetoresistance properties of infinite multilayers with bulk-only spin-dependent scattering [21]. Exactly the same unexpected results as in the classical theory have been obtained demonstrating that these surprising results are not due to a failure of the classical theory when the thickness of the layers is much smaller than the mean-free paths but that they are intrinsic effects. We hope that this study will encourage experimentalists to measure both the sheet conductance and the magnetoresistance of their samples so that a more rigorous comparison of the results obtained on different systems (based on the analysis of ΔG) will be possible.

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