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SPECTRUMS OF SUPERCONDUCTING STATES AND TRIPLET EFFECTS IN SUPERCONDUCTOR/FERROMAGNET MULTILAYERS

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Abstract. We report the results of studies of triplet superconductivity in structures with alternating superconductor and ferromagnet layers, as a part of the general problem of the properties of the spectra of superconductivity states depending on the magnetic state of the multilayer structure. Ferromagnetic layers are assumed monodomain and possessing inplane magnetic moments. In numerical examples, we used the parameters of the well-studied Nb/PdNi system. The critical temperatures and distributions of singlet and triplet currents depending on the relative orientation of the magnetic moments of the ferromagnetic layers are calculated in the formalism of the Usadel equations for 5- and 3-layer irregular structures. The following results are obtained. (1) The channeling effect of triplet pairs by a narrow central layer of a superconductor with complete suppression of the singlet component in it was confirmed. (2) The "0–1"-transition between the phases of a superconducting condensate of opposite symmetry induced by the transport current is predicted. (3) The effect of a double crossover of states on the dependence of the critical temperature, T_c, versus the angle θ between the magnetic moments of the ferromagnetic layers adjacent to the central layer of the superconductor in a 3-layer structure is predicted. The crossovers are reflected by a sharp turns in the T_c (θ) curve, while the infinitely small asymmetry of the structure eliminates the non-analyticity of this characteristic.

Keywords: Odd-frequency triplet superconductivity, Usadel equations.

Conflict of interests. The author declares no conflict of interests.

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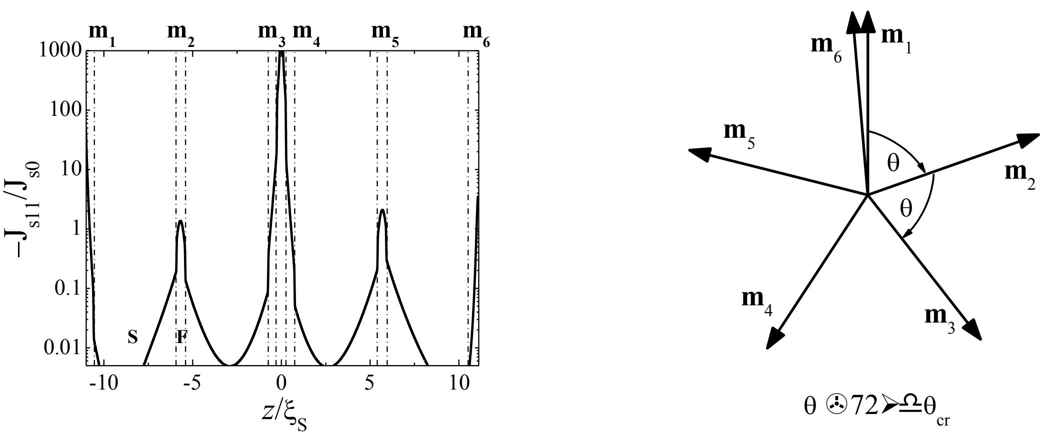
Introduction

In layered superconductor(*S*)/ferromagnet (*F*) structures, the superconducting order parameter is characterized by two properties due to the exchange interaction in the *F*-layers, namely, it has an oscillating character and includes triplet components in the case of nonuniform magnetization of the ferromagnetic subsystem [1, 2]. The devices of two types are based on these properties: the π-contact elements of logical circuits for nanoelectronics, and the spin valves in spintronics [1–5]. In the *S*/*F* multilayers, the oscillations of the order parameter result in the possibility of a realization of *spectra* of superconductivity states, as was proved in [5–8]. In the previous works [5–10], it was shown how to realize experimentally a given superconductivity state. Here, we report some of the triplet effects that occur near the transition between states in the structures *n*[F/S]/F1/S0/F2/*n*[S/F] (*n* = 1, 2,…) with the thin S0-layer and in-plane magnetized *F*-layers [10]. The calculations have carried out within the framework of Usadel equations formalism [11], and the structure's material parameters, applied in the simulations, are close to that of Nb/PdNi system [7, 8].

The thin Nb layer as a channel for the triplet components of the superconducting condensate

A thin layer of superconductor, S0, which is used as a “passive” buffer in the trilayer spin valve S/F1/S0/F2, has an appreciable effect on the distribution of supercurrents in the multilayer structures [9, 10]. Indeed, let the structure F/*n*[S/F/]S0/*n*[F/S/]F be in the superconducting “1-state” (the state with the antisymmetric eigenfunction with one node), when all magnetic moments of the *F*-layers are parallel to a given direction in the plane of layers (*XOY*). Further, let the mutual rotation of the magnetizations of *F*-layers contacting with S0-layer implyies the transition of the superconducting condensate to the “0-state” (described by eigenfunction without nodes) at some value θ_{cr} of the angle θ between magnetizations [10]. Then, the left neighborhood of the θ_{cr} value corresponds to the almost full suppression of the singlet component (s_0) and the most intensive triplet ones in the whole S0-layer. Moreover, there exist configurations of the orientations of magnetizations, when the triplet components (s_{11}) with spin’s ±1 projections are practically the only filling S0-layer. Thus, the singlet superconductor becomes a channel only for a triplet supercurrent. This effect calculated for the structure 2[F/S]/F/S0/F/2[S/F] with the spiral configuration of magnetic moments $\boldsymbol{m}_i$ (i = 1... 6) has demonstrated in Fig. 1.



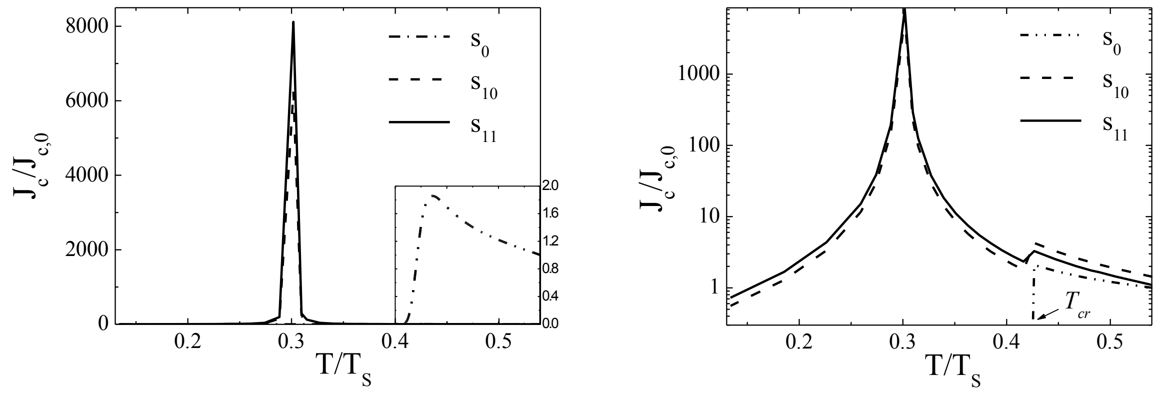
a *b*

Fig. 1. The distribution of the triplet component of the supercurrent in *S*/*F* structure under consideration, taken in relation to the singlet one (*a*); the magnetic moments configuration for which this distribution has been calculated (*b*)

The induction of «0–1» transition and the peak of the triplet supercurrent

The transport current can induce the nontrivial redistribution of singlet and triplet components of the superconducting condensate. Indeed, let the described above structure 2[F/S]/F/S0/F/2[S/F] be in the “0-state” reached from the “1-state” by the synchronous rotation of the magnetic moments of the even *F*-layers at an angle θ belonging to the small right vicinity of the θ_{cr} value. Then, when the transport current increases, the superconducting condensate can either (*A*) keep the “0-state” or (*B*) cross to the “1-state” at some point J_{cr}. The case (*B*) manifests itself on the temperature dependence of the critical current density by the weak jump down at the crossover point T_{cr} and by the peak of the triplet components at a point $T_{peak} < T_{cr}$, as we see from Fig. 2, where there are shown the curves $J_c(T)$ estimated for the center of S0-layer.

The same but smoothed curves characterize the current densities averaged over the S0 region.



a *b*

Fig. 2. The temperature dependencies of the singlet and triplet components of the critical current density at the symmetry axis of the F/2[S/F/]/S0/F/2[S/F] structure, calculated for the angle 82,5° between the magnetic moments of even and odd *F*-layers; inset: singlet component, scaled-up (*a*); the same on the logarithmic scale (*b*)

Repeated crossover in the symmetric and asymmetric 3-bilayers

In this section, we investigate the evolution of the superconducting critical state of the "minimal" structure F/S/F1(θ)/S0/F2(–θ)/S/F at the symmetrical rotation of the magnetic moments ($\boldsymbol{m}_1$ and $\boldsymbol{m}_2$) of inner *F*-layers (*F*1 and *F*2) in opposite planar directions θ from the initial state for which all magnetizations are parallel to a given vector $\boldsymbol{m}$. We assume that the superconducting condensate is initially in 1-state, as stipulated above. Fig. 3 shows the dependences of the critical temperature T_c versus the angle θ calculated for one of the values of the exchange energy (E_{ex}) of a ferromagnetic material (allowed by the diffusive limit of the theory of superconductivity) and for the different deviations ΔE of exchange energies of the *F*1 and *F*2 layers (E_{ex1} and E_{ex2}) from the E_{ex}.

As can be seen in Fig 3, the dependencies $T_c(\theta)$ reveal the complex oscillatory effect, which is well pronounced if the values of exchange energies of *F*-layers are equal to each other. Namely, the function $T_c(\theta)$ consists of three branches that correspond to the alternating "1", "0" and "1" states and are parted by the crossover points θ_{cr1} (~ 36°) and θ_{cr2} (~ 147°). Actually, first and third branches are the parts of a continuously differentiable function $T^{(1)}(\theta)$, as well as the segment of $T_c(\theta)$ between two crossover points is a part of the smooth function $T^{(0)}(\theta)$, where $T^{(0)}$ and $T^{(1)}$ are two of the eigenvalues of T_c for the structure under consideration. The branch $T^{(0)}$ includes the absolute maximum of the function $T_c(\theta)$ at the point $\theta = \pi/2$, that is, at antiparallel vectors $\boldsymbol{m}_1$ and $\boldsymbol{m}_2$ which, in turn, are orthogonal to the vector $\boldsymbol{m}$. It is worth noting that in this state, the triplet component s_{11} disappears only in the S0, but it is quite intensive in the *F*1 and *F*2 layers; note also that the existence of two local maximums (at θ = 0° and θ = 180°) is the expected effect of the vanishing of the triplet s_{11} pairs. Again, pay attention to the vicinities of the crossover points, $\theta_{cr1} - 0$ and $\theta_{cr2} + 0$ (which corresponds to the "1-state"), where the effect of the triplet component channeling by S0-layer should be observed.

The described behaviour of the $T_c(\theta)$ curve holds for the arbitrary values of $E_{ex1} = E_{ex2} = E_{ex}$ but, the even weak asymmetry ΔE in the exchange energies of the *F*-layers ($E_{ex1} = E_{ex} + \Delta E$, $E_{ex2} = E_{ex} - \Delta E$) results in the qualitative change of this characteristic. Namely, the points of the derivative discontinuity disappear on the curve $T_c(\theta)$ (see Fig. 3), and, simultaneously, the distribution of the singlet component loses its symmetry; moreover, the increasing in ΔE implies the full loss of the superconducting condensate in the half of the structure (which contains the more strong ferromagnet).

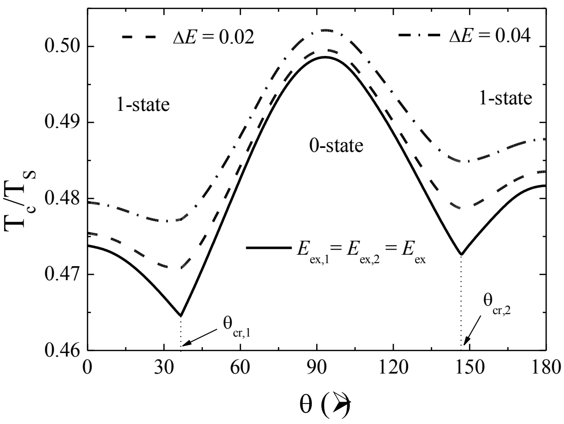


Fig. 3. The dependences of the critical temperature of the structure F/S/F1(θ)/S0/F2(–θ)/S/F on the angle θ at the different "asymmetry" of *F*-layers in the exchange energy (see the main text for explanations)

Conclusions

In this paper, we reported three results of projects implemented in the framework of the State Program of the Scientific Research "Nanotech" (2016–2018) and "Energy-Effectiveness" (2014–2015). The following results are obtained. (1) The channeling effect of triplet pairs by a narrow central layer of a superconductor with complete suppression of the singlet component in it was confirmed. (2) The "0–1"-transition between the phases of a superconducting condensate of opposite symmetry induced by the transport current is predicted. (3) The effect of a double crossover of states on the dependence of the critical temperature, T_c, versus the angle θ between the magnetic moments of the ferromagnetic layers adjacent to the central layer of the superconductor in a 3-layer structure is predicted. The crossovers are reflected by a sharp turns in the T_c (θ) curve, while the infinitely small asymmetry of the structure eliminates the non-analyticity of this characteristic.

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