Conditions for efficient spin injection from a ferromagnetic metal into a semiconductor

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We adapt the spin accumulation model of the perpendicular transport in metallic magnetic multilayers to the issue of spin injection from a ferromagnetic metal (F) into a semiconductor (N). We show that the problem of the conductivity mismatch between F and N can be solved by introducing a spin dependent interface resistance (tunnel junction preferably) at the F/N interfaces. In the case of a $F/N/F$ structure, a significant value of the magnetoresistance can be obtained if the junction resistance at the F/N and N/F interfaces is chosen between two threshold values depending on the resistivity, spin diffusion length and thickness of N. The problem is treated for various geometries (vertical or lateral $F/N/F$ structures).

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I. INTRODUCTION

Achieving spin-polarized electron injection into a semiconductor is one of the most important challenges in spin electronics today. A decade ago, Datta and Das[1] were the first to propose a device based on spin injection from a ferromagnetic metal into a semiconductor and analogous to the electro-optic modulator. In the same vein, various devices can be imagined, for example, to detect the information stored in a magnetic memory and treat it in a semiconductor heterostructure. What is required is a long spin lifetime in the semiconductor and an efficient injection of spin-polarized electrons. Extensive data on the spin relaxation in semiconductors or 2DEG have now been obtained. For example, time resolved optical experiments by Awschalom and co-workers[2] have shown that the spin lifetime in GaAs can be as long as 100 ns at low temperature and, even at room temperature, is still definitely longer than the spin lifetime in metals. Achieving an efficient spin injection is a more difficult requirement. Two approaches have been tried. Injection from a magnetic semiconductor gives excellent results, as shown, for example, by the recent experiments of Fiederling *et al.*[3] or Ohno *et al.*[4] However, as long as the Curie temperature of ferromagnetic semiconductors does not exceed definitely room temperature, this approach has a limited interest for applications. The second approach is based on spin injection from ferromagnetic metal such as Co and Fe which, even at room temperature, exhibit a significantly spin polarized conduction. However, even if one forgets the technical difficulties due to the reactivity of the transition metals with most semiconductors, there are fundamental problems which strongly limit the spin-polarization of the injected electrons, as this has been clearly shown by Schmidt *et al.*[5] By solving the spin transport equations at a F/SC interface between a ferromagnetic metal (F) and into a semiconductor (SC), Schmidt *et al.* find that the spin-polarization of the current in the semiconductor becomes very small when the resistivity of the SC is much higher than that of the F metal.[5] They also find that the magnetoresistance (MR) of a $F/SC/F$ structure similar to that proposed by Datta and Das[1] should be generally negligible when F is a metal.

In this paper we extend the calculation of Schmidt *et al.*[5] by developing a model in which, as in the standard pictures of the perpendicular GMR, a spin dependent interface resistance is introduced between the ferromagnetic metal and the semiconductor. We show that the spin polarization of the injected current can be significant when the interface resistance exceeds a threshold value related to the resistivity and spin diffusion length of the SC. For example, this can be done by introducing a tunnel barrier at the F/SC interface. We also show that a $F/SC/F$ structure can present a significant MR if the resistances of the tunnel junctions introduced at both F/SC interfaces are in a relatively narrow range depending on the resistivity, spin diffusion length and thickness of the SC.

As a matter of fact, some of the results we describe in this article are not completely new. A calculation of the spin injection effects in a multilayered structure with interface resistances has already been presented by Valet and Fert[6] and the only novelty here is the discussion of what can be expected from their expressions of the MR with the characteristic parameters of semiconductors and tunnel junctions. A large part of the paper will be devoted to quantitative predictions with realistic parameters for various geometries. While we were writing the paper, we became also aware of the recent article of Rashba[7] on spin injection. We agree with the results of this paper for the problem of the current spin polarization at a F/SC interface but not for the MR of a $F/SC/F$ structure. Our conditions for the existence of a significant MR are different (and more drastic) than those of Rashba and we explain the origin of this discrepancy.

II. EQUATIONS FOR SPIN-POLARIZED TRANSPORT AT INTERFACES AND PERTINENT PARAMETERS

As in the model of Schmidt *et al.*,[5] our calculation is based on the equations introduced phenomenologically by Johnson and Silsbee[8] and van Son *et al.*[9] to describe the spin transport between ferromagnetic and nonmagnetic conductors, and extended in a Boltzmann equation formalism by Valet and Fert.[6] We will consider interfaces parallel to the xy plane and a current density J parallel to the z axis. We adopt the notation of Valet and Fert (VF). $+(-)$ refers to the absolute spin direction of the electrons and $\uparrow(\downarrow)$ refers to the majority (minority) spin direction in a ferromagnetic material. We call $J_+(z)$ $[J_-(z)]$ and $\mu_+(z)[\mu_-(z)]$ the current

density and electrochemical potential of the spin + (spin −) electrons at position z (the difference between μ_+ and μ_- comes from spin accumulation effects[8,9]). We write

$$\rho_{\uparrow(\downarrow)}=2[1-(+)\beta]\rho_F^* \tag{1}$$

for the resistivity of the spin $\uparrow(\downarrow)$ channel in the metal F [the resistivity of the bulk metal is $(1-\beta^2)\rho_F^*$] and

$$\rho_{\uparrow(\downarrow)}=2\rho_N^* \tag{2}$$

for the resistivity of the nonmagnetic conductor N (metal or semiconductor). In the limit where the spin relaxation is much slower than the momentum relaxation, $J_{+(-)}$ and $\mu_{+(-)}$ in a given layer are determined by the following equations:[9]

$$J_{+(-)}=\frac{1}{|e|\rho_{+(-)}}\frac{\partial\mu_{+(-)}}{\partial z}, \tag{3}$$

$$J_+ + J_- = J, \tag{4}$$

$$\frac{\partial(J_+ - J_-)}{\partial z}=\frac{2eN(E_F)\Delta\mu}{\tau_{sf}}, \tag{5}$$

where τ_{sf} is the spin lifetime, $\rho_{+(-)}$ is the resistivity in the spin $+(-)$ channel, $2N(E_F)$ is the total density of states at the Fermi level, and $\Delta\mu=\mu_+(z)-\mu_-(z)$. Equation (5) holds for metals and in the degenerate Fermi gas regime of semiconductors. In a nondegenerate semiconductor, the equation expressing the balance between spin injection and spin relaxation has a slightly different form

$$\frac{\partial(J_+ - J_-)}{\partial z}=\frac{en\Delta\mu}{k_BT}\frac{1}{\tau_{sf}}, \tag{6}$$

where n is the total number of carriers. By combining Eqs. (3) and (5) or (6), one finds that the variation of the electrochemical potentials with z is determined by the equation

$$\frac{\partial^2\Delta\mu_{+(-)}}{\partial z^2}=\frac{\Delta\mu_{+(-)}}{l_{sf}^2}, \tag{7}$$

where l_{sf} is the spin diffusion length (l_{sf}^F or l_{sf}^N) in the material one considers. As expressed in Ref. 10, the spin diffusion length is given by

$$l_{sf}^N=\sqrt{\frac{\lambda\lambda_{sf}}{6}}=\sqrt{\frac{\tau_{sf}}{4e^2N(E_F)\rho_N^*}} \tag{8}$$

for a nonmagnetic metal or a degenerate Fermi gas semiconductor. $N(E_F)$ must be replaced by $2/[1/N_+(E_F)+1/N_-(E_F)]$ for a ferromagnetic metal when one supposes different densities of states in the spin + and spin − channels.[10] However, this is not an important matter here and, for simplicity, we keep the assumption of the VF model, $N_+(E_F)=N_-(E_F)=N(E_F)$. In the nondegenerate regime of a semiconductor, Eq. (8) becomes

$$l_{sf}^N=\sqrt{\frac{k_BT\tau_{sf}}{2ne^2\rho_N^*}}. \tag{9}$$

The boundary conditions at an interface $z=z_0$ are the continuity of J_+ and J_- and the discontinuity of μ_+ and μ_- associated with the existence of an interface resistance

$$\mu_{+(-)}(z=z_0^+)-\mu_{+(-)}(z=z_0^-)=r_{+(-)}J_{+(-)}(z=z_0), \tag{10}$$

where $\mu_+(z=z_0^+)$ and $\mu_-(z=z_0^+)$ [$\mu_+(z=z_0^-)$ and $\mu_-(z=z_0^-)$] are the chemical potentials on the right (left) side of the interface and, in the notation of the CPP-GMR (Refs. 6,11,12)

$$r_{+(-)}=2r_b^*[1-(+)\gamma]. \tag{11}$$

Equations (10),(11) hold for both a F/N interface between two metals ($r_b^*\simeq 10^{-16}-10^{-15}$ Ωm^2, Ref. 11) and a tunnel junction between a F metal and a nonmagnetic conductor (with a value of r_b^* which is much higher than for a metallic interface and can also be voltage dependent; γ is P in the usual notation of spin dependent tunneling[13]). We will see below that the important parameters in the spin injection problem are the interface resistance r_b^* and the products of the resistivity by the spin diffusion length

$$r_F=\rho_F^*\times l_{sf}^F, \tag{12}$$

$$r_N=\rho_N^*\times l_{sf}^N \tag{13}$$

for the ferromagnetic and nonmagnetic materials, respectively. For metals, r_F and r_N have similar values. In the case of Co and Cu, for example, taking data from CPP-GMR experiments $\rho_{Co}^*=7.5\times10^{-8}$ Ωm,[11] $\beta=0.46$,[11] $l_{sf}^{Co}=59$ nm,[12,14] $\rho_{Cu}^*=6\times10^{-9}$ Ωm,[11] $l_{sf}^{Cu}=1$ μm,[15] we find $r_{Co}=4.5\times10^{-15}$ Ωm^2 and $r_{Cu}=6\times10^{-15}$ Ωm^2. In contrast, when the ferromagnet is still a metal such as Co while the nonmagnetic material is a semiconductor presenting a much higher resistivity (and also a long spin diffusion length), one expects $r_N \gg r_F$. This is the condition for having a strong reduction of the current polarization in the semiconductor, at least in the situation without interface resistance of Schmidt *et al.*[5]

It is of interest to see how r_N is expected to vary as a function of the carrier density n. In a simple free electron model for a metal or a degenerate Fermi gas semiconductor, by combining Eq. (8) with $\rho=m/ne^2\tau$, we find for the product $\rho_N l_{sf}^N$:

$$r_N=\frac{\hbar\pi}{(3\pi^2)^{\frac{1}{3}}e^2}\sqrt{\frac{\tau_{sf}}{2\tau}}n^{-2/3}. \tag{14}$$

In the nondegenerate Fermi gas regime of a semiconductor with l_{sf}^N given by Eqs. (9), (14) becomes

$$r_N=\sqrt{2mk_BT\frac{\tau_{sf}}{\tau}}e^2n^{-1}. \tag{15}$$

In metals, the predominant contribution to the spin relaxation rate ($1/\tau_{sf}$) comes from the Yafet mechanism,[16] that is from the spin-orbit part of the scattering potentials producing the momentum scattering ($1/\tau$). The ratio τ_{sf}/τ depends on the level of the spin-orbit interaction and, as shown by ESR experiments,[17,18] can vary between about 10^3 for pure Cu to around 10^2 for the characteristic spin-orbit interaction of $3d$ elements. Similar values of n and not very different values of $\sqrt{\tau_{sf}/\tau}$ account for the not very different values of r_{Cu} and r_{Co} that we have quoted above. The values of r_F (or r_N) are also approximately temperature independent.[19,20]

In semiconductors the mechanisms of spin relaxation[21,22] are not limited to the Yafet mechanism of metals, so that the ratio τ_{sf}/τ is more system dependent. However, even if the ratio τ_{sf}/τ can be somewhat larger than in metals, the much larger values of r_N in semiconductors come mainly from the variation as $n^{-2/3}$ in Eq. (14) for the degenerate regime and then as n^{-1} in Eq. (15) for the nondegenerate regime. We have estimated r_N in the typical example of n-type GaAs samples in which Kikkawa and Awschalom[22] have measured the spin relaxation time. Since the interest of injection from a ferromagnetic metal comes from the possibility of spin injection at room temperature (RT), we consider the experimental data at RT. For the sample with a doping density $n=10^{16}$ cm^{-3}, the spin relaxation time at RT can be estimated at about 1.5×10^{-10} s (see Fig. 4 in Ref. 22). With $\mu=5400$ cm^2/V s for the mobility at RT and $m=0.07m_e$, on obtains from Eq. (9) $l_{sf}^N\simeq1.83$ μm and $r_N\simeq4.4\times10^{-9}$ Ωm^2. The value of r_N is larger than that of metals such as Cu or Co by 6 orders of magnitude. In contrast the spin diffusion length is only slightly larger than in a nonmagnetic metal such as Cu, that is still in the micron range. Our numerical applications for semiconductors in the next paragraphs will be based on values of r_N and l_{sf}^N, $r_N=4\times10^{-9}$ Ωm^2 and $l_{sf}^N=2$ μm, in the typical range found above for the GaAs sample of Ref. 22.

III. CURRENT SPIN POLARIZATION AT AN INTERFACE BETWEEN A FERROMAGNETIC METAL AND A NONMAGNETIC CONDUCTOR

We consider two semi-infinite ferromagnetic (F) and nonmagnetic (N) materials separated by the plane $z=0$. The solution of Eqs. (3)–(7) in F and N can be written as

$$\mu_{+(-)}^F=e\rho_F^*(1-\beta^2)Jz-(+)B[1-(+)\beta]\exp\left(\frac{z}{l_{sf}^F}\right)+C, \tag{16}$$

$$J_{+(-)}^F=[1+(-)\beta]\frac{J}{2}-(+)\frac{B}{2er_F}\exp\left(\frac{z}{l_{sf}^F}\right), \tag{17}$$

$$\mu_{+(-)}^N=e\rho_N Jz-(+)D\exp\left(-\frac{z}{l_{sf}^N}\right), \tag{18}$$

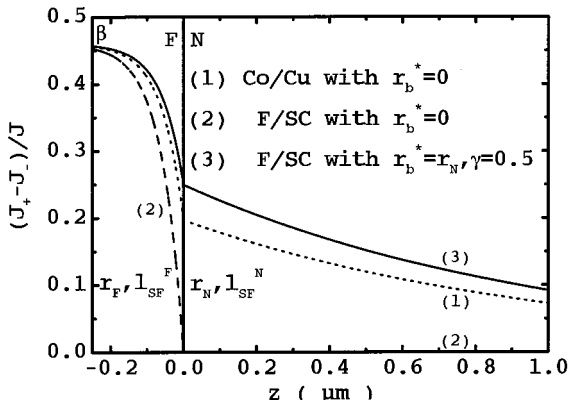

FIG. 1. Spin polarization of the current as a function of z at the F/N interface. Curve 1 is for $F=$Co ($r_F=4.5\times10^{-15}$ Ωm^2, $\beta=0.46$, $l_{sf}^F=60$ nm), $N=$Cu ($r_N=6\times10^{-15}$ Ωm^2, $l_{sf}^N=1$ μm) and without interface resistance. Curve 2 is for $F=$Co (same parameters than for curve 1), $N=$semiconductor ($r_N=4\times10^{-9}$ Ωm^2, $l_{sf}^N=2$ μm, see Sec. II) and without interface resistance. Curve 3 is for $F=$Co, $N=$semiconductor (same parameters as for curve 2) with a spin dependent resistance (tunnel junction) at the interface ($r_b^*=r_N=4\times10^{-9}$ Ωm^2, $\gamma=0.5$). The spin polarization is $\gamma/2$ at the interface for the particular case $r_b^*=r_N\gg r_F$ of curve 3. It reaches γ in the limit $r_b^*\gg r_N\gg r_F$ (curve not shown).

$$J_{+(-)}^N=\frac{J}{2}+(-)\frac{D}{2er_N}\exp\left(-\frac{z}{l_{sf}^N}\right), \tag{19}$$

where $r_F=\rho_F^* l_{sf}^F$, $r_N=\rho_N^* l_{sf}^N$. The coefficients B, C, and D can be obtained from the boundary conditions, that is Eq. (10) for μ_+ and μ_- and continuity of (J_+-J_-), and we have calculated the variation with z of μ_+, μ_-, J_+ and J_- for several values of the parameters. We will focus on the variation of the spin polarization of the current $\mathrm{SP}=(J_+-J_-)/J$, as a function of z in Fig. 1 and on its value $(\mathrm{SP})_I$ at the interface, which is given by the simple expression

$$(\mathrm{SP})_I=\left(\frac{J_+-J_-}{J}\right)_I=\frac{\beta r_F+\gamma r_b^*}{r_F+r_N+r_b^*}. \tag{20}$$

We first consider the case without interface resistance. For $r_b^*=0$, Eq. (20) becomes

$$(\mathrm{SP})_I=\frac{\beta}{1+r_N/r_F}. \tag{21}$$

When both F and N are metals, r_N and r_F have similar values, for example, $r_{\mathrm{Cu}}=6\times10^{-15}$ Ωm^2 and $r_{\mathrm{Co}}=4.5\times10^{-15}$ Ωm^2, as estimated in Sec. II for a typical Co/Cu multilayer. In this case, the SP of the current penetrating the semiconductor is only moderately reduced from its value β inside the ferromagnet, see curve 1 in Fig. 1, with, from Eq. (21), $(\mathrm{SP})_I=\beta/2.33$ at the Co/Cu interface.

In contrast, when, for a semiconductor, r_N is much larger than r_F, we obtain the curve 2 of Fig. 1 with a negligible polarization in the semiconductor. At the interface, from Eq. (21), the polarization is reduced to about $\beta r_F/r_N$. In the typical example discussed in the preceding section with, r_N

$\simeq 4\times10^{-9}$ Ωm^2, the spin asymmetry is reduced by 6 orders of magnitude. This strong reduction of the spin polarization of the injected current is that already discussed by Schmidt *et al.*[5,23]

On the other hand, what Eq. (20) says is that, even for $r_N \gg r_F$, the spin polarization remains large when there is a large enough spin dependent interface resistance r_b^*, more precisely for $r_b^* > r_N$. Curve 3 in Fig. 1 shows the variation of the SP for the threshold value of the resistance, $r_b^* = r_N \gg r_F$. In this case the SP at the interface is $\gamma/2$ (0.25 with the coefficient γ of curve 3). In the limit $r_b^* \gg r_N > r_F$, from Eq. (20), the spin polarization at the interface is simply the spin asymmetry coefficient of the interface resistance

$$(\mathrm{SP})_I = \gamma. \tag{22}$$

The very high resistance required by the condition $r_b^* \gg r_N$, together with a significant spin asymmetry coefficient γ, can be obtained with a tunnel junction, that is by introducing an ultrathin insulating layer between the ferromagnetic metal and the semiconductor. The resistances that can be obtained with alumina (ALO) layers are generally in the range $10^{-10}-10^{-4}$ Ωm^2 (10^2-10^8 $\Omega\mu$m^2) and, for tunneling from Co alloys for example, the coefficient γ (P in the usual notation of spin dependent tunneling) can reach 0.5.[24] Schottky barriers could also give large interface resistances but the existence of spin dependent tunneling through a Schottky barrier has never been clearly demonstrated, so that an oxide barrier of the type use for tunneling magnetoresistance seems a much more reliable solution. In agreement with Rashba,[7] we thus find that, with appropriate spin dependent interface resistances such as those introduced by oxide layers, there is no physical obstacle for the injection of a significantly spin-polarized current from a ferromagnetic metal into a semiconductor.

The physical mechanism explaining the influence of the interface resistance on the spin polarization of the injected current can be described as follows. In the absence of interface resistance, the Fermi energy splitting due to spin accumulation, $\Delta\mu = \mu_+ - \mu_-$, has the same value $\Delta\mu_I$ on both sides of the interface and, when one goes away from the interface, decreases exponentially with decay lengths l_{sf}^F (F side) or l_{sf}^N (N side). This is illustrated by Fig. 2(a) in the simple case of a Co/Cu interface and by the dashed curve of Fig. 2(b) for a Co/SC interface. The respective variations of the current spin polarization in F and N are obtained by integrating Eq. (5) with $\Delta\mu = \Delta\mu_I \exp(z/l_{sf}^F)$ between $-\infty$ and 0, and Eq. (5) [or Eq. (6)] with $\Delta\mu = \Delta\mu_I \exp(-z/l_{sf}^N)$ between 0 and $+\infty$, which actually means that these variations are proportional to the respective total numbers of spin flips in F and N. It turns out from the calculation of the integrals that, with the same $\Delta\mu_I$, these total numbers of spin flips in F and N are, respectively, proportional to $1/r_F$ and $1/r_N$. With $r_F \ll r_N$ when N is a semiconductor, this means that there are much more spin-flips and a stronger depolarization of the current in F than in N. In other words, the current is already completely depolarized when it crosses the interface.

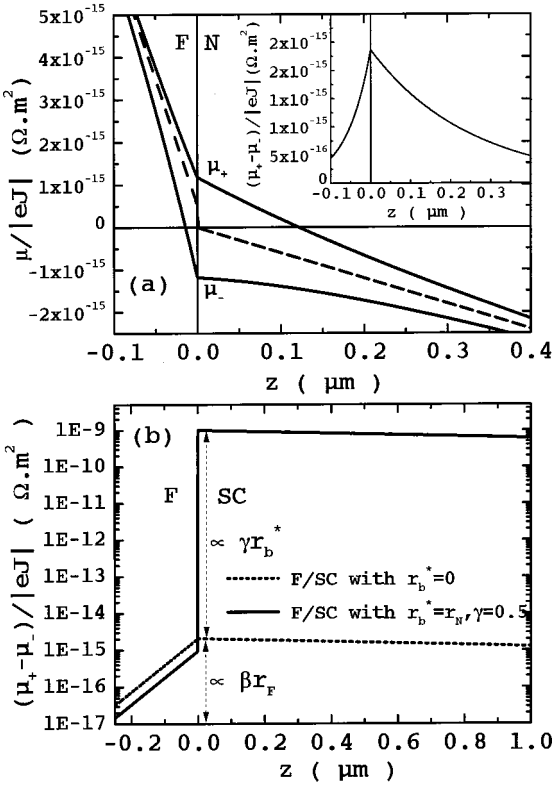

FIG. 2. (a) Variation of the electrochemical potentials μ_+ and μ_- as a function of z at a Co/Cu interface without interface resistance ($r_F = 4.5\times10^{-15}$ Ωm^2, $\beta = 0.46$, $l_{sf}^F = 60$ nm for Co, $r_N = 6\times10^{-15}$ Ωm^2, $l_{sf}^N = 1$ μm for Cu, $r_b^* = 0$). The dashed lines represent the asymptotes. The inset shows the variation of the spin accumulation parameter, $\Delta\mu = \mu_+ - \mu_-$, as a function of z. (b) Variation of the spin accumulation parameter as a function of z at a Co/SC interface [same values of r_b^*, l_{sf}^F, and β than in (a) for Co, $r_N = 4\times10^{-9}$, $l_{sf}^N = 2$ μm for SC] without interface resistance (dotted line) and with interface resistance ($r_b^* = r_N$, $\gamma = 0.5$, solid line). Note the logarithmic vertical scale in (b).

An interface resistance, by introducing a spin dependent discontinuity of $\Delta\mu$ at the interface and generating a much higher $\Delta\mu$ in N than in F [see solid line in Fig. 2(b)], leads to a more balanced number of spin flips in F and N, and restores the spin polarization at the interface and in the semiconductor. In the example of Fig. 2(b) with $r_b^* = r_N = 4\times10^{-9}$ Ωm^2 and $r_F = 5\times10^{-15}$ Ωm^2, one sees that the interface resistance induces a difference of about 6 orders of magnitude between the values of $\Delta\mu$ on the SC and F sides of the interface, which explains that the spin polarization in N is restored (curve 3 in Fig. 1).

IV. MAGNETORESISTANCE OF A *F*/*N*/*F* STRUCTURE, WITH AND WITHOUT INTERFACE RESISTANCE

We consider a N layer between $z = -t_N/2$ and $z = +t_N/2$ separating two semi-infinite layers of the same ferromagnetic metal. As above, we could write down solutions of Eqs. (3)–(7) similar to Eqs. (16)–(19) and determine the unknown coefficients of these solutions from the boundary conditions at the interfaces to finally derive the resistance difference

between the parallel and antiparallel configurations of the magnetic moments on the right and left sides. However this calculation has already been performed in the Valet-Fert model of the CPP-GMR.[6] From Eq. (40) of Ref. 6, the resistance change ΔR equals $2(r_{SI}^{AP}-r_{SI}^{P})$, where r_{SI}^{P} and r_{SI}^{AP} are, respectively, given by Eqs. (41) and (42). For the case of semi-infinite F layers we consider here, $t_F=\infty$ and, in this limit, a straightforward calculation leads to

$$\Delta R=\frac{2(\beta r_F+\gamma r_b^*)^2}{(r_b^*+r_F)\cosh\left(\frac{t_N}{l_{sf}^N}\right)+\frac{r_N}{2}\left[1+\left(\frac{r_b^*}{r_N}\right)^2\right]\sinh\left(\frac{t_N}{l_{sf}^N}\right)}, \tag{23}$$

where ΔR is the resistance change between the antiparallel and parallel configurations of the magnetizations in F_1 and F_2 for an unit area of the structure. The interesting situation for spin conservation in N and large MR is $t_N \ll l_{SF}^N$ and we consider only this situation. For $t_N \ll l_{SF}^N$, Eq. (23) becomes

$$\Delta R=\frac{2(\beta r_F+\gamma r_b^*)^2}{(r_b^*+r_F)+\frac{r_N}{2}\left[1+\left(\frac{r_b^*}{r_N}\right)^2\right]\frac{t_N}{l_{sf}^N}}. \tag{24}$$

As in the calculation of Schmidt *et al.*,[5] we will compare ΔR with the resistance in the parallel configuration for a device with both ferromagnetic contacts F_1 and F_2 having a thickness l_{sf}^F, that is with the resistance R^P between $z=-t_N/2-l_{SF}^F$ and $z=+t_N/2+l_{sf}^F$ for a periodic structure with $t_F=2l_{sf}^F$ [as a function of t_F, ΔR reaches its saturation value of Eqs. (23)–(24) for $t_F \simeq l_{sf}^F$, which justifies comparing ΔR with the above resistance]. From Eq. (40) of Valet and Fert,[6] we get

$$R^{(P)}=2(1-\beta^2)r_F+r_N\frac{t_N}{l_{SF}^N}+2(1-\gamma^2)r_b^* + 2\frac{(\beta-\gamma)^2 r_F r_b^*+r_N(\beta^2 r_F+\gamma^2 r_b^*)\tanh\left(\frac{t_N}{2l_{sf}^N}\right)}{(r_F+r_b^*)+r_N\tanh\left(\frac{t_N}{2l_{sf}^N}\right)}. \tag{25}$$

We first consider the case without interface resistance ($r_b^*=0$) and with two metals, that is with similar values for r_N and r_F. With $t_N \ll l_{SF}^N$, and therefore $r_N(t_N/l_{sf}^N) \ll r_N \simeq r_F$, Eqs. (24),(25) become

$$\Delta R \simeq 2\beta^2 r_F, \tag{26}$$

$$R^{(P)} \simeq 2(1-\beta^2)r_F, \tag{27}$$

and consequently

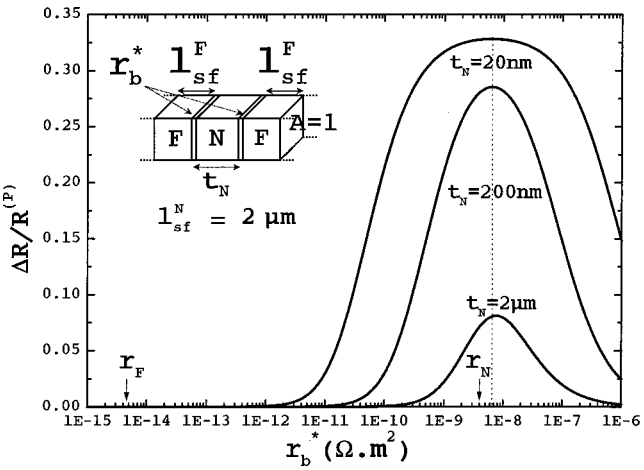

FIG. 3. Magnetoresistance versus interface resistance r_b^* of a $F_1/N/F_2$ structure where $F_1=F_2=$Co ($r_F=4.5\times10^{-15}$ Ωm^2, $\beta=0.46$, $l_{sf}^F=60$ nm), $N=$semiconductor ($r_N=4\times10^{-9}$ Ωm^2, $l_{sf}^N=2$ μm, see Sec. II), with $t_N=20$ nm($l_{sf}^N/100$), 200 nm($l_{sf}^N/10$), 2 μm(l_{sf}^N), for the thickness of N and $\gamma=0.5$ for the spin asymmetry coefficient of the interface resistance. The geometry of the structure is shown in the left top of the figure.

$$\frac{\Delta R}{R^{(P)}} \simeq \frac{\beta^2}{1-\beta^2}, \tag{28}$$

which is also the maximum value obtained by Schmidt et al[5] in the metallic case [see Eq. (10) in Ref. 5].

Still without interface resistance but when N is a semiconductor, we are in the limit $r_N \gg r_F$ and moreover taking into account the very high value of r_N/r_F estimated above, we can also reasonably assume $r_N/r_F \gg 4l_{sf}^N/t_N \gg 1$. From Eqs. (23)–(25), ΔR, $R^{(P)}$, and $\Delta R/R^{(P)}$ can be written as

$$\Delta R \simeq 8\beta^2 \frac{r_F^2}{r_N}\frac{l_{sf}^N}{t_N}, \tag{29}$$

$$R^{(P)} \simeq \rho_N^* t_N = r_N \frac{t_N}{l_{sf}^N}, \tag{30}$$

$$\frac{\Delta R}{R^{(P)}} \simeq 8\beta^2\left(\frac{r_F}{r_N}\frac{l_{sf}^N}{t_N}\right)^2. \tag{31}$$

Equation (31) expresses the strong reduction of $\Delta R/R^{(P)}$ already emphasized by Schmidt *et al.*[5]

We now consider the case of a $F/SC/F$ structure ($r_N \gg r_F$) with an interface resistance. It results from Eq. (24) that a significant MR is restored when the value of r_b^* is larger than about $r_N(t_N/l_{sf}^N)$ and smaller than $r_N(l_{sf}^N/t_N)$. In Fig. 3 we have plotted the MR calculated as a function of r_b^* for $\gamma=0.5$ (characteristic for tunneling from Co), typical values of r_F, l_{sf}^F, r_N, l_{sf}^N in metals and semiconductors (see Sec. I) and for three values of t_N/l_{sf}^N, respectively, 10^{-2}, 10^{-1}, and 1. We can see that, for $t_N/l_{sf}^N=10^{-1}$, a large MR is obtained in a relatively small range (a little more than a decade) centered at about 1.6 r_N. For $t_N/l_{sf}^N=10^{-2}$, the

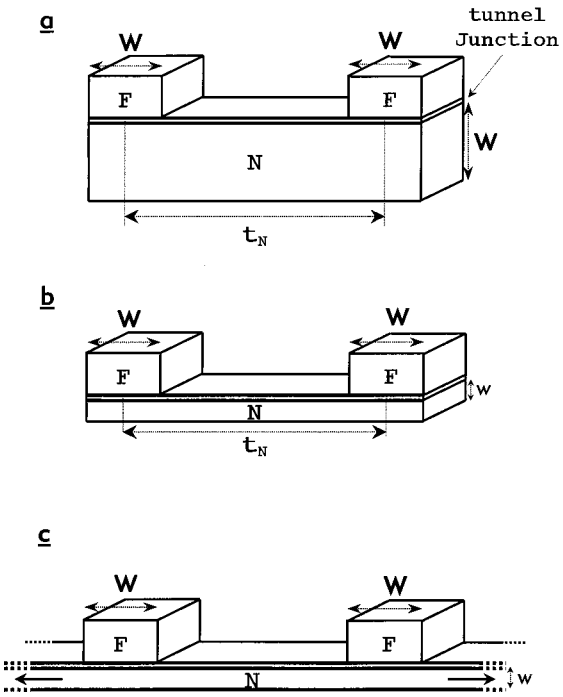

FIG. 4. Various geometries for a lateral $F/N/F$ structure. (a) Lateral geometry with the same widths W for the F and N channels, (b) Lateral geometry with different widths W and w for the F and N channels, respectively. (c) As in (b) but with possible extension of the spin accumulation on the right and left sides of N.

range of r_b^* with a large MR spreads over more than 2 decades around r_N. For $t_N/l_{sf}^N=1$, the peak of MR around r_N has almost completely vanished. The highest MR obtained in the limit $r_N(t_N/l_{sf}^N) \ll r_b^* \ll r_N(l_{SF}^N/t_N)$ is given by the following expressions:

$$\Delta R \simeq 2\gamma^2 r_b^*, \tag{32}$$

$$\frac{\Delta R}{R^{(P)}} \simeq \frac{\gamma^2}{1-\gamma^2} \tag{33}$$

and is practically reached at the maximum of the curve for $t_N/l_{sf}^N=10^{-2}$ in Fig. 3.

In a CPP device, that is with a perpendicular current through F and N layers (sketch in Fig. 3), t_N can be as thin as a few nm, so that, with $l_{sf}^N/t_N \simeq 10^2-10^3$, there is a fairly broad range between $r_N(t_N/l_{sf}^N)$ and $r_N(l_{sf}^N/t_N)$ in which the MR approaches its highest value of Eq. (33). In contrast, for ''lateral devices'' of the type represented in Fig. 4(a), when one takes into account the limitations imposed by the current technologies for t_N, one sees that, with l_{sf}^N in the micron range at RT, t_N cannot be smaller than l_{sf}^N by more than an order of magnitude. This corresponds to the conditions of Fig. 3 with $t_N=l_{sf}^N/10$, which lead to significant MR in a range of r_b^* limited to about a decade around r_N and to a value of the MR at the maximum somewhat smaller than in the limit of Eq. (33).

When the tunnel resistance r_b^* exceeds $r_N(l_{sf}^N/t_N)$, we see from Eq. (24) that ΔR saturates at the value $4\gamma^2 r_N(l_{sf}^N/t_N)$ while, from Eq. (25), $R^{(P)}$ is still increasing as r_b^*, so that $\Delta R/R^{(P)}$ tends to zero,

$$\frac{\Delta R}{R^{(P)}} \cong \frac{2r_N l_{sf}^N}{(1-\gamma^2)r_b^* t_N} \ll 1 \tag{34}$$

for $r_b^* \gg r_N(l_{sf}^N/t_N)$. This result is at odds with that of Rashba[7] who finds, from Eq. (25) in Ref. 7, that ΔR continues to increase proportionally to the tunnel resistance without saturation and that $\Delta R/R^{(P)}$ does not tend to zero in the limit of very large values of r_b^*.

We conclude that achieving a large MR requires correlated values of the tunnel resistance r_b^* and thickness t_N, and that, to obtain a large MR, one may be led to choose r_b^* in a relatively narrow range between $r_N(t_N/l_{sf}^N)$ and $r_N(l_{sf}^N/t_N)$. The physical mechanisms explaining the condition $r_N(t_N/l_{sf}^N) < r_b^* < r_N(l_{sf}^N/t_N)$ and the origin of the discrepancy with the result of Rashba can be described in the following way. We will consider successively the three regimes with (i) r_b^* much smaller than $r_N(t_N/l_{sf}^N)$, (ii) r_b^* between $r_N(t_N/l_{sf}^N)$ and $r_N(l_{sf}^N/t_N)$, (iii) r_b^* much larger than $r_N(l_{sf}^N/t_N)$.

(i) For $r_b^* \ll r_N(t_N/l_{sf}^N)$, the discontinuities in the electrochemical potentials (μ_+ and μ_-) introduced by the interface resistances are too small to generate a high enough splitting $\Delta\mu_N$ (in comparison with $\Delta\mu_F$) and polarize the current in N. This issue has already been discussed at the end of Sec. III for the structure with a single interface. The threshold $r_b^* \cong r_N(t_N/l_{sf}^N)$ is what is required to induce a spin polarization of the order of γ in the P configuration and lower $R^{(P)}$ below $R^{(AP)}$ (the required value of r_b^* is smaller than in the case of Sec. III with a single interface because, in the P configuration, both F_1 and F_2, separated by only t_N, contribute to polarize the current).

(ii) The regime $r_N(t_N/l_{sf}^N) \ll r_b^* \ll r_N(l_{sf}^N/t_N)$ is illustrated in Fig. 5. The predominant contribution to the variation of the electrochemical potential comes from the potential drops at the interfaces. In the AP configuration, this gives rise to a splitting $2\gamma r_b^* eJ$ between μ_+ and μ_- which is negligibly relaxed by the spin flips in N since the number of these spin flips, proportional to $\Delta\mu_N t_N/e^2 r_N l_{sf}^N \propto r_b^* t_N J/e r_N l_{sf}^N$ (as it can be seen by extrapolating the calculation of Sec. III to the depth t_N of N), is much too small in comparison with J/e. In the AP configuration $J_+ \cong J_- \cong J/2$, $R^{(\mathrm{AP})} \cong r_b^*$, while, in the P configuration, $J_{+(-)} \cong [1+(-)\gamma]J$, $R^{(P)} \cong r_b^*(1-\gamma^2)$. The upper limit of r_b^* for this regime is clear : as r_b^* increases, the characteristic splitting $\Delta\mu_N$ of this regime in the AP state increases as $2\gamma r_b^* eJ$, the number of spin flips in N increases as $r_b^* t_N J/e r_N l_{sf}^N$ and, when it becomes larger than about J/e, $\Delta\mu_N$ cannot be maintained at the level $2\gamma r_b^* J$ and relaxes to zero.

(iii) In the regime $r_b^* \gg r_N(l_{sf}^N/t_N)$ (or, equivalently, $t_N \gg l_{sf}^N r_N/r_b^*$), the spin accumulation $\Delta\mu_N$ of the AP configuration is completely relaxed by the spin flips in the volume t_N of N, as shown in Fig. 6 and $R^{(AP)} \cong R^{(P)} \cong r_b^*(1-\gamma^2)$.

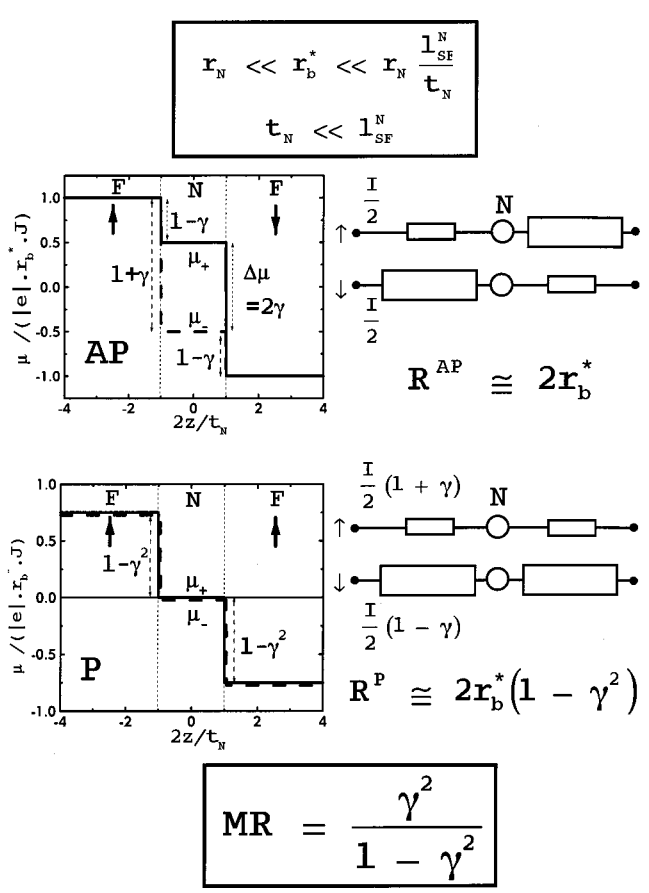

FIG. 5. Variation of the electrochemical potentials μ_+ (solid line) and μ_- (dashed line) throughout a $F/N/F$ structure having tunnel resistance r_b^* at the F/N interfaces in the resistance range required to obtain a significant MR, that is $r_N(t_N/l_{sf}^N) \ll r_b^* \ll r_N(l_{sf}^N/t_N)$. The top and bottom graphs are for the AP and P configurations, respectively. The sketches on the right indicate the equivalent resistor schemes, the current distributions and the resistances $R^{(AP)}$ and $R^{(P)}$. The MR equals $\gamma^2/(1-\gamma^2)$.

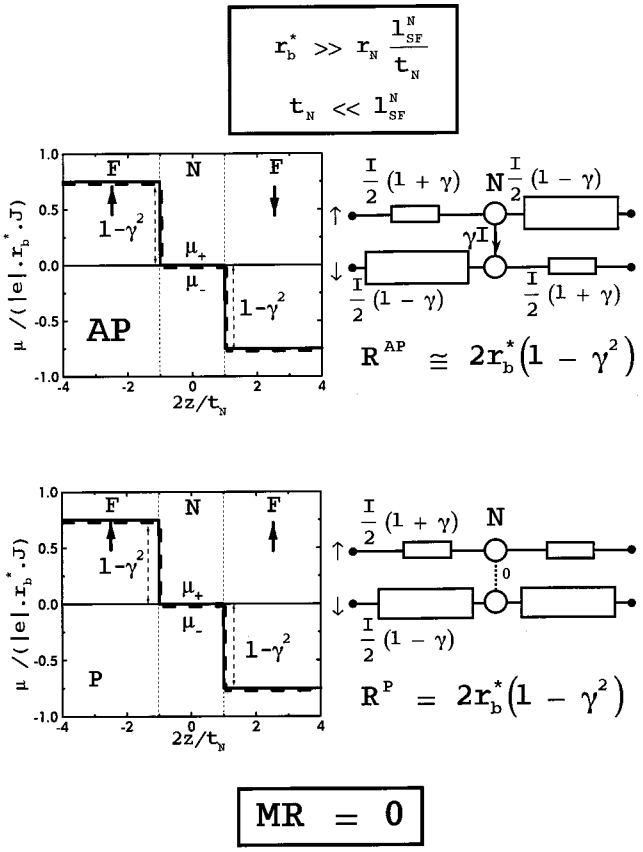

FIG. 6. Variation of the electrochemical potentials μ_+ (solid line) and μ_- (dashed line) throughout a $F/N/F$ structure having tunnel resistance r_b^* at the F/N interfaces in the range $r_b^* \gg r_N(l_{sf}^N/t_N)$. The profile of the electrochemical potential is the same in the AP (top) and P (bottom) configurations and the MR is 0. The sketches on the right indicate the equivalent resistor schemes, the current distributions and the resistances $R^{(AP)}$ and $R^{(P)}$.

Rashba[7] does not take into account that, at constant spin lifetime in N and constant current, on increasing r_b^*, the number of spin flips in N follows the rise of $\Delta\mu_N$. Consequently, his calculation does not find that, for $r_b^* > r_N(l_{sf}^N/t_N)$, the rise of $\Delta\mu_N$ saturates and the MR drops down to zero. This regime without MR will be easily understood by the readers who are familiar with the magnetic tunnel junctions. It corresponds to the situation of a double magnetic junction $F/I/N/I/F$ where I is the insulating barrier. When N is a metal and r_N is small, the condition $r_b^* \gg r_N(l_{sf}^N/t_N)$ is generally fulfilled and, as one knows, there is no MR.

We thus conclude that a $F/N/F$ structure can present a significant MR if spin dependent tunnel junctions are introduced at the F/N interfaces and if the junction resistances r_b^* are chosen in a range which can be relatively narrow, especially in the case of a ''lateral'' device of the Datta and Das type.[1] The curves of Fig. 3 have been calculated with numerical data on Co and n-type GaAs for which the spin lifetime at RT has been determined by kikkawa and Awschalom.[22] In this typical case and for $t_N = l_{sf}^N/10$, we find that the MR is restored for junction resistances around 10^{-8} $\Omega\mathrm{m}^2$. In the usual language of the research on tunnel junctions, this corresponds to 10 $\mathrm{k}\Omega$ for 1 $\mu\mathrm{m}^2$, which is a standard value for junctions with alumina barrier. The exponential dependence of the resistance with the barrier thickness makes that r_b^* can be swept in a very broad range and adapted to various types of semiconductors.

However the calculation above have been developed for a certain type of geometry [$F/N/F$ trilayer with CPP current or ''lateral'' structure of the type shown in Fig. 4(a)] and we will see in the next section that the conditions for significant MR can be somewhat different with different types of geometry.

V. STRUCTURES WITH DIFFERENT GEOMETRY

We have seen in the preceding sections that the crossover between different regimes is controlled by balance conditions between the spin relaxation in some volume of F and N or between spin relaxation in some volume of N and spin injection through a tunnel junction. This makes that different

types of geometry lead to different conditions.

We first consider a structure of the type of Fig. 4(b) similar to that of Fig. 4(a) but with a width of the N channel w smaller than that of the F channels and junctions W. Compared to the geometry with $w=W$ and for the same $\Delta\mu$, the relaxation in N is divided by the factor W/w and no longer proportional to $\Delta\mu_N t_N/er_N l_{sf}^N$ but to $\Delta\mu_N t_N w/er_N l_{sf}^N W$. Consequently the condition for having a significant current spin polarization in the P configuration and a large MR is no longer $r_b^* \gg r_N(t_N/l_{sf}^N)$ but $r_b^* \gg r_N(t_N W/l_{sf}^N w)$. The same type of scaling can be used for the upper threshold value of the junction resistance, so that the condition for having a large MR become $r_N(t_N W/l_{sf}^N w) \ll r_b^* \ll r_N(l_{sf}^N W/wt_N)$. In other words, the resistance range with MR is upscaled by the factor W/w.

In the structure of Fig. 4(c), the N layer spreads from $-\infty$ to $+\infty$ towards the left and the right in the horizontal plane, so that the spin accumulation $\Delta\mu$ spreads over l_{sf}^N on both sides of t_N. Consequently, in comparison with the preceding case, the relaxation in N is enhanced by the factor l_{sf}^N/t_N and the condition for large MR becomes $r_N(t_N/l_{sf}^N)^2(W/w) \ll r_b^* \ll r_N(W/w)$. Similar expressions can be obtained in various situations, N spreading not only to the left and the right of Fig. 4 but also in the horizontal directions perpendicular to the figure plane, two-dimensional electron gas, etc. It turns out that, depending on the geometry of the structure, the resistance range required to obtain a large MR, is shifted upward or downward. Fortunately, the exponential dependence of the tunnel resistance on the barrier thickness makes that the resistances of tunnel junctions can be chosen in an extremely broad range and adapted to various geometry types.

VI. CONCLUSIONS

We have presented a calculation of the spin injection in a semiconductor from a ferromagnetic metal at a F/SC interface and for a $F/SC/F$ structure. Our calculation extends that of Schmidt *et al.*[5] by introducing spin dependent interface resistances (in practice tunnel junctions). At a F/SC interface, in contrast with the strong reduction of the spin polarization in the semiconductor predicted in the calculation without interface resistance,[5] we find that the spin polarization can be restored to a significant level when the interface resistance r_b^* exceeds a threshold value related to the resistivity and spin diffusion length of the semiconductor, that is for $r_b^* > r_N = \rho_N^* l_{sf}^N$. For a $F/SC/F$ structure, whereas the MR (resistance difference between the P and AP configurations) is negligible without interface resistance,[5] a significant MR can be restored if the resistances r_b^* of the tunnel junctions are in the range

$$r_N \frac{t_N}{l_{sf}^N} < r_b^* < r_N \frac{l_{sf}^N}{t_N}. \tag{35}$$

This condition is at odds with the condition $r_b^* > r_N$ proposed by Rashba. Our upper limit comes from the increase of the spin relaxation rate in the semiconductor (compared to the spin injection rate) as the junction resistance and therefore the chemical potential splitting increase. The condition above is for a CPP-like device and we have also calculated how this condition is shifted in various lateral structures of the Datta and Das type. We have illustrated the results of our model by numerical calculations with parameters estimated for cobalt and a n-type GaAs semiconductor for which Kikkawa *et al.* have measured the spin relaxation time (the interest of magnetic metals with respect to magnetic semiconductors being for spin injection at room temperature, our numerical calculations are based on RT data) and we find that the conditions for efficient spin injection can be obtained with realistic values of the resistance and spin asymmetry coefficient of the tunnel junctions. We hope that our results can be an useful guide for the design of spin electronic devices combining ferromagnetic metals with semiconductors.

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which τ_{sf}/τ is temperature independent. The weak temperature dependence of r_F (or r_N) justifies the use of LT data at any temperature.

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