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Spin-accumulation-induced resistance in mesoscopic ferromagnet-superconductor junctions

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We present a description of spin-polarized transport in mesoscopic ferromagnet-superconductor (F/S) systems, where the transport is diffusive and the interfaces are transparent. It is shown that the spin reversal associated with Andreev reflection generates an excess spin density close to the F/S interface, which leads to a spin contact resistance. Expressions for the contact resistance are given for two-terminal and four-terminal geometries. In the latter the sign depends on the relative magnetization of the ferromagnetic electrodes.
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Andreev reflection (AR) is the elementary process which enables electron transport across a normal metal-superconductor (N/S) interface, for energies below the superconducting energy gap Δ.[1] The incoming electron with spin-up takes another electron with spin-down to enter the superconductor as a Cooper pair with zero spin. This corresponds to a reflection of a positively charged hole with a reversed spin direction.

The spin reversal has important consequences for the resistance of a ferromagnetic-superconductor (F/S) interface. A suppression of the transmission coefficient has been reported in F/S multilayers,[2] and in transparent ballistic F/S point contacts a reduction of the conductance has been predicted and observed.[3–5] In F/S point contacts the Andreev reflection process is limited by the lowest number of the available spin-up and spin-down conductance channels, which are not equal due to a separation of the spin bands in the ferromagnet, caused by the exchange interaction. However, in most experiments the dimensions of the sample exceed the electron mean free path l_e, and therefore the electron transport cannot be described ballistically.

We present a description for spin-polarized transport in diffusive F/S systems, in the presence of Andreev reflection for temperatures and energies below Δ.[6] We will show that the AR process at the F/S interface causes a spin accumulation close to the interface, due to the different spin-up and spin-down conductivities $\sigma_\uparrow$ and $\sigma_\downarrow$ in the ferromagnet.

In a first approximation we will ignore the effects of phase coherence in the ferromagnet, which in the presence of a superconductor can give rise to the proximity effect.[7–10] The spin-flip length (λ_{sf}^F) of the electrons in the ferromagnet, which is the distance an electron can diffuse before its spin direction is randomized, is much larger than the exchange interaction length. This means that all coherent correlations in the ferromagnet are expected to be lost beyond the exchange length, but the spin of the electron is still conserved.

Transport in a diffusive metallic ferromagnet is usually described in terms of its spin-dependent conductivities $\sigma_{\uparrow,\downarrow} = e^2 N_{\uparrow,\downarrow} D_{\uparrow,\downarrow}$, where $N_{\uparrow,\downarrow}$ are the spin-up and spin-down density of states at the Fermi energy and $D_{\uparrow,\downarrow}$ the spin-up and spin-down diffusion constants.[11–14] In a homogeneous one-dimensional (1D) ferromagnet, the current carried by both spin directions ($j_{\uparrow,\downarrow}$) is distributed according to their conductivities:

$$j_{\uparrow,\downarrow} = -\left(\frac{\sigma_{\uparrow,\downarrow}}{e}\right)\frac{\partial \mu_{\uparrow,\downarrow}}{\partial x}, \tag{1}$$

where $\mu_{\uparrow,\downarrow}$ are the electrochemical potentials of the spin-up and spin-down electrons, which are equal in a homogeneous system. In a nonhomogeneous system, however, where current is injected into or extracted from a material with different spin-dependent conductivities, the electrochemical potentials can be unequal. This is a consequence of the finite spin-flip scattering time τ_{sf}, which is usually considerably longer than the elastic scattering time τ_e. The transport equations therefore have to be supplemented by

$$D\frac{\partial^2(\mu_\uparrow - \mu_\downarrow)}{\partial^2 x} = \frac{\mu_\uparrow - \mu_\downarrow}{\tau_{sf}}, \tag{2}$$

where $D = \{[N_\downarrow/(N_\uparrow + N_\downarrow)D_\uparrow] + [N_\uparrow/(N_\uparrow + N_\downarrow)D_\downarrow]\}^{-1}$ is the spin-averaged diffusion constant. Equation (2) describes that the difference in μ decays over a length scale $\lambda_{\mathrm{sf}} = \sqrt{D\tau_{sf}}$, the spin-flip length.

To describe the F/S system, the role of the superconductor has to be incorporated. We assume that the interface resistance itself can be ignored, which is justified in metallic diffusive systems with transparent interfaces. The Andreev reflection can then be taken into account by the following boundary conditions at the F/S interface ($x=0$):

$$\mu_\uparrow|_{x=0} = -\mu_\downarrow|_{x=0}, \tag{3}$$

$$j_\uparrow|_{x=0} = j_\downarrow|_{x=0}. \tag{4}$$

Here the electrochemical potential of the superconductor S is set to zero. Equation (3) is a direct consequence of AR, where an excess of electrons with spin-up corresponds to an excess of holes and therefore a deficit of electrons with spin-down and vice versa. Equation (4) arises due to the fact that the total Cooper pair spin in the superconductor is zero, so there can be no net spin current across the interface. Note

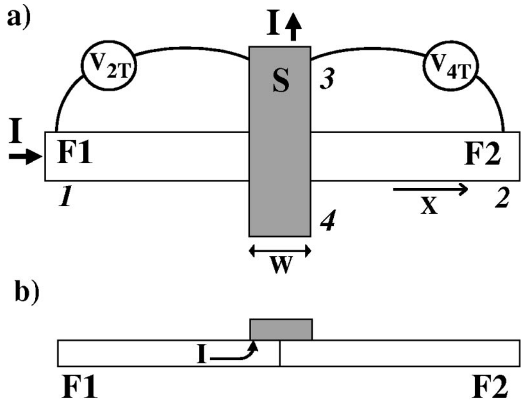

FIG. 1. (a) Top view of a cross type F/S geometry. S is the superconducting strip on top of two ferromagnetic strips $F1$ and $F2$. The magnetization of $F2$ can be parallel or antiparallel to the magnetization of $F1$. The x axis is taken along the ferromagnetic strips, where from $x=0$ to $x=W$ the superconducting strip covers the ferromagnetic strips. (b) Side view.

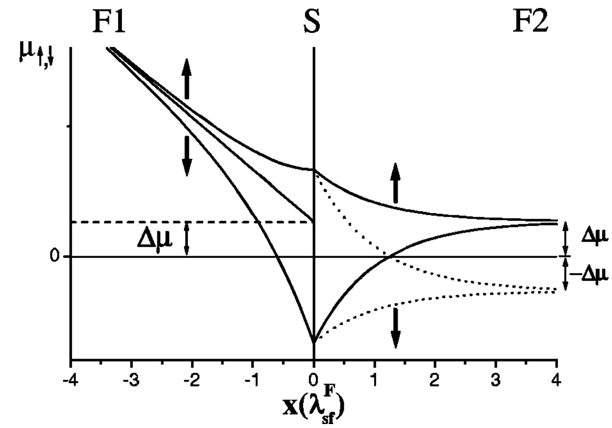

FIG. 2. Electrochemical potential in the ferromagnetic strip of Fig. 1 as a function of distance along the x axis in units of the spin-flip length λ_{sf}^F. The potential of the superconductor at $x=0$ is set to zero. The solid curves at $x>0$ yield the chemical potentials for the two spin directions when the ferromagnetic electrode $F2$ is magnetized parallel to the magnetization of $F1$. The dotted curves yield the electrochemical potentials for antiparallel magnetization.

that for Eqs. (3) and (4) to be valid, no spin-flip processes are assumed to occur at the interface as well as in the superconductor.

Equations (1)–(4) now allow the calculation of the spatial dependence of the electrochemical potentials of both spin directions, which have the general forms

$$\mu_{\uparrow}=A+Bx+\frac{C}{\sigma_{\uparrow}}e^{x/\lambda_{sf}^F}+\frac{D}{\sigma_{\uparrow}}e^{-x/\lambda_{sf}^F}, \tag{5}$$

$$\mu_{\downarrow}=A+Bx-\frac{C}{\sigma_{\downarrow}}e^{x/\lambda_{sf}^F}-\frac{D}{\sigma_{\downarrow}}e^{-x/\lambda_{sf}^F}, \tag{6}$$

where A, B, C, and D are constants defined by the boundary conditions. For simplicity we first calculate the contact resistance at the F/S interface in a two-terminal configuration, noted by V_{2T} in Fig. 1(a), ignoring the presence of the second ferromagnetic electrode $F2$. In this configuration we find

$$\mu_{\uparrow}|_{x=0}=-\mu_{\downarrow}|_{x=0}=\frac{\alpha_F\lambda_{sf}^F eI}{\sigma_F(1-\alpha_F^2)A}, \tag{7}$$

where $\alpha_F=(\sigma_{\uparrow}-\sigma_{\downarrow})/(\sigma_{\uparrow}+\sigma_{\downarrow})$ is the spin polarization of the current in the bulk ferromagnet, and λ_{sf}^F, $\sigma_F=\sigma_{\uparrow}+\sigma_{\downarrow}$, and A are the spin-flip length, the conductivity, and the cross-sectional area of the ferromagnetic strip, respectively. Note that at the interface the electrochemical potentials are finite, despite the presence of the superconductor. This is illustrated in the left part of Fig. 2, where the spin-up and spin-down electrochemical potentials are plotted as a function of x in units of λ_{sf}^F. Defining a contact resistance as $R_{FS}=\Delta\mu/eI$ at the F/S interface yields[15]

$$R_{FS}=\frac{\alpha_F^2\lambda_{sf}^F}{\sigma_F(1-\alpha_F^2)A}. \tag{8}$$

Note that this is exactly half the resistance which would be measured in a two-terminal geometry of one ferromagnetic electrode directly coupled to another ferromagnetic electrode with antiparallel magnetization. One may therefore consider the F/S interface as an ''ideal'' domain wall (which does not change the spin direction), the superconductor acting as a magnetization mirror.

The presence of the contact resistance at a F/S boundary clearly brings out the difference between a superconductor and a normal conductor with infinite conductivity. In the latter case the boundary condition Eq. (3) at the interface is replaced by $\mu_{\uparrow}=\mu_{\downarrow}=0$, and no contact resistance would be generated.[11,12] An interesting feature to be noticed from Fig. 2 is that the electrochemical potential of the minority spin at the interface is *negative*.

The second observation to be made here is that the excess charge density $n_c\sim\mu_{\uparrow}+\mu_{\downarrow}$ is zero, whereas the spin density $n_s\sim\mu_{\uparrow}-\mu_{\downarrow}$ has a maximum close to the interface. This is a direct consequence of the AR process, where a net spin current is not allowed to enter the superconductor. Continuity of the spin currents at the F/S interface results in a spin accumulation in the ferromagnet, being built up over a distance of the spin-flip length λ_{sf}^F.

The magnitude of the spin-dependent contact resistance is in the range 20–100 mΩ, depending on the exact conductivity of the ferromagnetic strip σ_F, the spin-flip length λ_{sf}^F, and the spin polarization α_F, and can be easily measured in a multiterminal geometry.[17,18]

To identify the contact resistance, the four-terminal resistance is measured by sending a current through terminals 1 and 3, and measuring the voltage between terminals 2 and 4, as illustrated by V_{4T} in Fig. 1(a). We assume that all current flows into the superconductor at $x=0$, which is reasonable to assume when the thickness d_F of the ferromagnetic strip is small compared to the width W of the superconductor and the width W of the superconductor is in the order of the spin-flip length of the ferromagnetic strip, $d_F<W\lesssim\lambda_{sf}^F$ [cf. Fig. 1(b)]. Now the second ferromagnetic electrode ($F2$) has to be included in the calculation. This is done by requiring Eqs. (3) and (4) to include the spin currents of both ferromagnetic electrodes and requiring their spin-up and down-spin electrochemical potentials to be continuous. For the re-

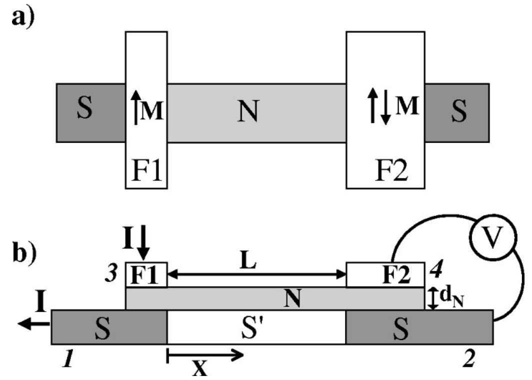

FIG. 3. (a) Top view of an $F/N/S$ geometry. N is a normal metal strip coupling to the two superconducting strips S. In the region S' a superconductor may be present (see text). On top of the normal metal two ferromagnetic strips $F1$ and $F2$ are placed. (b) Side view, terminals 3 and 1 are used for current injection and extraction, whereas terminals 2 and 4 measure the voltage. M refers to the magnetization of the ferromagnetic electrodes $F1$ and $F2$. L is the distance between the two ferromagnetic electrodes and d_N is the thickness of the normal metal.

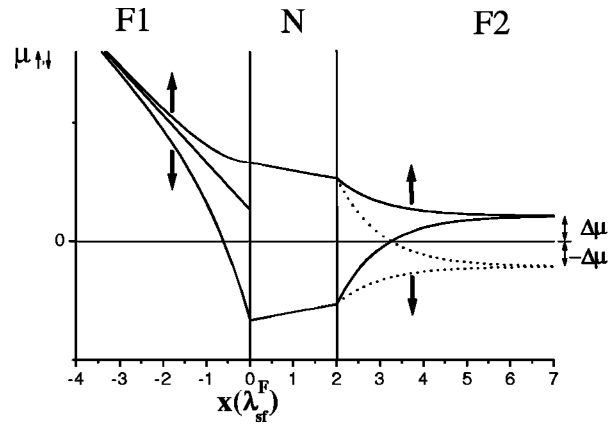

FIG. 4. Electrochemical potential versus distance. The coordinate $x=0$ defines the position of the ferromagnetic electrode $F1$. The coordinate $x=L=2\lambda_{sf}^F$ defines the position of the ferromagnetic electrode $F2$. The solid curves for $x>L$ yield the chemical potentials for the two spins when the ferromagnetic electrode $F2$ is magnetized parallel to the magnetization of $F1$. The dotted curves yield the chemical potentials for antiparallel magnetization.

sistance in the four-terminal geometry of Fig. 1, the calculation yields

$$R_{FS'}=\pm\frac{1}{2}\frac{\alpha_F^2\lambda_{sf}^F}{\sigma_F(1-\alpha_F^2)A}, \tag{9}$$

where the sign refers to the parallel (+) or antiparallel (−) relative orientation of the magnetization of the two ferromagnetic electrodes. In the case of antiparallel arrangement, one therefore has the rather unique situation that the voltage measured can be outside the range of source and drain contacts.[19]

The above holds as long as the spin-flip length λ_{sf}^F exceeds the width W of the superconductor. The complication of the above experiment would be that it requires the width of the superconductor to be shorter than the spin-flip length in the ferromagnet, which is expected to be in the range 20–200 nm.[18] To remedy these complications, we consider an alternative geometry.

The geometry ($F/N/S$) of Fig. 3 consists of two superconducting strips S, which are coupled by a thin layer of normal metal N, which has a larger spin-flip length (λ_{sf}^N) than the spin-flip length of the ferromagnet (λ_{sf}^F).[11] On top of the normal metal, two ferromagnetic strips $F1$ and $F2$ are placed. Current is injected by $F1$ through the normal metal, into the superconductor, whereas the voltage is detected by $F2$.

In the absence of a spin-polarized current I, the measured resistance $R=V/I$ will decay exponentially with $R_0\exp(-CL/d_N)$, where $R_0\approx\rho_N d_N/A_C$ is the resistance of the normal metal between the superconductor and the current injector $F1$. Here ρ_N is the resistivity of the normal metal, A_C the contact area between $F1$ and S, d_N the thickness of the normal metal, C a constant of order unity, and L the distance between the two ferromagnetic strips. This resistance will therefore vanish in the regime $L\gg d_N$. However, in the presence of a spin-polarized current I, a spin density is created at the current injector $F1$, stretching out towards the voltage probe $F2$.

To calculate the signal at $F2$, we have to include the normal region. First, we assume that the superconductor in the region S' in Fig. 3 is absent. We take the nonequilibrium spin density to be uniform in the normal metal in the region under $F1$, which is allowed as the thickness of the normal metal is small compared to the spin-flip length (λ_{sf}^N) in the normal metal, $d_N\ll\lambda_{sf}^N$. The electrochemical potentials in the normal region between the two ferromagnetic strips are described by solutions of Eqs. (5) and (6), with the constants $A=B=0$. We then calculate the resistance in the relevant limit that the distance L does not exceed the spin-flip length of the normal region, $L\lesssim\lambda_{sf}^N$. The expression for the resistance in this limit is given by

$$R_{FNS}=\pm\frac{\alpha_F^2\lambda_{sf}^F}{2\sigma_F A(1-\alpha_F^2)+\dfrac{L\sigma_F^2 A}{\sigma_N\lambda_{sf}^F}(1+\alpha_F)^2(1-\alpha_F)^2}, \tag{10}$$

where σ_N is the conductivity of the normal metal and L is the distance between the two ferromagnetic electrodes. When $L>\lambda_{sf}^N$, the signal will decay exponentially.

Equation (10) and Fig. 4 show that, even though no charge current flows in the N layer, nevertheless a signal is generated at the ferromagnetic electrode $F2$. In addition, Eq. (10) shows that the signal changes sign when the polarization of $F2$ is reversed. A reduction of the thickness of the N film will reduce the signal. This is a consequence of the fact that although no charge current flows, the spin-up and spin-down currents are nonzero, and their magnitude (and the associated voltage) depends on the resistance of the N layer.

The above analysis is based on classical assumptions, where the superconducting proximity effect has been ignored in the normal metal. However, it is known that a superconductor modifies the electronic states in the N layer,[7,8] which would be the case when a superconductor is present in the region S' (cf. Fig. 3).

In this situation Eq. (10) would still hold, for the electrochemical potentials in the normal metal satisfy the boundary condition of Eq. (3). When the thickness d_N of the normal layer is of the order of the superconducting coherence length ξ, a gap Δ_N will be developed in the normal metal. This will prohibit the opposite spin currents in the normal metal to flow, and therefore no signal will be detected at the ferromagnetic electrode $F2$. One could control and eliminate the induced gap Δ_N by applying a magnetic field parallel to the ferromagnetic electrodes.

To conclude, we have shown that the spin reversal associated with Andreev reflection in a diffusive ferromagnet-superconductor junction leads to a spin contact resistance. The contact resistance is due to an excess spin density, which exists close to the F/S interface, on a length scale of the spin-flip length in the ferromagnet. In a multiterminal geometry the contact resistance can have a positive and negative sign, depending on the relative orientation of the ferromagnetic electrodes.

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[1] A. F. Andreev, Zh. Éksp. Teor. Fiz. **46**, 1823 (1963) [Sov. Phys. JETP **19**, 1228 (1964)].

[2] J. Aarts, J. M. E. Geers, E. Brück, A. A. Golubov, and R. Coehoorn, Phys. Rev. B **56**, 2779 (1997), and references therein.

[3] M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. Lett. **74**, 1657 (1995).

[4] R. J. Soulen *et al.*, Science **282**, 85 (1998).

[5] S. K. Upadhyay, A. Palanisami, R. N. Louie, and R. A. Buhrman, Phys. Rev. Lett. **81**, 3247 (1998).

[6] In our analysis of the F/S interface, we only take into account the electron transport below Δ. This distinguishes our work from the studies of spin injection in superconductors, which can only occur for energies above Δ.

[7] W. Belzig, C. Bruder, and G. Schön, Phys. Rev. B **54**, 9443 (1996).

[8] S. Guéron, H. Pothier, Norman O. Birge, D. Esteve, and M. H. Devoret, Phys. Rev. Lett. **77**, 3025 (1996).

[9] M. Giroud *et al.*, Phys. Rev. B **58**, R11 872 (1998).

[10] M. Leadbeater, C. J. Lambert, K. E. Nagaev, R. Raimondi, and A. F. Volkov, Phys. Rev. B **59**, 12 264 (1999).

[11] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985); M. Johnson, *ibid.* **70**, 2142 (1993).

[12] P. C. van Son, H. Van Kempen, and P. Wyder, Phys. Rev. Lett. **58**, 2271 (1987).

[13] T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).

[14] S. Hershfield and H. L. Zhao, Phys. Rev. B **56**, 3296 (1997).

[15] See also V. I. Fal'ko, C. J. Lambert, and A. F. Volkov, Pis'ma Zh. Eksp. Teor. Fiz. **69**, 497 (1999) [JETP Lett. **69**, 532 (1999)].

[16] P. M. Tedrow and R. Meservey, Phys. Rev. Lett. **26**, 192 (1971); Phys. Rev. B **7**, 318 (1973); R. Meservey and P. M. Tedrow, Phys. Rep. **238**, 173 (1994).

[17] The value of α_F can only be estimated in relation with the values taken from the tunnel junction and point contact experiments (Refs. 4, 5, and 16) since in our description the spin polarization of the current is not solely determined by the density of states at the Fermi level, but also includes the different spin diffusion constants.

[18] J. Ph. Ansermet, J. Phys.: Condens. Matter **10**, 6027 (1998), and references therein.

[19] This is made possible by the Andreev reflection provided by the superconductor. In the absence of the superconductor, one would always measure an electrochemical potential between the source and drain contacts.