Journal of Magnetism and Magnetic Materials xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

How experimentally to detect a solitary superconductivity in dirty ferromagnet-superconductor trilayers?

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ARTICLE INFO

Article history:
Received 31 August 2016
Accepted 21 December 2016
Available online xxxx

Keywords:
Superconductivity
Solitary superconductivity
Ferromagnet
Spin valve

ABSTRACT

We theoretically study the proximity effect in the thin-film layered ferromagnet (F) – superconductor (S) heterostructures in F_1F_2S design. We consider the boundary value problem for the Usadel-like equations in the case of so-called "dirty" limit. The "latent" superconducting pairing interaction in F layers taken into account. The focus is on the recipe of experimental preparation the state with so-called solitary superconductivity. We also propose and discuss the model of the superconducting spin valve based on F_1F_2S trilayers in solitary superconductivity regime.

1. Introduction

The coexistence of two antagonistic phenomena – superconductivity (S) and ferromagnetism (F) in artificial layered structures is possible due to the proximity effect [1]. The singlet superconducting condensate can penetrate from the S layer into the F layer, and nonmonotonically decays on very short distance about $\xi_I = \sqrt{D/2I}$ (where I is the exchange field and D is the diffusion coefficient in a ferromagnet) into the F layer. For strong ferromagnets such as Fe, Ni or Co the decay depth is approximately few nanometers. The peculiarity of the FS proximity effect and interplay between the S and F parameter orders give rise to a number of interesting phenomena and effects (see reviews [2–4] and the references therein), for example, the reentrant [5–7] and solitary superconductivity [8,9], nonmonotonic behaviors of the critical temperature T_c as function of the mutual alignment of the magnetizations of the F layers [10,11] and so on.

Rich physics of the FS proximity effect and rapid progress in area of the spintronics and superconducting electronics make this field promising for spin valve applications. For example, spin valve devices based on three-layer FS systems switched by a weak external magnetic field were proposed in [12–14]. In a recent experimental work [15] the difference $\Delta T(\alpha) = T_c(\alpha) - T_c(0^\circ)$ (where α is angle between magnetizations of the adjacent F layers) was measured in F_1F_2S (Fe/Cu/Fe/Cu/Pb) trilayer design. It has been shown that its highest value reached at the perpendicular magnetic alignment when $\Delta T(\alpha = 90^\circ) \approx 40\,\text{mK}$. Further, the difference $\Delta T(\alpha = 90^\circ) \approx 800\,\text{mK}$ was achieved for a similar F_1F_2S (CrO_2/Cu/Ni/MoGe) system [16].

Earlier we theoretically investigate a solitary superconductivity for F_1F_2S system [7–9]. The solitary superconductivity corresponds to a localized region on the phase diagram of $T_c(d_f)$, in which $T_c > 0$ and thickness d_f belongs to region $[d_f^*, d_f^{**}]$, where $d_f^* > 0$. This occurs only at the antiparallel (AP) mutual magnetic aligned of F_1 and F_2 layers. The superconductivity does not occur at the parallel (P) orientation that makes relevant the study of states with solitary superconductivity, as they may prove to be the most promising for the superconducting spin valve applications.

In main goal this work is how experimentally to detect the solitary superconductivity.

2. Theoretical background

Near the superconducting transition the self-consistent equations for the superconducting order parameters has the form [1]

$$\Delta_i(\mathbf{r})\left(\ln t + \ln\frac{T_{cs}}{T_i}\right) = 2\pi T_c \mathrm{Re}\sum_{\omega>0}^{\infty}\left(F_i(\mathbf{r},\omega) - \frac{\Delta_i(\mathbf{r})}{\omega}\right), \quad i = (f1, f2, s), \tag{1}$$

where $t = T_c/T_{cs}$ is the reduced critical temperature (T_{cs} and T_i is the superconducting critical temperature for the bulk material (S and F_i, respectively) without spin exchange interaction), ω is the Matsubara frequency.

The pair amplitudes $F_{s,(i)}$ satisfy the Usadel-like equations [17]

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http://dx.doi.org/10.1016/j.jmmm.2016.12.149
0304-8853/

Please cite this article in press as: M.V. Avdeev, Y.N. Proshin, How experimentally to detect a solitary superconductivity in dirty ferromagnet-superconductor trilayers?, Journal of Magnetism and Magnetic Materials (2017), http://dx.doi.org/10.1016/j.jmmm.2016.12.149

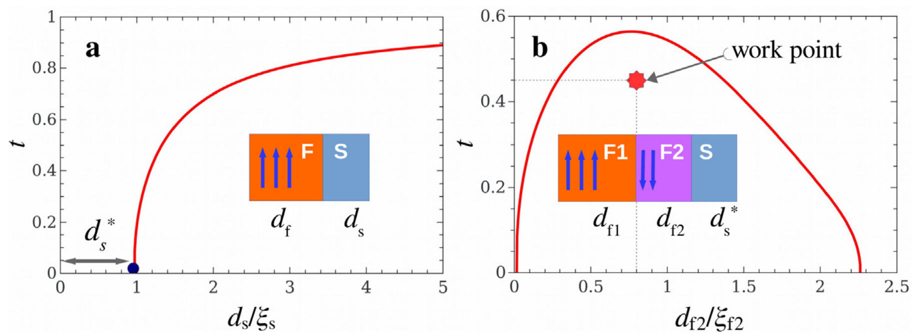

Fig. 1. (a) The reduced critical temperature versus the S layer thickness for the FS bilayer system ($d_s^* = 0.95\xi_s$). (b) The phase diagrams of the solitary superconductivity for the FS trilayer at AP state. The red star denote the work point of spin valve (see text). Other parameters of the system are: $l_s/\xi_s = 0.5, \sigma_s = 1, \sigma_{f2} = 3, \sigma_{f1} = 1, d_{f1}/\xi_{I1} = 10, l_f/\xi_I = 0.5, I/\pi T_{cs} = 10, T_{cs}/T_{cf} = 1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\left[|\omega| - iI_i - \frac{D_i}{2}\frac{d^2}{dx^2}\right]F_i(x,\omega) = \Delta_i(x). \tag{2}$$

Here I_i is the exchange interaction in F layers, D_i is the diffusion constant.

For pair amplitude F_i, we have Kupriyanov-Likichev like boundary conditions [18] derived by microscopic approach in the work [6]. For the F_2S and F_1F_2 interfaces they have the form

$$\begin{aligned}
&\frac{4D_s}{\sigma_s v_F^s}\frac{d}{dx}F_s = \frac{4D_{f2}}{\sigma_{f2} v_F^{f2}}\frac{d}{dx}F_{f2} = F_s - F_{f2},\\
&\frac{4D_{f1}}{\sigma_{f1} v_F^{f1}}\frac{d}{dx}F_{f1} = \frac{4D_{f2}}{\sigma_{f2} v_F^{f2}}\frac{d}{dx}F_{f2} = F_{f1} - F_{f2}.
\end{aligned} \tag{3}$$

The boundary conditions at the outer surfaces have the form

$$\frac{d}{dx}F_{s,f} = 0. \tag{4}$$

The parameters σ_s and σ_f are the transparencies from the S and F side, respectively [2] and v_F^i is Fermi velocity.

Then, the solutions of Eqs. (2) for F_1F_2S trilayers have the form

$$\begin{aligned}
F_1 &= \frac{\Delta_1}{\omega - iI_1} + C_1(\omega)\cosh k_{I1}(x + d_{f1} + d_{f2}),\\
F_2 &= \frac{\Delta_2}{\omega - iI_2} + A(\omega)\cosh k_{I2}x + B(\omega)\sinh k_{I2}x,\\
F_s &= \frac{\Delta_s}{\omega} + C_s(\omega)\cosh k_s(x - d_s),
\end{aligned} \tag{5}$$

where $k_s^2 = 2\omega/D_s, k_I^2 = 2(\omega - iI)/D_f$. The set of solutions (5) and the appropriate boundary conditions (3), (4) are sufficient to determine the coefficients C_1, A, B, C_s that are linear combinations of the gaps $\Delta_s, \Delta_1, \Delta_2$. Finally, inserting the solutions (5) into Eqs. (1) and solving the resulting secular equation, we calculate the critical temperature T_c for the F_1F_2S system.

3. Results and discussion

In this section, we focus on preparation of the F_1F_2S system model to detect the solitary superconductivity. We also discuss its of the spin valve applications. As was mentioned above the solitary superconductivity in FFS system may be observed only in the AP state [7–9]. In order to prepare state with a well-defined solitary superconductivity experimentalists should adhere to the following algorithm. Firstly the superconductivity in the FS bilayer is investigated. Without loss of generality the F layer thickness is assumed much greater than coherence length $d_f \gg \xi_I$. Further at the fixed d_f the S layer thickness d_s should be changed to find the critical value d_s^* at which the critical temperature T_c is close to zero. Thus, in Fig. 1a the dependence of the reduced critical temperature t on the S layer thickness d_s for the FS bilayer system is shown. It is seen that superconductivity disappears at $d_s^* \approx \xi_s$ (for convenience, the thickness d_s of the S layer and mean free path l_s is normalized on the coherence length $\xi_s = \sqrt{D_s/2\pi T_{cs}}$, while all length relating to the both F_1 and F_2 layers are normalized on the coherence lengths $\xi_{I1,2} = \sqrt{D_{f1,2}/2I_{1,2}}$ respectively).

Next, the samples of the F_1F_2S trilayers should be prepared with various thicknesses d_{f2} of the intermediate F_2 layer at fixed both d_{f1} and d_s^* thicknesses. It is important that the F_1F_2S system should be in the AP state. In Fig. 1b it is clearly seen that a superconductivity is restored with the d_{f2} increase. The critical temperature T_c begins to rise and reaches to the maximum value $t = 0.565$ at $d_{f2} \approx 0.76\xi_{I2}$. With further increase of the intermediate layer thickness, the critical temperature decreases monotonically up to zero. As was mentioned above, such an extraordinary nonmonotonic dependence $T_c(d_{f2})$ is called solitary superconductivity. Note again that for the parallel state, the system is always in the resistive state [7–9] and hence, the difference $\Delta T = T_c^{AP} - T_c^P \equiv T_c^{AP}$ is a maximal. The physical reason for this phenomenon is simple: the exchange field of the intermediate F_2 layer, which is a strong depairing factor for the superconducting state, is partially compensated at AP state, herewith the "effective" exchange field becomes smaller and superconductivity appears. For more complete compensations of the effective exchange field the soft magnetic materials with low Curie temperature (such as $Ni_{1-x}Cu_x$ or Pr) alloys should be used for both F layers [7–9].

The deviation of the magnetic alignment from the AP state results in the fast vanishing of this compensation and, as a result, in the reduction of the critical temperature [7–9]. This important feature of the system with solitary superconductivity makes them the most promising for superconducting spin valve applications, because the high values of difference ΔT are necessary for stable operation of spin valve. In order to consider the model of spin valve we choose the work point in the phase diagram at $d_{f2} = 0.8\xi_{I2}$ and $T^* = 0.45T_{cs}$ (the red octagonal star in Fig. 1b). At the AP state $T^* < T_c$ and system is in the superconducting state. Upon a change in the magnetic alignment from the AP state to the P state by weak external magnetic field, the superconductivity disappears, and system switches in resistive state.

4. Summary

In this work we consider the feature of states with a solitary superconductivity for the asymmetrical F_1F_2S trilayers. The appearance of these states for dirty F_1F_2S trilayers is a result of partial compensation of *effective* exchange fields of F layers at AP state. Based on out results we propose the way for observation of solitary superconductivity in real experiments. We also discus the spin valve model in solitary superconductivity regime. We shown that in this case the difference ΔT between two superconducting and resistive states is maximal. It leads to more stable operation of spin valve.

Acknowledgements

The work is partially supported by the RFBR (16-02-01016). YNP is also thankful to the subsidy allocated to Kazan Federal University for performing the project part of the state assignment in the area of scientific activities.

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