Enhancement of giant magnetoresistance due to spin mixing in magnetic multilayers with a superconducting contact

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We study the giant magnetoresistance (GMR) ratio in magnetic multiayers with a single superconducting contact in the presence of spin-mixing processes. It has been recently shown [F. Taddei, S. Sanvito, J. H. Jefferson, and C. J. Lambert, Phys. Rev. Lett. **82**, 4938 (1999)] that the GMR ratio of magnetic multilayers is strongly suppressed by the presence of a superconducting contact when spin flipping is not allowed. In this paper we demonstrate that the GMR ratio can be dramatically enhanced by spin-orbit interaction and/or noncollinear magnetic moments. The system is described using a tight-binding model with either *s-p-d* or *s-d* atomic orbitals per site.

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Hybrid nanostructures form a fascinating melting pot for studying the interplay between fundamental quantum phenomena, often revealing new and unexpected physics. One recently recognized class of such structures, involving the coexistence of superconducting contacts and ferromagnetic domains, has led to the identification of a number of fundamental issues,[1–7] several of which are currently unresolved. In this paper, we examine one such issue, posed by experiments on giant magnetoresistance (GMR) in magnetic (M) multilayers with superconducting (S) contacts and current-perpendicular-to-the-plane (CPP). Recognizing that the subgap conductance of such structures is mediated by Andreev scattering, it was recently noted[8] that in the absence of spin-flip processes, the conductance of a metallic (i.e., diffusive) multilayer in the presence of aligned magnetic moments is almost identical to that of the multilayer when adjacent moments are anti-aligned and therefore the conventional GMR ratio should be strongly suppressed. Since large GMR ratios are observed experimentally,[9] it is clear that even a qualitative understanding of transport in such structures must incorporate the effects of spin mixing. The aim of this paper is to present the first theoretical description of CPP GMR in M multilayers with S contacts, which incorporate spin-flip scattering. As sources of spin mixing we consider both spin-orbit (SO) coupling and noncollinear magnetizations in adjacent magnetic layers.

The system under consideration is a disordered magnetic multilayer consisting of an alternating sequence of magnetic layers each of length l_M and nonmagnetic layers (N) of length l_N. The building block of the magnetic structure is the bilayer $[M/N]$ of length $l_B = l_N + l_M$. The magnetic moments of even-numbered M layers make an angle θ relative to those of odd-numbered M layers. Experimentally, θ can be varied by applying an external magnetic field with antiparallel (AP) alignment ($\theta=\pi$) typically occurring at zero field and parallel (P) alignment ($\theta=0$) at large enough fields. The current flows perpendicular to the planes of the multilayer, which makes contact with a metallic normal lead on the left-hand side of the multilayer and a superconducting lead on the right-hand side. GMR is the drastic increase in electrical conductance $G(\theta)$ that occurs when the system switches from the AP to the P alignment with the conventional GMR ratio defined by $\rho = [G(0) - G(\pi)]/G(\pi)$.

Following,[8] the multilayer and leads are modeled using a tight-binding Hamiltonian on a cubic lattice with hoppings to nearest neighbors. Lattice imperfections and impurities are simulated by adding to the on-site energies a random number in the range $[-W/2, +W/2]$. The on-site Hamiltonian has the following structure:

$$H = \begin{pmatrix} H^{p\uparrow} & \mu_{xy} & \Delta & 0 \\ \mu_{xy}^* & H^{p\downarrow} & 0 & -\Delta \\ \Delta^\dagger & 0 & H^{h\downarrow} & -\mu_{xy} \\ 0 & -\Delta^\dagger & -\mu_{xy}^* & H^{h\uparrow} \end{pmatrix}, \tag{1}$$

where $H^{p\uparrow(\downarrow)}$ is the Hamiltonian for up (down)-spin particles (s and d bands), $H^{h\uparrow(\downarrow)} = -H^{p\uparrow(\downarrow)*}$ is the Hamiltonian for up(down)-spin holes, and Δ is the superconducting order parameter. Here $\mu_{xy} = -\mu_x + i\mu_y$, where $\mu_{x(y)}$ is the $x(y)$ component of the exchange field $\vec{\mu}$. Note that $\vec{\mu}$ is nonzero only for electrons in the d band in the M layers and Δ is nonzero only on the right-hand-side superconducting lead. Within the tight-binding formulation, SO interaction can be included by adding to the Hamiltonian the following term:

$$V_{\mathrm{SO}} = V_1 \sum_{i,j,\alpha,s} \vec{\boldsymbol{\sigma}} \cdot \vec{R}_{i,j} c_{\alpha,i}^{\sigma\dagger} c_{\alpha,j}^{-\sigma}, \tag{2}$$

where V_1 is a constant that determines the interaction strength, $\vec{\boldsymbol{\sigma}}$ is a vector of Pauli matrices, $\vec{R}_{i,j}$ is the unit vector that connects site i with the neighboring site j. $c_{\alpha,i}^{\sigma}$ is the annihilation operator for electrons of spin σ in the α (s,d) band on site i. In the presence of disorder, Eq. (2) produces spin-flip scattering since it couples electrons with different spin on neighboring sites.

In the presence of disorder, to study the largest possible sample cross sections, we consider two orbitals per site, which is the minimal model capable of reproducing scattering potential at the N/M interface and interband scattering.[10] The tight-binding parameters are chosen to reproduce the GMR ratio and conductances obtained from an *ab initio* material specific calculation for Cu/Co multilayers.[11]

In the presence of spin-flip scattering the two-spin-fluid approximation does not hold and the zero-temperature, zero-bias, normal-state Landauer formula takes the form

$$G^{\mathrm{NN}}=\frac{e^2}{h}\sum_{\sigma\sigma'}\mathrm{Tr}\{t^{\sigma\sigma'\dagger}t^{\sigma\sigma'}\},\qquad(3)$$

where $t^{\sigma\sigma'}$ is the matrix of transmission amplitudes for injected σ'-spin electrons on the left-hand lead into σ-spin electrons on the right-hand lead. When the right-hand lead is in the superconducting state, the conductance is given by[12]

$$G^{\mathrm{NS}}=\frac{e^2}{h}2\sum_{\sigma\sigma'}\mathrm{Tr}\{r_a^{\sigma\sigma'\dagger}r_a^{\sigma\sigma'}\},\qquad(4)$$

where $r_a^{\sigma\sigma'}$ is the Andreev reflection matrix for injected σ'-spin electrons in the left-hand lead to be reflected into σ-spin holes. In what follows, the scattering amplitudes are calculated exactly by solving the Bogoliubov-de Gennes equation using an efficient recursive Green's function technique.[8,11,13]

We shall now turn to the central results of this paper, namely, that in the presence of strong-enough spin mixing, either produced by SO coupling or noncollinear moments, GMR in the presence of an S contact approaches that of two normal contacts, with values of ρ of the order of 100%. First consider the effect of SO coupling within the multilayer. Figure 1 shows the conventional GMR ratio as a function of the SO interaction strength V_1 for a disordered multilayer of 40 bilayers, with $l_M=15$ and $l_N=8$. As expected, in the NN case (where both leads are in the normal state) ρ decreases monotonically from $\simeq 200\%$ at $V_1=0$, to zero at large V_1 ($\simeq 0.17$ eV). In contrast for the NS case (where the right-hand lead is now in the superconducting state) ρ initially increases with increasing V_1, eventually joining the NN curve at $V_1\simeq 0.08$ eV. As a second source of spin mixing, consider the effect of noncollinear magnetic moments when $V_1=0$. Figure 2 shows the θ dependence of the GMR ratio defined as $\rho(\theta)=[G(\theta)-G(\pi)]/G(\pi)$. Whereas in the NN case $\rho(\theta)$ decreases monotonically with increasing θ, in the NS case $\rho(\theta)$ exhibits a pronounced maximum around $\theta=\pi/8$.

To understand these results, first consider the case of noncollinear moments. In the presence of two normal-metallic contacts, the conductance $G(\theta)$ has been theoretically studied in Refs. 14 and 15 where it is predicted that $G(\theta)-G(\pi)$ tends monotonically to zero as θ varies from 0 to π. In addition, the dependence of the resistance on the angle θ

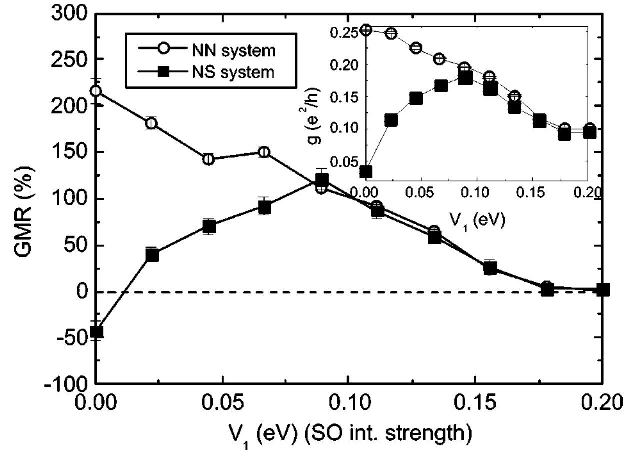

FIG. 1. Conventional GMR ratio as a function of the SO interaction strength for NN and NS cases. Results correspond to disordered multilayers ($W=0.6$ eV) comprising 40 bilayers with $l_M=15$ and $l_N=8$. Samples are formed by repeating (3×3) disordered unit cells in the transverse plane and summing over 25 k points in the two-dimensional Brillouin zone. The points are an average over 20 disorder realizations and the error bars represent the standard deviations from the mean. In the insert, comparison between the conductances in the P alignment for the NN and NS cases as functions of the SO interaction strength.

has been experimentally found[16] to contain a term proportional to $\cos^2(\theta/2)$ and a second term proportional to $\cos^4(\theta/2)$. In the presence of an S contact, where $G(0)\simeq G(\pi)$, this behavior is drastically changed by the presence of an extremum that occurs at some intermediate angle θ_c, the value of which depends on the interplay between competing effects. Since $\theta(H)$ is a function of the applied magnetic field H, the presence of an S contact introduces a new characteristic field H_c for which $\theta(H_c)=\theta_c$. For a disordered multilayer of 22 bilayers, with $l_M=30$ and $l_N=16$, the

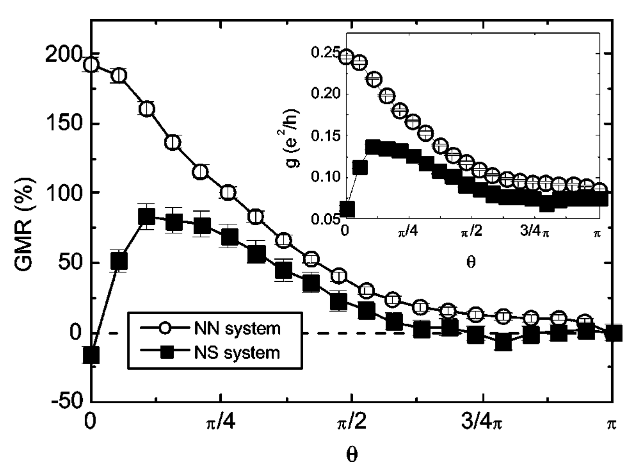

FIG. 2. θ-dependent GMR ratio for NN and NS cases in the absence of SO coupling. Results correspond to disordered multilayers ($W=0.6$ eV) of 22 bilayers with $l_M=30$, $l_N=16$, considering a (3×3) unit cell in the transverse plane, and a sum over 25 k points in the two-dimensional Brillouin zone. The points are the average over 50 realizations of disorder. In the insert, θ-dependent conductance for NN and NS cases in the absence of SO coupling.

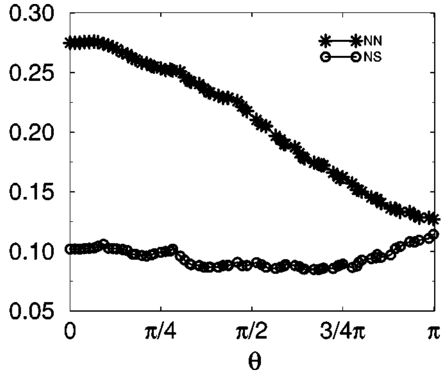

FIG. 3. θ-dependent conductance for NN and NS cases in the absence of SO coupling for a clean multilayer. The multilayer is modeled by a material-specific *spd*-band Hamiltonian (see Ref. 8), with Co as M material, Cu as N material, and Pb as S material. $l_M=7$ and $l_N=10$, considering a (1×1) unit cell in the transverse plane, summing over about 5000 k points in the two-dimensional Brillouin zone.

insert in Fig. 2 shows the θ dependence of the conductance divided by the number of open channels in the normal lead. As expected $G^{\mathrm{NN}}(\theta)$ is a monotonic function of θ, whereas $G^{\mathrm{NS}}(\theta)$ possesses an extremum at $\theta_c\simeq\pi/8$. To understand why the extremum is a maximum, recall that for $\theta=0$ or $\theta=\pi$, when spin is conserved, current flows when a right-going (spin σ) electron passes through the multilayer, Andreev reflects as a left-going (spin $-\sigma$) hole, which retraverses the multilayer. An M layer whose moment is aligned with the spin of the incident electron is antialigned with the spin of the outgoing hole and consequently the number of aligned and antialigned M layers encountered by a given quasiparticle is the same for both $\theta=0$ and $\theta=\pi$ (only the order differs). When the elastic mean-free-path is comparable with the total multilayer length, the resistance of traversed layers add in series and therefore, apart from small differences due to interference effects,[17] $G^{\mathrm{NS}}(0)\simeq G^{\mathrm{NS}}(\pi)$. Furthermore, since a quasiparticle must necessarily traverse regions in which it is a minority spin, both $G^{\mathrm{NS}}(0)$ and $G^{\mathrm{NS}}(\pi)$ are low-conductance states. In contrast, as θ increases from zero, this conductance bottleneck is removed, because an Andreev reflected minority hole can spin convert to a majority hole, thereby avoiding antialigned moments on its return journey. Of course this initial increase in $G^{\mathrm{NS}}(\theta)$ is eventually overcome by the usual GMR effect that decreases $G^{\mathrm{NS}}(\theta)$ as $\theta\rightarrow\pi$, thereby producing an overall maximum.

In the absence of disorder, the nature of the extremum is determined by interface scattering and band structure. To illustrate this consider a clean multilayer that is perfectly periodic and therefore the variation of the conductance with θ arises from tuning of the ballistic spin filtering by the structure. Figure 3 shows the conductance divided by the number of open channels in the left-hand side normal lead. As expected, $G^{\mathrm{NN}}(\theta)$ is a monotonic function of θ, whereas $G^{\mathrm{NS}}(\theta)$ exhibits a minimum around $\pi/2$ and then increases. (In this case, translational invariance in the transverse direction allowed us to use a full *ab initio*, *spd* Hamiltonian to obtain the results of Fig. 3.) In the NN case, the dependence

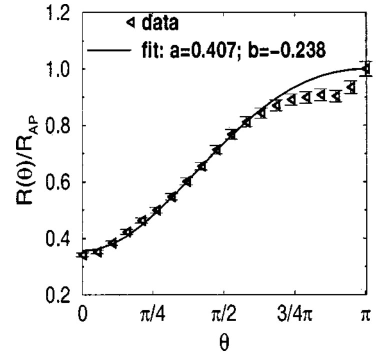

FIG. 4. Plot of the ratio $R(\theta)/R(\pi)$ along with the best fit to the function (5). The value of the fitting parameters are $a=0.407$ and $b=-0.238$. Results correspond to a disordered multilayer with the same parameters as in Fig. 2.

of the multilayer resistance on θ predicted by our model is in good agreement with experiment.[16] In Ref. 16 the ratio between the resistance at a given θ and the resistance with AP alignment has been found to fit the following function:

$$\frac{R(\theta)}{R(\pi)}=1-a\cos^2(\theta/2)+b\cos^4(\theta/2), \tag{5}$$

where a and b are fitting constants. In Fig. 4 we show the plot of such a ratio for the disordered multilayer considered above, along with the best fit to function (5). In addition we also checked that this ratio cannot be fitted with the same accuracy assuming a pure dependence on $\cos^2(\theta/2)$ (i.e., with $b=0$). For $G^{\mathrm{NS}}(\theta)$ however, no such analytic results currently exist.

Let us now turn attention to the effect of SO coupling. Figures 5(a) and 5(b) show the conductances as a function of the SO strength V_1 for, respectively, the NN and the NS case. In the NN case [Fig. 5(a)] G_P^{NN} decreases as V_1 increases and eventually joins the curve for $G_{\mathrm{AP}}^{\mathrm{NN}}$. This can be understood in terms of the heuristic model presented in Ref. 1, because, as the SO strength increases, the average length

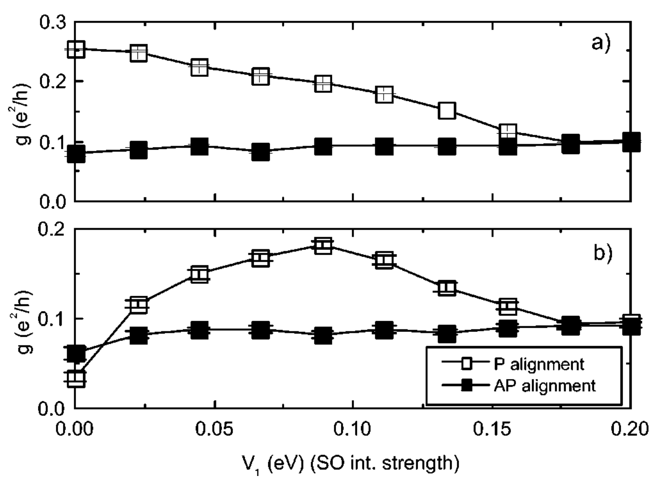

FIG. 5. Conductances for P and AP alignments as functions of the SO interaction strength for the NN case (a) and for the NS case (b). Results correspond to a disordered multilayer with the same parameters as in Fig. 1.

required for a spin to flip (spin relaxation length λ_{sf}) gets shorter. Therefore in the P alignment, an injected majority electron travels through the multilayer for a length λ_{sf} before being scattered into a minority spin, thereby producing a decrease in the conductance. This suggests that the value of V_1 for which $G_P^{\mathrm{NN}} \simeq G_{\mathrm{AP}}^{\mathrm{NN}}$ corresponds to a spin-relaxation length λ_{sf} close to the period l_B of the multilayer. We have carried out a range of simulations that show that this value of V_1 does not depend on the overall length of the multilayer, but decreases with increasing l_B. As expected, the conductance with AP alignment does not change significantly with V_1.

In the NS case [Fig. 5(b)] the conductance in the P aligned state rapidly increases with V_1, reaching a maximum and thereafter decreases, eventually joining the curve for the AP configuration. Clearly the enhancement in G_P^{NS} is produced by the onset of spin-flip scattering. The abrupt increase is understandable, since even a relatively small probability for spin flipping opens a highly conductive ''channel'' if the spin-flip events take place in the vicinity of the interface. As one can see in the insert of Fig. 1 for larger values of V_1, the conductance G_P^{NS} joins G_P^{NN} and together they decrease thereafter. As in the normal case $G_{\mathrm{AP}}^{\mathrm{NS}}$ depends weakly on V_1. The value $V_1 \simeq 0.08$, at which G^{NS} is maximum, corresponds to a spin-relaxation length close to the total length of the multilayer and, as expected, separate simulations show that this value of V_1 decreases with increasing total length. Similarly the value of V_1 at which the GMR ratio (of Fig. 1) vanishes corresponds to a spin-relaxation length of the order of the bilayer thickness l_B and is independent of the total length of the system.

In conclusion, we have demonstrated that spin mixing plays a crucial role in determining both the qualitative and quantitative features of GMR in magnetic multilayers with a S contact. In contrast with the normal case, where spin mixing suppresses GMR, we find that the GMR ratio can be dramatically enhanced by the presence of spin-orbit interactions and/or noncollinear magnetic moments. In experiments carried out to date, the presence of large spin-orbit scattering[18] presumably masks the mechanism shown in Fig. 2, which is predicted to be a generic feature in the absence of other spin mixing processes. This suggests that lighter metals and superconductors would be more appropriate for observing the extrema predicted in this paper. Finally we note that for the future it would be of interest to examine spin mixing in nondiffusive NS structures such as clean spin valves,[19] where the GMR ratio can be nonzero or negative, even in the absence of spin-flip processes.

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