Crossed Andreev Reflection-Induced Magnetoresistance

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(Received 5 December 2005; published 23 August 2006)

We show that very large negative magnetoresistance can be obtained in magnetic trilayers in a current-in-plane geometry owing to the existence of *crossed* Andreev reflection. This spin valve consists of a thin superconducting film sandwiched between two ferromagnetic layers whose magnetization is allowed to be either parallelly or antiparallelly aligned. For a suitable choice of structure parameters and nearly fully spin-polarized ferromagnets, the magnetoresistance can exceed −80%. Our results are relevant for the design and implementation of spintronic devices exploiting ferromagnet-superconductor structures.

DOI: 10.1103/PhysRevLett.97.087001 PACS numbers: 74.45.+c, 72.25.−b, 85.75.−d

Giant magnetoresistance (GMR) is the pronounced response in the resistance of magnetic multilayers to an applied magnetic field [1–5]. This phenomenon has prompted a very large interest owing to its broad range of applications, spanning from magnetic recording to position sensor technology, and to the fundamental interest in spin-dependent effects [4]. A magnetic multilayer consists of an alternating sequence of ferromagnetic (F) and nonmagnetic layers (N). The relative orientation of magnetic moments in the F layers can be driven from antiparallel (AP), in the absence of external field, to parallel (P), with a small (up to some hundreds of oersteds) magnetic field. GMR was originally demonstrated [5] in Fe/Cr multilayers with current flowing parallel to the planes, the so-called current-in-plane (CIP) configuration. In the CIP measurement, the magnetoresistance (MR) ratio, defined as the maximum relative change in resistance resulting from applying the external field, is typically around 10% for a number of layers of the order of 50–100 [5]. These values can be increased up to ~100% in the case of current flow perpendicular to the multilayer plane (CPP configuration) [6].

In this Letter, we show that the limitations of the CIP configuration can be overcome by employing a *superconductor* (S) in the nonmagnetic portion of the multilayer. The use of superconductors in spintronics is not new. As a matter of fact, superconductors were used already in the very first CPP experiment [6] in order to minimize the extra resistance introduced in contacting the multilayered structure to the measuring apparatus. The peculiar properties of FS structures have been studied for several years and this field has been recently reviewed in Ref. [7].

The structure we envision (see Fig. 1) consists of two identical diffusive ferromagnetic layers (F_1 and F_2), of thickness t_F, separated by a (s-wave) superconducting layer of thickness t_S. The layers are assumed to be in good metallic contact and have length L and width w. The magnetization of the two ferromagnets is allowed to be aligned in either a parallel or an antiparallel configuration [8]. The trilayer is connected to ferromagnetic leads separated by an insulating layer (light-yellow regions in Fig. 1) of the same thickness as the S layer. The magnetization of the upper F leads is equal to the one relative to layer F_1 and, analogously, for the lower F leads. In the CIP

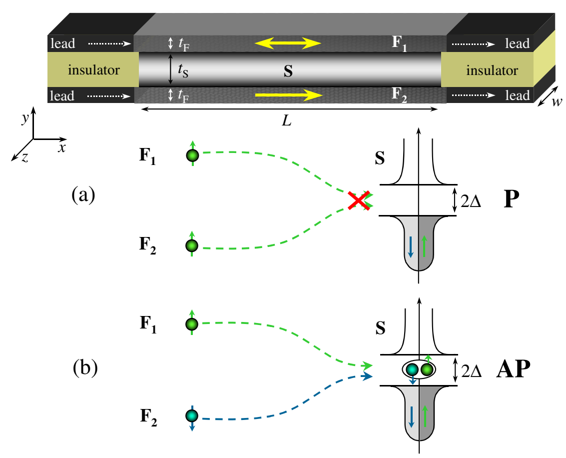

FIG. 1 (color online). Sketch of the FSF spin valve. A thin superconducting film is sandwiched between two identical ferromagnetic layers whose magnetizations (yellow arrows) can be aligned in both the parallel (P) and antiparallel (AP) configurations. An electric current (white dashed arrows) is allowed to flow through the system parallel to the layers. The schematic representation of the spin-valve effect for *half-metallic* ferromagnets, showing the diagrams of the superconducting density of states, is displayed in (a) and (b). (a) In the P alignment, the lack of quasiparticles with opposite spin hinders the condensation of two electrons injected from the ferromagnets in a Cooper pair in S. As a consequence, the electric transport is confined within the F layers. (b) In the AP configuration, two electrons with opposite spin injected from the F layers can form a Cooper pair within the superconductor thanks to crossed Andreev reflection, thus "shunting" the current through the whole structure (see text).

configuration, charge transport in the system is dominated by *crossed* Andreev reflection (CAR) leading to a dramatic enhancement of the magnetoresistance. CAR was analyzed in several papers [9], notably in relation to quantum information processing [10], and very recently it was observed experimentally in *FS* [11] and in *NS* [12] structures. Here we emphasize its potential for spintronics.

Let us first describe qualitatively the principle of operation of the present spin valve. For the sake of clarity, let us first consider a *half-metallic* (i.e., with only one spin species) ferromagnet [13] in good metallic contact with a *S* layer. Quasiparticles with energy below the superconductor gap can be transferred into the superconductor as Cooper pairs only through an Andreev reflection (AR) process [14]. The latter consists of a coherent scattering event in which a spin-up (-down) electronlike quasiparticle, originating from the *F* layer, is retroreflected at the interface with the superconductor as a spin-down (-up) holelike quasiparticle into the ferromagnet. Since only quasiparticles (electron- and holelike) of one spin type exist in the ferromagnet, no current can flow between the *F* and *S* layers [15]. Similarly, in the case of the *FSF* trilayer in the *P* configuration [see Fig. 1(a)], the two *F* layers cannot transfer charge into the superconductor. Current is confined to the *F* layers, and it consists of fully polarized quasiparticles. If the *S* layer is thin enough, quasiparticles can also tunnel through it [this will occur for t_S values up to some superconductor coherence lengths (ξ_0)]. In the *AP* configuration [see Fig. 1(b)], each of the two *F* layers can contribute separately to the quasiparticle current through the structure just like in the *P* configuration. More importantly, CAR does take place. In this case, a Cooper pair is formed in the superconductor by a spin-up electron originating from the F_1 layer and a spin-down electron from the F_2 layer. In the AR language, this can be described as the transmission of a spin-up electronlike quasiparticle from one of the *F* layers to a spin-down holelike quasiparticle in the other *F* layer. This is now possible since the quasiparticles involved belong to the majority spin species in each of the two layers. A charge current can therefore flow through the *S* layer as a supercurrent, thereby shunting the conduction channels in the ferromagnets [16]. This contribution to the current will dominate, at least when the structure is long enough and the quasiparticle contribution in the *F* layers becomes negligible (note that the conductance of each *F* layer in the diffusive regime is proportional to ℓ/L, where $\ell \ll L$ is the mean free path). As a result, one can expect the conductance G_{AP} of the *AP* configuration to be much larger than the conductance G_P of the *P* configuration. This can give rise to a large, *negative* value of the MR ratio, defined as:

$$\mathrm{MR} = \frac{G_P - G_{AP}}{G_P}. \tag{1}$$

A simple expression for the MR ratio for half-metallic ferromagnets in the diffusive regime can be derived as follows. In the *P* configuration, the conductance is approximately given by [15]

$$G_P \simeq 2\frac{e^2}{h}\frac{\ell}{L}N_\uparrow; \tag{2}$$

i.e., it is proportional to the number $N_\uparrow$ of open channels for spin-up electrons of each *F* layer and inversely proportional to L. In the *AP* configuration, the conductance can be roughly separated in two contributions. One (G^*), due to CAR, is virtually *independent* of L. The other comes from the direct transmission of quasiparticles [proportional to $(2e^2/h)(\ell/L)N_\uparrow$]:

$$G_{AP} \simeq G^* + \alpha 2\frac{e^2}{h}\frac{\ell}{L}N_\uparrow, \tag{3}$$

with α being a numerical factor ~ 1. As a result,

$$\mathrm{MR} \simeq 1 - \alpha - G^*\frac{h}{2e^2}\frac{L}{\ell}\frac{1}{N_\uparrow}, \tag{4}$$

negative and large for $L \gg \ell$. This is in contrast to what expected in a *FNF* trilayer, where the MR value is *positive* [5] since the *AP* configuration yields a reduction of the structure conductance. For non-half-metallic ferromagnets, the charge current will still be dominated by CAR, but the effect will be reduced.

This qualitative understanding of the effect can be validated by a numerical calculation of the conductance, which was performed within the Landauer-Büttiker scattering approach. In the presence of superconductivity, the zero-temperature and zero-bias conductance can be written as $G = G_\uparrow + G_\downarrow$ [17], where

$$G_\sigma = \frac{e^2}{h}\left[\mathcal{T}^\sigma + \mathcal{T}_a^\sigma + 2\frac{\mathcal{R}_a^\sigma\mathcal{R}_a^{\sigma\prime} - \mathcal{T}_a^\sigma\mathcal{T}_a^{\sigma\prime}}{\mathcal{R}_a^\sigma + \mathcal{R}_a^{\sigma\prime} + \mathcal{T}_a^\sigma + \mathcal{T}_a^{\sigma\prime}}\right] \tag{5}$$

is the spin-dependent conductance [18]. In Eq. (5), $\mathcal{T}^\sigma$ ($\mathcal{T}_a^\sigma$) is the spin-dependent normal (Andreev) transmission probability for quasiparticles injected from the left lead and arriving on the right lead, while $\mathcal{R}_a^\sigma$ is the Andreev reflection probability for quasiparticles injected from the left lead [19]. Similarly, $\mathcal{T}_a^{\sigma\prime}$ and $\mathcal{R}_a^{\sigma\prime}$ are the Andreev scattering probabilities for quasiparticles injected from the right lead. e is the electron charge and h is the Planck constant. The scattering amplitudes were evaluated numerically by making use of a recursive Green's function technique based on a tight-binding version [20] of the Bogoliubov-de Gennes equations

$$\begin{pmatrix} \mathcal{H} & \Delta \\ \Delta^* & -\mathcal{H}^* \end{pmatrix}\begin{pmatrix} u \\ v \end{pmatrix} = E\begin{pmatrix} u \\ v \end{pmatrix}, \tag{6}$$

where $\mathcal{H}$ is the single-particle Hamiltonian, and u (v) is the coherence factor for electronlike (holelike) excitations of energy E, measured from the condensate chemical potential μ. Within the tight-binding description, $\mathcal{H}$ and Δ are matrices with elements $(\mathcal{H})_{ij} = \epsilon_i\delta_{ij} - \gamma\delta_{\{i,j\}}$ and

$(\Delta)_{ij} = \Delta_i \delta_{ij}$, where ϵ_i is the on-site energy at site i, γ is the hopping potential, and Δ_i is the superconducting gap ($\{\ldots\}$ stand for first-nearest-neighbor sites). In particular, $\epsilon_i = \epsilon_S$ in the S region, $\epsilon_i = \epsilon_I$ in the insulating barrier, and $\epsilon_i = \epsilon_F = \epsilon_S \mp h_{\mathrm{exc}}$ in the F layers, h_{exc} denoting the ferromagnetic exchange energy, with the upper (lower) sign referring to the majority (minority) spin species. Δ_i is assumed to be constant and equal to a zero-temperature gap (Δ_0) in the S region and zero everywhere else. Note that this is realistic when the S layer thickness is larger than ξ_0 [21]. Furthermore, disorder due both to impurities and lattice imperfections is introduced by the Anderson model, i.e., by adding to each on-site energy a random number chosen in the range $[-U/2, U/2]$, U being a fraction of the Fermi energy. In what follows, we shall indicate energies in units of Δ_0 and lengths in units of the lattice constant a (of the order of the Fermi wavelength).

In order to analyze the behavior of conductances and MR as a function of the various parameters, we used a two-dimensional (2D) model of the structure; i.e., we assumed a single lattice site in the z direction (see Fig. 1). In our calculations, the tight-binding parameters were chosen to describe metallic materials: $\epsilon_S = 20$, $\epsilon_I = 10^3$, $\gamma = 10$, so that $\xi_0 = (2a/\pi)\sqrt{4(\gamma/\Delta_0)^2 - \epsilon_0\gamma/\Delta_0^2} = 9.0$. We set $U = 8$ and $L = 150$, so that the F layers are in the diffusive regime. To avoid a self-consistent calculation of the superconducting gap, we limited our analysis to values of $t_S \geq 30$ (corresponding to $\simeq 3.3\xi_0$) [21,22]. In addition, the conductance was calculated by performing an ensemble average over 100 realizations of disorder.

The conductance and MR dependence on S layer thickness is shown in Fig. 2. Here we chose the ferromagnetic thickness $t_F = 5$ and $h_{\mathrm{exc}} = 20$ (the mean free path turns out to be $\ell \simeq 21$). For this latter value, the ferromagnet polarization ($\mathcal{P}$) [23] is equal to 100%. Figure 2(a) shows that in the P configuration the conductance G_P is initially slightly decreasing and roughly constant for $t_S \gtrsim 5.5\xi_0$. This is due to the fact that quasiparticles in the two F layers (for large enough t_S values $\gtrsim 5.5\xi_0$) are decoupled, but some direct tunneling can occur through thinner S layers. In the AP configuration, the conductance G_{AP} decreases until the value $t_S \simeq 8.5\xi_0$ is reached and thereafter remains almost constant. Such a behavior is expected since, on the one hand, for t_S of the order of some ξ_0, the conductance is dominated by the supercurrent (mediated by CAR between the F_1 and F_2 layers). On the other hand, by increasing t_S, the two F layers tend to decouple and the current through the structure is only due to quasiparticles flowing separately through them, independently of t_S. The resulting MR ratio is shown in Fig. 2(b) and exhibits very large negative values around -70% for $t_S \simeq 3.5\xi_0$ and about -25% for $t_S \simeq 6.5\xi_0$. It is noteworthy to mention that when the S layer is in the normal state (i.e., a FNF trilayer) MR $\simeq (0.7 \pm 1.8)\%$ for $t_S = 4.5\xi_0$.

The role of the F layer thickness on the conductance and magnetoresistance is analyzed in Fig. 3, for fixed $t_S = 40$ and $\mathcal{P} = 100\%$. Figure 3(a) shows that the conductance in the P alignment increases linearly with t_F according to the estimate in Eq. (2). In the AP configuration, the conductance is again linear in t_F with the same slope, but it is shifted upwards as compared to G_P. This is in agreement with Eq. (3): the difference $G_P - G_{AP} \sim G^*$. As a consequence, the MR ratio [see Fig. 3(b)] starts from $\simeq -70\%$ at $t_F \simeq 0.5\xi_0$ and thereafter decreases by increasing the value of t_F.

We finally analyze the behavior of MR, for $t_S = 40$ and $t_F = 5$, as a function of the polarization of the F layers. Figure 4 shows that the value of the MR ratio remains smaller than $\sim -30\%$ up to $\mathcal{P} \simeq 87\%$ and then grows to larger negative values. Highly spin-polarized ferromagnets are thus required for the effect to be maximized. The fluctuations present in the MR($\mathcal{P}$) curve can be ascribed

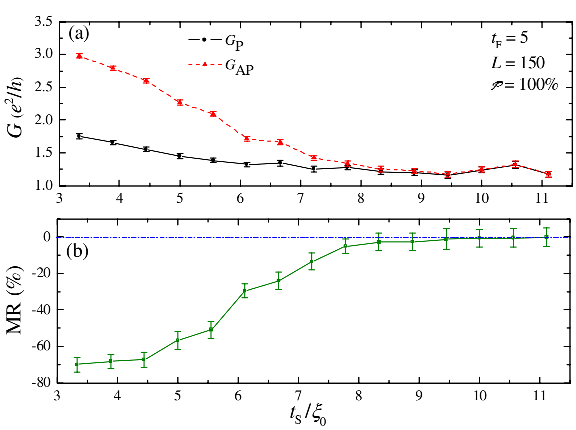

FIG. 2 (color online). (a) Conductance in the P (black circles) and AP (red triangles) configurations versus t_S with $t_F = 5$. (b) Resulting MR ratio. Data were obtained assuming $L = 150$, $\mathcal{P} = 100\%$, and $U = 8$ (see text). In (a), the error bars correspond to the standard error over all disorder configurations. Lines are guides to the eye.

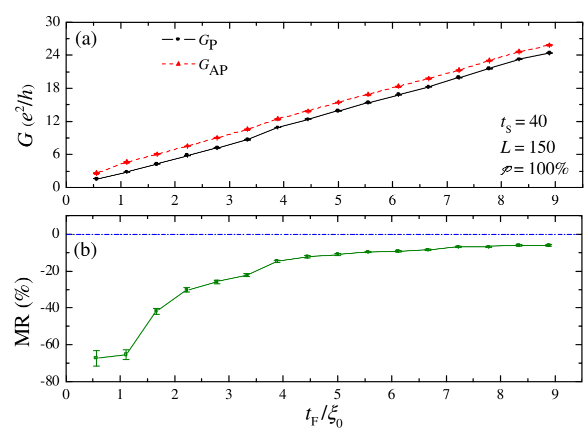

FIG. 3 (color online). (a) Conductance in the P (black circles) and AP (red triangles) configurations versus t_F with $t_S = 40$. (b) Resulting MR ratio. The same parameters as for Fig. 2 were used.

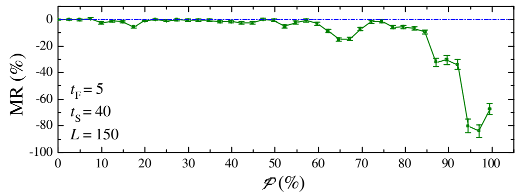

FIG. 4 (color online). MR ratio versus $\mathcal{P}$ with $t_S = 40$ and $t_F = 5$. The same parameters as for Fig. 2 were used.

to opening and closing of conducting channels in the F layers as well as to size effects.

A 3D structure was also considered, allowing the system to extend in the z direction (see Fig. 1). The calculations, performed for several values of the structure width (w), confirmed qualitatively the overall results found in the 2D case. We finally stress the importance of a good metallic contact between F and S layers. The presence of a barrier at the FS interface would indeed lead to a suppression of CAR and therefore of the MR value.

In conclusion, we have investigated theoretically spin transport in a ferromagnet-superconductor-ferromagnet trilayer in the current-in-plane geometry. We showed that very large and negative magnetoresistance values (exceeding -80%) can be achieved. Such an effect relies entirely on the existence of crossed Andreev reflection. The results presented here are promising in light of the implementation of novel-concept magnetoresistive devices such as, for instance, spin switches as well as magnetoresistive memory elements. To this end, half-metallic ferromagnets such as CrO_2 [13,24], NiMnSb [25], Sr_2FeMoO_6 [26], and $La_{2/3}Sr_{1/3}MnO_3$ [27] appear as particularly suitable. Also, the $Ga/Ga_{1-x}Mn_xAs$ material system, exploiting a superconductor in combination with heavily doped ferromagnetic semiconductor layers, appears to be a good candidate for the implementation of this structure, thanks to the $Ga_{1-x}Mn_xAs$ predicted half-metallic nature (for $x \geq 0.125$) [28] and to its well-developed technology [29].

We thank V. Dediu, M. V. Feigel'man, and S. Sanvito for valuable discussions. This work was partially supported by MIUR under FIRB "Nanotechnologies and Nanodevices for Information Society" Contract No. RBNE01FSWY.

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