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Detection of small exchange fields in S/F structures

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ABSTRACT

Ferromagnetic materials with exchange fields E_{ex} smaller or of the order of the superconducting gap Δ are important for applications of corresponding (s-wave) superconductor/ferromagnet/superconductor (SFS) junctions. Presently such materials are not known but there are several proposals how to create them. Small exchange fields are in principle difficult to detect. Based on our results we propose reliable detection methods of such small E_{ex}. For exchange fields smaller than the superconducting gap the subgap differential conductance of the normal metal–ferromagnet–insulator–superconductor (NFIS) junction shows a peak at the voltage bias equal to the exchange field of the ferromagnetic layer, $eV = E_{ex}$. Thus measuring the subgap conductance one can reliably determine small $E_{ex} < \Delta$. In the opposite case $E_{ex} > \Delta$ one can determine the exchange field in scanning tunneling microscopy (STM) experiment. The density of states of the FS bilayer measured at the outer border of the ferromagnet shows a peak at the energy equal to the exchange field, $E = E_{ex}$. This peak can be only visible for small enough exchange fields of the order of few Δ.

1. Introduction

As we know from the quantum theory of magnetism the ferromagnetic metal can be described by the presence of the so-called exchange field, E_{ex}. This field is responsible for many interesting phenomena in artificially fabricated superconductor/ferromagnet (S/F) hybrid structures [1–4]. Let us briefly review the essence of the S/F proximity effect.

Upon entering of the Cooper pair into the ferromagnetic metal it becomes an evanescent state and the spin up electron in the pair lowers its potential energy by E_{ex}, while the spin down electron raises its potential energy by the same amount. In order for each electron to conserve its total energy, the spin up electron must increase its kinetic energy, while the spin down electron must decrease its kinetic energy to make up for these additional potential energies in F. As a consequence, the center of mass motion is modulated and superconducting correlations in the F layer have the damped oscillatory behavior [5,6]. If we neglect the influence of other possible parameters of ferromagnetic metal (like magnetic scattering rate) the characteristic lengths of the decay and the oscillations are equal to $\xi_f = \sqrt{\mathcal{D}_f/E_{ex}}$, where $\mathcal{D}_f$ is the diffusion coefficient in the ferromagnetic metal [1].

The length ξ_f is also the length of decay and oscillations of the critical current in Josephson S/F/S junctions [7,8]. Negative sign of the critical current corresponds to the so-called π-state [9–13]. S/F/S π-junctions have been proposed as potential elements in superconducting classical and quantum logic circuits [14–16]. For instance, S/F/S junctions can be used as complementary elements (π-shifters) in RSFQ circuits (see Ref. [17] and references therein). S/F/S based devices were also proposed as elements for superconducting spintronics [18]. Finally, S/F/S structures have been proposed for the realization of the so-called φ-junctions with a φ drop in the ground state, where $0 < \varphi < \pi$ [19,20].

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Presently known ferromagnetic materials have large exchange fields, $E_{ex} \gg \Delta$, and therefore short characteristic length of oscillations, $\xi_f \ll \xi_s$, where $\xi_s = \sqrt{\mathcal{D}_s/2\Delta}$ is the superconducting coherence length and $\mathcal{D}_s$ is the diffusion coefficient in the superconductor. This requires very high precision in controlling the F layer thickness in the fabrication process of the Josephson π-junctions. In already existing S/F/S structures the roughness is often larger than the desired precision. The way to solve this problem is to invent ferromagnetic materials with small exchange fields.

In this paper we review several proposals for ferromagnetic materials with exchange fields E_{ex} smaller or of the order of the superconducting gap Δ. Then based on our results we propose reliable detection methods of such small exchange fields in experiments. Another detection method was recently suggested in [21].

2. Ways to generate small exchange fields

The easiest way to create small exchange field is to apply an external magnetic field B to the normal metal lead, in which case $E_{ex} = \mu_B B$, where μ_B is the Bohr magneton.

It may be also an intrinsic exchange field of weak ferromagnetic alloys. For example, in Ref. [22] exchange fields for $Pd_{1-x}Ni_x$ with different Ni concentration, obtained by a fitting procedure (see also [23]), were reported. Considering Nb as a superconductor with $\Delta = 1.3$ meV, we can estimate the exchange field in $Pd_{1-x}Ni_x$: for 5.5% of Ni fitting gives $E_{ex} = 0.11$ meV, which is 0.1 Δ, for 6% of Ni it gives $E_{ex} = 0.45$ meV, which is 0.4 Δ, for 7% of Ni it gives $E_{ex} = 2.8$ meV, which is 2.2 Δ, and for 11.5% of Ni $E_{ex} = 3.9$ meV, which is 3 Δ.

Another promising alloy with small exchange field, $Pd_{0.99}Fe_{0.01}$, was studied in [24–26].

Finally, a small exchange field can be induced by a ferromagnetic material into the adjacent normal metal layer. In recent proposal [27], a thin normal metal layer was placed on top of the ferromagnetic insulator. It was shown that the ferromagnetic insulator may induce effective exchange field in the normal metal layer [27]:

$$E_{ex}^{eff} = \hbar \mathcal{D} G_\phi \rho / d, \tag{1}$$

where $\mathcal{D}$ is the diffusion coefficient in the normal metal, G_ϕ is a surface conductance-like coefficient for the normal metal/ferromagnetic insulator interface, ρ is the resistivity of the normal metal, and d is the thickness of the normal metal layer in the direction, perpendicular to the ferromagnetic insulator surface. The field E_{ex}^{eff} is expected to be much smaller than the exchange field inside standard ferromagnets. Interestingly, such exchange field is possible to tune at the sample fabrication stage since it is inversely proportional to the normal metal layer thickness d. This gives a flexibility with respect to material constraints. We also note that as $E_{ex}^{eff} \propto G_\phi$, inducing the tunnel barrier at the normal metal/ferromagnetic interlayer interface, one can further reduce the value of the effective exchange field.

Below we suggest direct measurements of such small exchange fields. The detection methods are different in case of the exchange field smaller, $E_{ex} < \Delta$, and larger than the superconducting gap, $E_{ex} > \Delta$.

We should mention that we propose methods of small exchange field detection in the ideal case of ferromagnetic layer with homogeneous magnetization and the absence of magnetic and spin–orbit scattering in contact with a superconductor. However, in case of realistic ferromagnets situation can be more complicated. We discuss some possible limitations of the detection at the end of the following two sections.

3. Detection of exchange fields smaller than the superconducting gap

In this section we consider the following SIFN structure: a ferromagnetic wire F of a length d_f (smaller than the inelastic relaxation length [28,29]) is attached at $x=0$ to a superconducting (S) and at $x = d_f$ to a normal (N) electrode. The interface at $x=0$ is a tunnel barrier while at $x = d_f$ we have a transparent interface. We will show that the subgap differential conductance of such a structure has a peak at the bias voltage equal to the exchange field of the ferromagnetic metal in case when $E_{ex} < \Delta$ [30,31]. Thus we propose to determine small $E_{ex} < \Delta$ in experiments by measuring the subgap differential conductance of NFIS junctions at low temperatures.

In this paper we consider the diffusive limit, i.e. we assume that the elastic scattering length is much smaller than the decay length of the superconducting condensate into the F region. Here and below we consider for simplicity $\mathcal{D}_f = \mathcal{D}_s \equiv \mathcal{D}$ and $\hbar = k_B = 1$. In order to describe the transport properties of the system we solve the Usadel equation in the F layer, that in the so-called θ-parametrization reads [32,33]

$$\frac{\mathcal{D}}{2i}\partial_{xx}^2\theta_{f\uparrow(\downarrow)} = \left(E \pm E_{ex}\right)\sinh\theta_{f\uparrow(\downarrow)}. \tag{2}$$

Here the positive and negative signs correspond to the spin-up ↑ and spin-down ↓ states, respectively. Because of the high transparency of the F/N interface the functions $\theta_{f\uparrow(\downarrow)} = 0$ at $x = d_f$. While at the tunneling interface at $x=0$ we use the Kupriyanov–Lukichev boundary condition [34]:

$$\partial_x\theta_{f\uparrow(\downarrow)}|_{x=0} = \frac{R_F}{d_f R_T}\sinh[\theta_{f\uparrow(\downarrow)}|_{x=0} - \Theta_s], \tag{3}$$

where R_F and R_T are the normal resistances of the F layer and SF interface, respectively ($R_T \gg R_F$), and $\Theta_s = \mathrm{arctanh}(\Delta/E)$ is the superconducting bulk value of the parametrization angle in the S layer, θ_s. Once the functions $\theta_{f\uparrow(\downarrow)}$ are obtained one can compute the current through the junction. In particular we are interested in the Andreev current, i.e. the current for voltages smaller than the superconducting gap due to Andreev processes at the S/F interface.

Due to the tunneling barrier at the S/F interface the proximity effect is weak and hence we linearize Eqs. (2) and (3) with respect to $R_F/R_T \ll 1$. After a straightforward calculation we obtain the Andreev current at zero temperature in this limit [35,36]:

$$I_A = \frac{W\Delta^2}{4eR_T}\sum_{j=\pm}\int_0^{eV}\frac{dE}{\Delta^2 - E^2}\mathrm{Re}\left[\sqrt{\frac{i\Delta}{E + jE_{ex}}}\tanh\left(\sqrt{\frac{E + jE_{ex}}{i\Delta}}\frac{d_f}{\xi_s}\right)\right], \tag{4}$$

where $W = \xi_s R_F / d_f R_T$ is the diffusive tunneling parameter [34,37,38]. In the tunneling limit $W \ll 1$.

We evaluate Eq. (4) in the long-junction limit, i.e. when $d_f \gg \xi_f$, and $E_{ex} \lesssim eV < \Delta$. We obtain for the Andreev current

$$I_A = \frac{\Delta\xi_s R_F}{ed_f R_T^2}\sum_{j=\pm}\frac{\arctan(c_j^+) + \arctan(c_j^-)}{\sqrt{\Delta + jE_{ex}}}, \quad c_j^+ = \sqrt{\frac{eV + jE_{ex}}{\Delta + jE_{ex}}}, \quad c_j^- = \sqrt{\frac{eV - jE_{ex}}{\Delta + jE_{ex}}}. \tag{5}$$