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SUPERCONDUCTIVITY

Proximity Effect in a Superconducting Triplet Spin Valve S1/F1/S2/F2

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Abstract—Critical temperatures of multilayer structures of the superconductor/ferromagnet/ferromagnet (S/F/F) type are obtained using the matrix method for solving the linearized Usadel equations. The influence of an additional superconductor layer on the effects of a three-layer spin valve is considered. The possibility of increasing the efficiency of the spin valve modes with an additional superconducting layer S in the place of the layer N is discussed in comparison with an additional normal layer in the S/F/N/F structure.

Keywords: superconductivity, ferromagnetism, proximity effect, critical temperature, spin valve

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1. INTRODUCTION

The mutual effect of two competing states—superconductivity and ferromagnetism—at the interface has been the subject of intense experimental and theoretical studies over the past two decades. One of the most amazing manifestations of the interaction between them is the nonmonotonic dependence of the critical transition temperature into the superconducting state, T_c, on the thickness of the ferromagnetic layer in the superconductor/ferromagnet system. It was previously shown that T_c of a three-layer S/F1/F2 structure [1] (S is a singlet superconductor, F1 and F2 are ferromagnetic metals) and the multilayer S/F1/N/F2 structure [2] (N is a normal metal) can be a nonmonotonic function of the angle α between magnetizations of the two ferromagnetic layers, unlike the monotonic behavior of $T_c(\alpha)$ obtained for a three-layer F1/S/F2 heterostructure [3]. This property can be used to switch the heterostructure from the superconducting state to the normal one and vice versa, by applying a low magnetic field in a certain direction [1, 2], i.e., for manufacturing a superconducting spin valve with infinite magnetoresistance. There is a number of experimental works (see, e.g., references in [4]), in which the dependence of T_c on the angle between the magnetic moments in the S/F1/N/F2 structure with the same ferromagnets as F layers was observed. The maximum temperature difference was within 50 mK, therefore, to increase the effect, one of the iron-group metal ferromagnets (F2) was substituted for ferromagnetic semimetallic chromium oxide CrO_2 [5] or the ferromagnetic Heusler's semimetal alloy [6]. In this work, we consider the effect of an additional superconducting layer S2 in the S1/F1/S2/F2 heterostructure, in which the long-range triplet component of the superconducting pairing is generated at the noncollinear orientation of the magnetizations of the ferromagnetic layers [7]. The dependence of $T_c(\alpha)$ on the thickness of the additional superconducting layer S2 is calculated. In comparison with the S/F1/N/F2 structure, it is discussed which of the layers and how it affects the spin valve modes. The conditions under which the superconductivity in the additional layer S2 is suppressed and it performs a role of a normal layer, are studied, as well as the conditions when the superconductivity of this layer is preserved and affects the junction temperature T_c of the heterostructure.

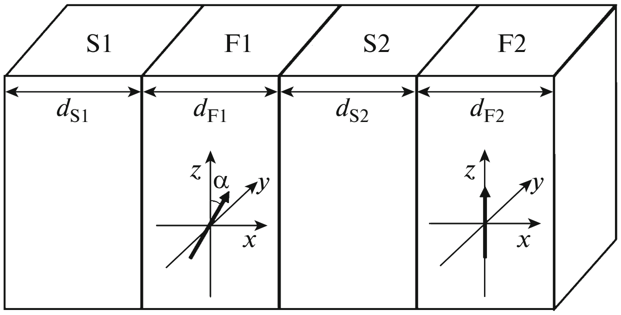

Fig. 1. S1/F1/S2/F2 heterostructure. The outer boundary of the S1 layer corresponds to the coordinate $x = 0$. Bold arrows in F layers denote the directions of the exchange fields **h** lying in the yz plane.

2. MODEL AND NUMERICAL METHOD

The S1/F1/S2/F2 structure infinite in the y and z directions is considered (Fig. 1). The exchange field of the F1 layer is in the yz plane, $\mathbf{h} = (0, h\sin\alpha, h\cos\alpha)$, whereas the exchange field of the F2 layer is directed along the z axis, $h = (0, 0, h)$. The angle α changes from 0 (parallel configuration, P) to π (antiparallel configuration, AP).

To calculate the critical temperature T_c as a function of parameters of the spin valve, which can be described in the diffusion limit utilizing the Usadel equations, the matrix method was applied [8–10].

The following approximations were used in the simulation: all contact boundaries are transparent ($\gamma_B = 0$), the diffusion constants and specific resistances are the same ($\gamma = 1$), the absolute values of the exchange fields in both ferromagnetic layers are the same.

3. RESULTS AND DISCUSSION

The results of the numerical calculations of T_c as a function of the angle α and thicknesses of S2 and N layers of S1/F1/S2/F2 and S1/F1/N/F2 heterostructures are shown in Figs. 2–5.

Figure 2 shows the direct switching mode of the spin valve ($T_c^{AP}(\alpha = 180°) > T_c^{P}(\alpha = 0°)$), which is realized at thin ferromagnetic layers.

Figure 3 shows the triplet mode of the spin valve (T_c(noncollinear)) $< T_c^{P}, T_c^{AP}$), which is realized at slightly larger thicknesses of ferromagnet layers.

Figure 4 shows the critical temperature T_c for the parallel and antiparallel orientation of magnetizations as a function of the thickness of the additional S and N layers for the direct switching mode.

Figure 5 shows the critical temperature T_c for the parallel and orthogonal orientation of magnetizations as a function of the thickness of the additional S and N layers for the triplet switching mode.

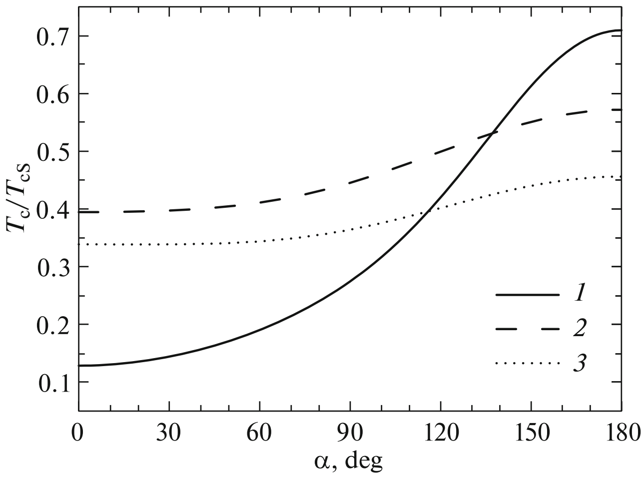

Fig. 2. Critical temperature T_c versus the angle α for the S1/F1/F2 (*1*), S1/F1/S2/F2 (*2*), and S1/F1/N/F2 (*3*) structures. The thicknesses of the layers $d_{S1}/\xi_{S1} = 2.76$, $d_{F1}/\xi_{F1} = 0.15$, $d_{F2}/\xi_{F2} = 0.15$, $d_{S2}/\xi_{S2} = d_N/\xi_N = 1$, the direct switching mode.

Figure 6 shows the difference between the critical temperatures $\Delta T_{c\_dir} = T_c^{AP} - T_c^{P}$ for the antiparallel and parallel orientation of magnetizations as a function of the thickness of additional S and N layers for the direct switching mode.

Figure 7 shows the difference between the critical temperatures $\Delta T_{c\_tr} = T_c^{P} - T_c(\alpha = 90°)$ for the parallel and orthogonal orientation of the magnetizations as a function of the thickness of the additional S and N layers for the triplet switching mode.

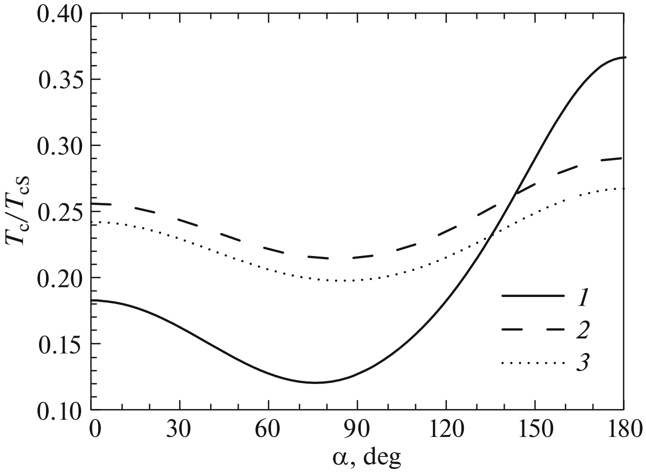

Fig. 3. Critical temperature T_c versus the angle α for the S1/F1/F2 (*1*), S1/F1/S2/F2 (*2*), and S1/F1/N/F2 (*3*) structures. The thickness of the layers $d_{S1}/\xi_{S1} = 2.76$, $d_{F1}/\xi_{F1} = 0.3$, $d_{F2}/\xi_{F2} = 0.7$, $d_{S2}/\xi_{S2} = d_N/\xi_N = 1$, the triplet switching mode.

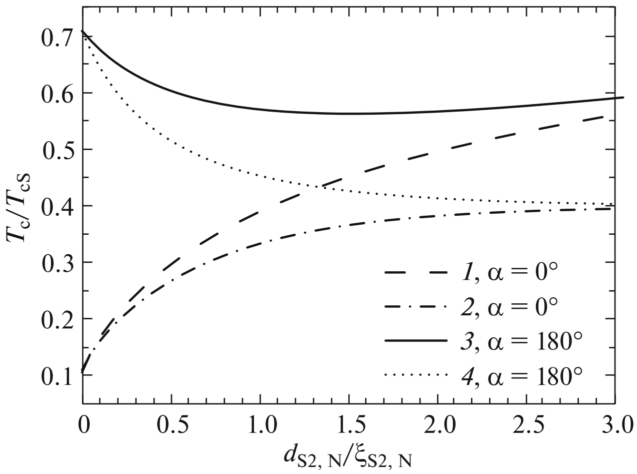

Fig. 4. Dependence of the critical temperature T_c on the thickness d_{S2} in the S1/F1/S2/F2 structure (*1*, *3*) and thickness d_N in the S1/F1/N/F2 structure (*2*, *4*). The thicknesses of other layers $d_{S1}/\xi_{S1} = 2.75$, $d_{F1}/\xi_{F1} = 0.15$, and $d_{F2}/\xi_{F2} = 0.15$.

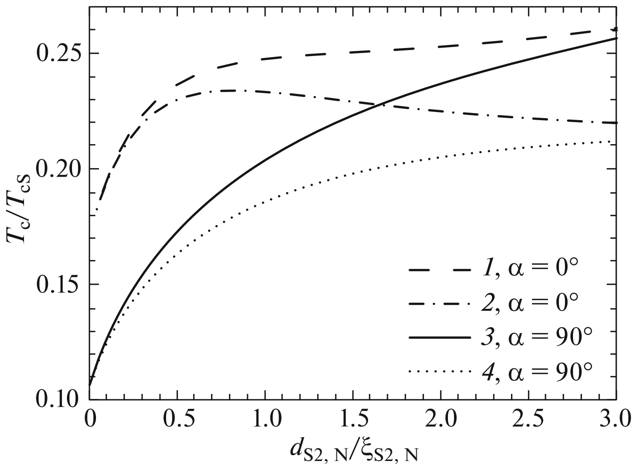

Fig. 5. Dependence of the critical temperature T_c on the thickness d_{S2} in the S1/F1/S2/F2 structure (*1*, *3*) and the thickness d_N in S1/F1/N/F2 structure (*2*, *4*). The thickness of other layers $d_{S1}/\xi_{S1} = 2.75$, $d_{F1}/\xi_{F1} = 0.3$, and $d_{F2}/\xi_{F2} = 0.7$.

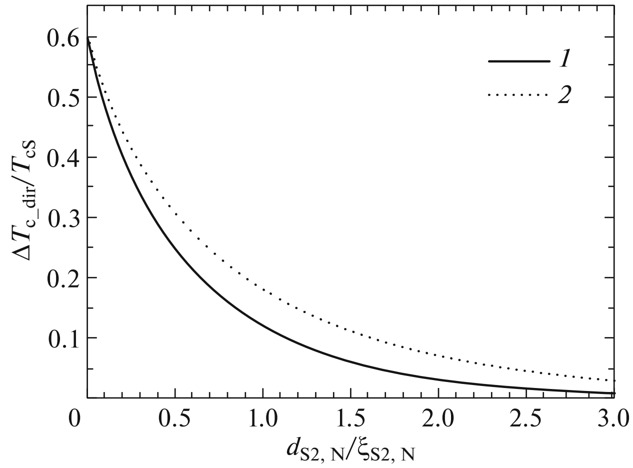

Fig. 6. Dependence of ΔT_{c_dir} on the thickness d_N in the S1/F1/N/F2 structure (*1*) and the thickness d_{S2} in the S1/F1/S2/F2 structure (*2*) for the direct mode.

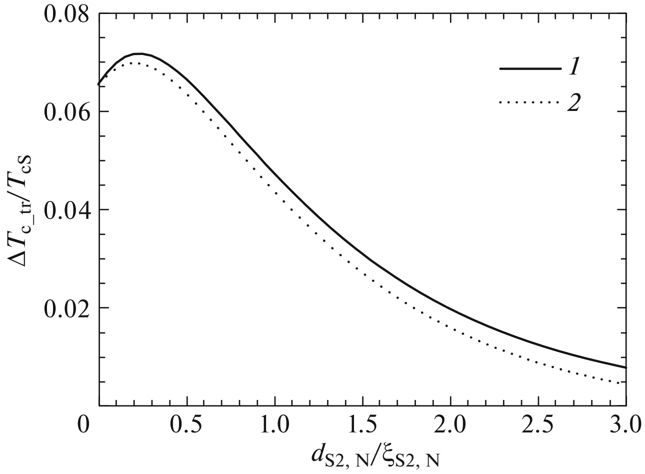

Fig. 7. Dependence of ΔT_{c_tr} on the thickness d_N in the S1/F1/N/F2 structure (*1*) and the thickness d_{S2} in the S1/F1/S2/F2 structure (*2*) for the triplet mode.

The average temperature value increases for the direct spin valve mode with a superconducting layer, whereas with a normal layer it almost does not change, Fig. 4. It is seen in Fig. 6 that an increase in the thickness of the additional layer reduces the amplitude of the temperature change. In comparison with the normal layer, the superconducting layer enhances the efficiency of the direct mode, the amplitude becomes larger, the same for the average T_c change.

For the triplet mode with the superconducting layer, the average temperature value increases, the same as in the direct mode, Fig. 5. It is seen in Fig. 7 that at the small thickness of the additional layer, the amplitude of the temperature change even slightly increases. The amplitudes of the temperature variation of the S1/F1/S2/F2 and S1/F1/N/F2 structures are approximately the same.

At large thicknesses of ferromagnetic layers, at which the inverse mode of the spin valve is realized ($T_c^{AP} < T_c^{P}$), the superconducting state in the *S*2 layer is suppressed and the critical temperatures of the S1/F1/S2/F2 and S1/F1/N/F2 structures coincide.

4. CONCLUSIONS

The dependences of the temperature of the superconducting transition of the S1/F1/S2/F2 spin valve are obtained. The possibility of the nonmonotonic T_c behavior in such structure is shown. In the S1/F1/S2/F2 and S1/F1/N/F2 structure, there may be a slight increase in the efficiency of the triplet mode in comparison with the S1/F1/F2 structure. An additional small-thickness layer necessary for decoupling the magnetizations of the ferromagnetic layers increases the efficiency of the triplet mode in comparison with the three-layer structure, while, for the direct mode, the additional layer reduces it. This facilitates the experimental observation of the triplet spin-valve effect in the superconductor–ferromagnet heterostructure without using "exotic" ferromagnetic semimetals.

For a more detailed and deep understanding of the mechanisms for implementing various spin valve modes, it is necessary to calculate the distribution of the spin-singlet and spin-triplet components of the superconducting pairing over the layers of such heterostructures. Further work will be devoted to this.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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