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Proximity effects in superconducting triplet spin-valve F2/F1/S

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ABSTRACT

We investigate the critical temperature T_c of F2/F1/S trilayers (Fi is a ferromagnetic metal and S is a singlet superconductor), where the long-range triplet superconducting component is generated at noncollinear magnetizations of the F layers. In this paper we demonstrate a possibility of the spin-valve effect mode selection (standard switching effect, the triplet spin-valve effect or reentrant $T_c(\alpha)$ dependence) by the variation of the F2/F1 interface transparency.

1. Introduction

We investigate the critical temperature T_c of F2/F1/S trilayers (Fi is a ferromagnetic metal, S is a singlet superconductor), where the long-range triplet superconducting component is generated at noncollinear magnetizations of the F layers [1]. An asymptotically exact numerical method is employed to calculate T_c as a function of the trilayer parameters, in particular, mutual orientation of magnetizations and F2/F1 interface transparencies. Earlier, we demonstrated that T_c in such structures can be a nonmonotonic function of the angle α between magnetizations of the two F layers [2,3]. The minimum is achieved at an intermediate α, lying between the parallel (P, $\alpha=0$) and antiparallel (AP, $\alpha=\pi$) cases. This implies a possibility of a "triplet" spin-valve effect: at temperatures above the minimum T_c^{TR} but below T_c^P and T_c^{AP}, the system is superconducting only in the vicinity of the collinear orientations. At certain configuration of parameters, we predict a reentrant T_c behavior. At the same time, considering only the P and AP orientations, we find that both the "standard" ($T_c^P < T_c^{AP}$) and "inverse" ($T_c^P > T_c^{AP}$) switching effects are possible depending on parameters of the system. It was shown recently [4] the existence of the anomalous dependence of the spin-triplet correlations on the angle α in F/F/S structures. In this paper we demonstrate a possibility of the spin-valve effect mode selection (standard switching effect, the triplet spin-valve effect or reentrant $T_c(\alpha)$ dependence) by the variation of the F2/F1 interface transparency.

2. Results and discussion

To prove this statement we calculate the critical temperature of F2/F1/S structure (see Fig. 1) for arbitrary values of the angle α and F2/F1 interface transparencies.

We suppose that F metals are monodomain ferromagnets with generally different values of the exchange field energy, H_{F1} and H_{F2}. We also assume that interfaces are not magnetically active and can be described by the spin independent suppression parameters γ and γ_B [5]

$$\gamma_{BF1S} = R_{BF1S}\mathcal{A}_B/\rho_{F1}\xi_{F1}, \quad \gamma_{F1S} = \rho_S\xi_S/\rho_{F1}\xi_{F1}, \tag{1}$$

$$\gamma_{BF2F1} = R_{BF2F1}\mathcal{A}_B/\rho_{F2}\xi_{F2}, \quad \gamma_{F2F1} = \rho_{F1}\xi_{F1}/\rho_{F2}\xi_{F2}, \tag{2}$$

where R_{BF1S}, R_{BF2F1} and $\mathcal{A}_B$ are the resistance and the area of the F1S and F2F1 interfaces; $\rho_{S(F1,F2)}$ is the resistivity of the S(F1,F2) layer and the coherence lengths are related to the diffusion constants $D_{S(F1,F2)}$ as $\xi_{S(F1,F2)} = \sqrt{D_{S(F1,F2)}/2\pi T_{cS}}$ (T_{cS} is the critical temperature for an isolated superconductor). For simplicity, we also suppose that conditions of dirty limit are fulfilled for all the films. Under the above assumptions, we can use the following linearized Usadel equations [1,6]:

$$\xi_{F2}^2\frac{d^2}{dx^2}f_0 - \Omega f_0 + ih_{F2}f_3 = 0, \tag{3}$$

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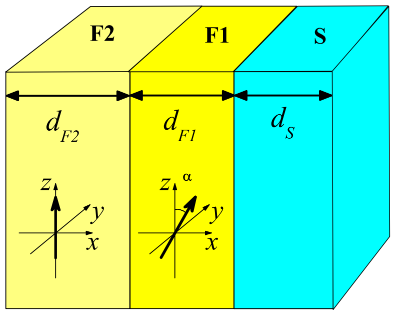

Fig. 1. F2/F1/S trilayer. The F1/S interface corresponds to $x=0$. The thick arrows in the F layers denote direction of the exchange fields **h** lying in the (y,z) plane. The angle between the in-plane exchange fields is α.

$$\xi_{F2}^2 \frac{d^2}{dx^2} f_1 - \Omega f_1 = 0, \tag{4}$$

$$\xi_{F2}^2 \frac{d^2}{dx^2} f_3 - \Omega f_3 + i h_{F2} f_0 = 0, \tag{5}$$

$$\xi_{F1}^2 \frac{d^2}{dx^2} p_0 - \Omega p_0 + i h_{F1} p_3 \cos \alpha = 0, \tag{6}$$

$$\xi_{F1}^2 \frac{d^2}{dx^2} p_1 - \Omega p_1 - h_{F1} p_3 \sin \alpha = 0, \tag{7}$$

$$\xi_{F1}^2 \frac{d^2}{dx^2} p_3 - \Omega p_3 + h_{F1}(i p_0 \cos \alpha + p_1 \sin \alpha) = 0, \tag{8}$$

$$\xi_S^2 \frac{d^2}{dx^2} s_0 - \Omega s_0 = 0, \tag{9}$$

$$\xi_S^2 \frac{d^2}{dx^2} s_1 - \Omega s_1 = 0, \tag{10}$$

$$\xi_S^2 \frac{d^2}{dx^2} s_3 - \Omega s_3 + \Delta = 0, \tag{11}$$

here index $i = 0, 1, 3$ represents triplet condensate functions with 0 and 1 spin projections and a singlet condensate function (f – in the left F2 layer; p – in the right F1 layer; and s – in the S layer), respectively; $\Omega = \omega / \pi T_{cS}$, $h_{F1,F2} = H_{F1,F2} / \pi T_{cS}$, and $\Delta = \Delta_s / \pi T_{cS}$ are the Matsubara frequency, exchange field energy, and superconductor order parameter, respectively, normalized by πT_{cS}.

System of equations (3)–(11) must be supplemented by boundary conditions. At the free interfaces of the structure ($x = -(d_{F1} + d_{F2})$, $x = d_S$), they have the form

$$\frac{df_i}{dx} = 0, \quad \frac{ds_i}{dx} = 0. \tag{12}$$

The boundary conditions at the F2F1 interface (for $x = -d_{F1}$) have the form [1,7]

$$\gamma_{F2F1} \xi_{F2} f_i = \xi_{F_1} \frac{d}{dx} p_i, \quad f_i + \gamma_{BF2F1} \xi_{F2} \frac{d}{dx} f_i = p_i. \tag{13}$$

Finally, the boundary conditions at the FS interface have the form

$$\gamma_{F1S} \xi_{F1} \frac{d}{dx} p_i = \xi_S \frac{d}{dx} s_i, \quad p_i + \gamma_{BF1S} \xi_{F1} \frac{d}{dx} p_i = s_i. \tag{14}$$

Solving Eqs. (3)–(10) with boundary conditions (12)–(14) we can reduce the problem of calculating T_c to an effective set of equations for the singlet component s_3 in the S layer: the set includes the self-consistency equation and the Usadel equation with effective boundary conditions. Now we have the "canonical form" of the problem that has been solved in [8]:

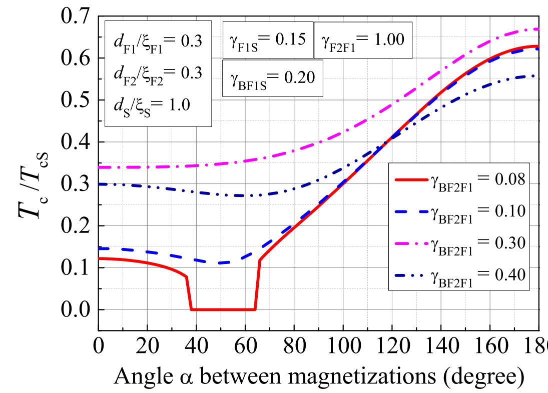

Fig. 2. Dependence of the transition temperature T_c on the angle α between magnetizations under the different F2/F1 interface transparencies.

$$\Delta \ln \frac{T_{cS}}{T_c} = 2 \frac{T_c}{T_{cS}} \sum_{\Omega > 0} \left(\frac{\Delta}{\Omega} - s_3 \right), \tag{15}$$

$$\xi_S^2 \frac{d^2}{dx^2} s_3 - \Omega s_3 + \Delta = 0, \tag{16}$$

$$\xi_S \frac{d}{dx} s_3(0) = W(\Omega) s_3(0), \quad \frac{d}{dx} s_3(d_S) = 0. \tag{17}$$

The explicit expression for $W(\Omega)$ is presented in [3].

The results of numerical calculations of T_c as a function of the mutual orientation of magnetizations and F2/F1 interface transparencies of the trilayer F2/F1/S are given in Fig. 2 (see the figure legend). The figure demonstrates a possibility of the spin-valve effect mode selection (the standard switching effect for $\gamma_{BF2F1} = 0.3$, the triplet spin-valve effect for $\gamma_{BF2F1} = 0.1$ or the reentrant $T_c(\alpha)$ dependence for $\gamma_{BF2F1} = 0.08$) by the variation of the F2/F1 interface transparency.

Thereby we show that the realization of one of the spin-valve effect modes can be done not only by the variation of the F layers thicknesses, but also by the variation of the F2/F1 interface transparency. It is explained by changes in the interference conditions for the condensate functions. This interference depends on both the F layers' thicknesses and the F2/F1 interface transparency.

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