



Interelectronic interaction in dirty FS trilayers: A manifestation of “hidden” superconductivity

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ABSTRACT

The properties of the ferromagnet/superconductor (FS) system are theoretically studied. Electron–electron pairing interaction in F layers is taken into account. The boundary value problem for the Usadel-like equations is considered in the case of so-called “dirty” limit. It is shown that both asymmetry and interelectronic interaction essentially influence on the critical properties of the F_1SF_2 trilayer. The appearance of the solitary superconductivity is predicted for this asymmetrical trilayer.

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1. Introduction

It is well known that in artificial layered structures consisting of the superconductor (S) and ferromagnet (F) layers, the interplay between the S and F parameter orders can lead to a several striking phenomena such as the nonmonotonic behaviors of the critical temperature and the Josephson current as a function of the ferromagnetic layer thickness [1–3]. In particular, re-entrant and periodically re-entrant superconductivity was predicted in works [4–6]. Later the re-entrant superconductivity experimentally was discovered in bilayers V/Fe [7] and Nb/Cu_{1-x}Ni_x [8]. Note, a solitary superconductivity was also recently theoretically proposed in clean FS system [9,10]. Most recently, the appearance of peculiar solitary re-entrant superconductivity caused by external magnetic field is predicted for the F_1F_2S system [11].

The coexistence of two antagonistic phenomena in FS systems is possible due to the proximity effect [12]. The superconducting correlations can penetrate from the S layer into the F layer, even though there is no pairing interaction and, consequently, the superconducting order parameter vanishes. The singlet superconducting correlations decay on very short distance $\xi_l = \sqrt{D/I}$ (where I is exchange field and D is diffusion constant in F) into the ferromagnet layer [1–3,13,14]. For strong ferromagnets such as Fe, Ni or Co the decay depth is approximately few nanometers.

There is great interest to these FS layered heterostructures due to possible spin valve applications. Thus the spin valve device based on the three layered FS systems switched by weak external magnetic field was proposed in works [15–17]. Changing the

mutual orientation of the magnetizations of the ferromagnets can control the critical temperature T_c of these systems, and, therefore, the switching between two different states, i.e. the superconducting state with antiparallel (AP) orientation of the magnetizations of F layers and the resistive state with parallel (P) one. Note that the superconducting switch based on the fourlayered FSFS system can have up to seven different states [18].

An electron–electron interaction in a ferromagnet (F) was neglected in the standard approach to the proximity effect theories for the layered SF structures (see for example [1–3] and references therein). In other words a superconducting order parameter Δ_f and an interelectronic interaction constant λ_f were taken as zero for a ferromagnet. Actually this interaction exists, but it is suppressed by strong exchange field I and can be reveal itself if an exchange field disappears. So, in this case a ferromagnet is transformed to normal metal and that “unhidden” interelectronic interaction can lead to superconducting correlations and, therefore, a superconductivity onset with critical temperature T_{cf} , estimated by the standard BCS expression.

Previously we shown that a consideration of this interaction in the clean FS structures limit [19–21] can explain a surprisingly high critical temperature T_c ($T_c \sim 5$ K) in the short-periodic Gd/La superlattice [22,23]. Note that gadolinium is a strong ferromagnet with a Curie temperature $T_C \approx 290$ K.

Below we analyze this problem for dirty case based on solutions of boundary value problem for the Usadel function, changing different parameters of asymmetrical F_1SF_2 trilayer (thicknesses of layers, boundary transparencies, and so on). Taking into account an interelectronic interaction leads to an appearance of “hidden” superconductivity of F layers which can be manifest itself in the

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proximity effect conditions. It will be especially expressed if exchange fields in both F layers have opposite signs. We discuss influence of the interelectronic interaction on the critical temperature and predict the *solitary* superconductivity for dirty FSF trilayer.

2. Taking into account the electron–electron pairing interaction in the F layers. Main equations

The critical temperature T_c at the second order transition for F_1SF_2 trilayers is obtained from the set of the self-consistent equations [24] for the superconducting gaps $\Delta_{sf}(\mathbf{r})$ in S and F layers, respectively

$$\Delta_s(\mathbf{r}) \ln t = 2\pi T_c \Re \sum_{\omega>0} \left(F_s(\mathbf{r}, \omega) - \frac{\Delta_s(\mathbf{r})}{\omega} \right),$$

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

where $t = T_c/T_{cs}$ is the reduced critical temperature (T_{cs} is the superconducting critical temperature for the bulk S material, T_i is “virtual” critical temperature for normal metal corresponding F_i material in which an exchange field is assumed be lacking, $I_i=0$), ω is the Matsubara frequency.

The pair amplitude $F_{s(i)}$ satisfies the Usadel-like equations [25–27] for S layer

$$\left[|\omega| - \frac{D_s}{2} \frac{d^2}{dx^2} \right] F_s(x, \omega) = \Delta_s(x), \quad (2)$$

and for F layers

$$\left[|\omega| - iI_{fi} - \frac{D_{fi}(I)}{2} \frac{d^2}{dx^2} \right] F_{fi}(x, \omega) = \Delta_{fi}(x), \quad D_{fi}(I) = \frac{D_{fi}}{1 - i2I\tau_f}, \quad (3)$$

where $D_{s,fi}$ is the diffusion constant in corresponding layer, and τ_f is the elastic scattering time of non-magnetic impurities in F layer. Note, that in the presence of exchange interaction the diffusion constant $D_{fi}(I)$ in (3) is complex.

For pair amplitude F , we have the boundary conditions derived by microscopic approach in the work [6]. For the F_1S and SF_2 interfaces they have the form

$$\frac{4D_s}{\sigma_s v_F^s} \frac{d}{dx} F_s = \frac{4D_{f1}(I)}{\sigma_{f1} v_F^{f1}} \frac{d}{dx} F_{f1} = F_s - F_{f1},$$

$$\frac{4D_s}{\sigma_s v_F^s} \frac{d}{dx} F_s = \frac{4D_{f2}(I)}{\sigma_{f2} v_F^{f2}} \frac{d}{dx} F_{f2} = F_{f2} - F_s, \quad (4)$$

respectively. Here $v_F^{s,f}$ is the Fermi velocity for S and F layers, respectively. The boundary conditions at the outer surfaces have the form.

$$\frac{d}{dx} F_{f1,f2} = 0. \quad (5)$$

The parameters σ_s and σ_{fi} are the transparencies from the S and F_i side, respectively [1]. Note, that the boundary conditions at the interface (4) take into account the fulfillment of the condition of detailed balance

$$\sigma_{f1} v_F^{f1} N_{f1} = \sigma_s v_F^s N_s, \quad \sigma_s v_F^s N_s = \sigma_{f2} v_F^{f2} N_{f2}$$

where $N_{s,f}$ is the density of states on the Fermi surface for the S and F layers, respectively.

For simplification we use approximation [28] $\Delta_{sf}(x) \approx \langle \Delta_{sf}(x) \rangle = \Delta_{sf}$. For qualitative examination the approximation is

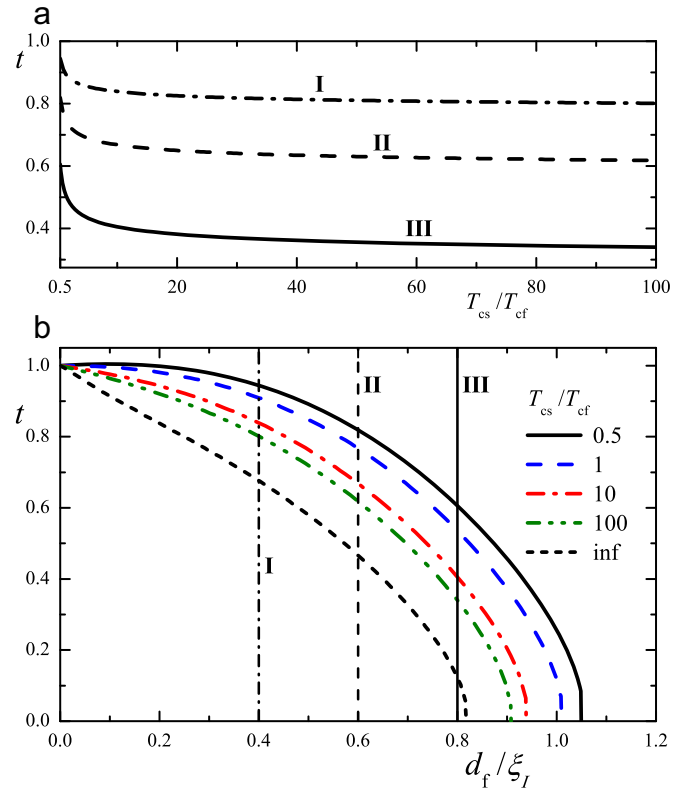


Fig. 1. The influence of the interelectronic interaction on the FSF system. (a) The critical temperature T_c as a function of the ratio T_{cs}/T_{cf} : (I) $d_f = 0.4\xi_f$, (II) $d_f = 0.6\xi_f$, (III) $d_f = 0.8\xi_f$; (b) The critical temperature T_c vs thicknesses d_f of F layers at same value of T_{cs}/T_{cf} . Other parameters of the system are $d_s/\xi_s = 1.25$, $l_s/\xi_s = 0.7$, $\sigma_s = 100$, $\sigma_f = 100$, $l_{f1}/\xi_{f1} = l_{f2}/\xi_{f2} = 0.3$, $h/\pi T_{cs} = h_2/\pi T_{cs} = 6$.

justified for thin-film systems under consideration. The approximation in use is much better [28] than popular single-mode approximation [1,2].

Then, the solutions of Eqs. (2), (3) for F_1SF_2 trilayers have the form

$$F_1 = \frac{\Delta_1}{\omega - iI_1} + C_1(\omega) \cosh k_{f1} \left(x + d_{f1} + \frac{d_s}{2} \right), \quad \left(-d_{f1} - \frac{d_s}{2} < x < -\frac{d_s}{2} \right);$$

$$F_s = \frac{\Delta_s}{\omega} + A(\omega) \cosh k_s x + B(\omega) \sinh k_s x, \quad \left(-\frac{d_s}{2} < x < \frac{d_s}{2} \right);$$

$$F_2 = \frac{\Delta_1}{\omega - iI_2} + C_2(\omega) \cosh k_{f2} \left(x - d_{f2} - \frac{d_s}{2} \right), \quad \left(\frac{d_s}{2} < x < \frac{d_s}{2} + d_{f2} \right); \quad (6)$$

where $k_s^2 = 2\omega/D_s$, $k_f^2 = 2(\omega - iI)/D_f(I)$. The set of solutions (6) and appropriate boundary conditions (4), (5) is sufficient to determine the coefficients C_1 , C_2 , A , B which are linear combinations of the gaps Δ_s , Δ_1 , Δ_2 . Finally, inserting (6) into (1) and solving the resulting secular equation, we calculate the critical temperature T_c of the F_1SF_2 trilayers.

3. Numerical results

In this section we present and discuss the numerical results for the F_1SF_2 systems. We consider the case of antiparallel orientation (AP state) of the magnetization in F layers. Similar to [20], we assume practically fully transparency of the SF interfaces ($\sigma_s = \sigma_f = 100$). All lengths related to the S and $F_{1,2}$ layers are

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