Proximity Effect and Spontaneous Vortex Phase in Planar SF-Structures

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The proximity effect in SF structures was examined. It is shown that, due to the oscillations of the induced superconducting order parameter in a ferromagnet, the critical temperature of an SF-bilayer becomes minimal when the thickness of the ferromagnetic layer is close to a quarter of the period of spatial oscillations. It is found that the spontaneous vortex state arisen in the superconductor due to the proximity of the magnetic domain structure of a ferromagnet brings about noticeable magnetoresistive effects.

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In recent years, considerable interest has been shown in metallic multilayer systems with alternating magnetic and nonmagnetic layers. The normal metal-ferromagnet structures (NF systems) exhibiting giant magnetoresistance have already found practical use in computer technology [1]. Promising elements based on the multilayer superconductor-ferromagnet structures (SF-systems), such as the FSF spin valve [2], Josephson SFS π-junction [3], and others, were also being suggested and studied. The coexistence of superconductivity and ferromagnetism is the problem of long-standing interest. The antagonism of these two phenomena differing in spin ordering is a cause for the strong suppression of superconductivity in the contact area of the S and F materials [3]. The appearance of oscillating sign-reversal order parameter in the F layer near the SF interface [3] is another fundamental consequence of the proximity a ferromagnet and a superconductor. Inspite of numerous theoretical works, experimental studies of the SF structures are in their infancy. In particular, the influence of a real domain structure on the indicated and other phenomena in the SF systems still remains to be studied. In this work, three different types of SF structures differing in size and geometry were prepared and studied: a continuous thin-film strip of SF bilayer, a macroscopic superconducting $S-F-S$ bridge (Notarys-Mercereau bridge [4]), and a one-dimensional chain of submicron (mesoscopic) $S-F-S$ bridges. The goal of this work was to observe the following effects: (i) influence of the $F$-layer thickness and the sign-reversal order parameter on the critical temperature $T_{c,SF}$ of the SF-bilayer; (ii) appearance of a spontaneous vortex state due to the proximity of the magnetic domain structure of a ferromagnet; and (iii) appearance of additional resistive contributions in the $S-F-S$-bridge chains caused by the injection of nonequilibrium quasiparticles from the SF regions into a superconductor.

Experimental studies were carried out on the bilayer $Nb-Cu/Ni$ SF-structures, in which the $Cu_{0.44}Ni_{0.57}$ alloy films with the Curie temperature $T_C \sim 150\,K$ were used as a ferromagnetic layer [7]. Bottom superconducting Nb layer with a thickness of 9 – 11 nm (close to the coherence length) was sputtered by dc-magnetron. Top copper-nickel alloy film was deposited in a single vacuum cycle by rf-diode sputtering. Weak ferromagnetism of the $Cu/Ni$ alloy allowed us to retain the superconductivity of the SF bilayer with $T_{c,SF}$ close to the standard helium temperatures of 2 – 4K and compare the obtained results with the results of Josephson experiments [5] on the $Nb-Cu_{0.44}Ni_{0.57} – Nb$ sandwiches, in which a weak ferromagnetism was necessary for the fabrication of continuous homogeneous $F$-layers whose thickness would be comparable with the pair-decay length $\xi_F$. Inasmuch as the pair-decay length in the layers of classical ferromagnetic materials (Co, Fe, Ni) is close to 1nm, the fabrication of thin-film Josephson SFS-junctions using these metals is a challenge. The use of ferromagnetic alloys with low Curie temperatures allowed us to increase the pair-
To study the resistive processes in the current flow along the SF-bilayer in more detail, planar \( S - SF - S \) structures were prepared (their different projections are shown in the insets in Figs. 2, 3). The SF-bilayer was situated only in the central section of superconducting bridge and formed by a ferromagnetic strip, which completely spanned the superconducting bridge and suppressed superconductivity in a square area of \( 10 \times 10 \mu m \). To avoid the effects discussed in the preceding paragraph, the \( F \)-layer thickness was taken to be large enough (18 nm) to suppress appreciably the \( S \)-layer and exclude the formation of a barrier associated with the oscillations of superconducting order parameter in the ferromagnet. The bridges with above-mentioned sizes and the superconducting bridges with \( F \)-islands of submicron size described in the last section of this article were formed using electron-beam lithography. A two step resistive junction obtained with a minimal transport current of 0.5 \( \mu A \) is shown in Fig. 2a. The higher temperature step with normal resistance \( R_n \) of the structure corresponds to the superconducting transition in the ferromagnet-free thin niobium film. The transition at \( T_{c, SF} = 3.6 - 3.8K \) corresponds to the resistive transition in the SF-bilayer with thickness \( d_S = 4 \) nm and \( d_F = 10 \) nm. As it is seen in Fig. 2b, the lower-temperature transition broadens sizably with an increase in transport current. However, at the temperature \( T^* = 2.6 - 2.65K \) new sharp step arises, evidencing the abrupt dramatic increase in the critical current of the \( S - SF - S \) bridge below this temperature. The bridge current-voltage characteristics (CVC’s) for different temperatures (in the absence of applied magnetic field) are shown in Fig. 3. One can clearly see that the jumplike increase in the critical current below \( T^* \) is associated with a cardinal change of the resistive mechanism in the bridge. In the temperature range \( T^* < T < T_{c, SF} \), the characteristics exhibit constant differential resistance corresponding to the magnetic-flux flow regime. The behavior below \( T^* \) is typical for long superconducting bridges, in which the dissipation is caused by the sequential appearance of vortex slip lines incipient at the bridge edges. The appearance of each line is displayed on the CVC as a new slanted step, which was experimentally recorded using a repeated current scan in the corresponding area. The unexpected, at first glance, zero-field flux-flow regime at high temperatures can easily be explained by the presence, in the superconductor, of a spontaneous vortex phase associated with the stray magnetic field in the domain walls of the ferromagnetic film. The appearance of the spontaneous vortex phase was theoretically

decay length by several orders of magnitude and observe the transition of a Josephson SFS-junction to the \( \pi \)-state upon a decrease in temperature [3].

Figure 1 shows the experimental geometry and the measured critical temperature \( T_{c, SF} \) of the bilayer SF-structures with a superconducting niobium layer of thickness 11 nm, close to the coherence length in the thin-film niobium (\( 7 - 8 \) nm), and different thicknesses \( d_F \) of a ferromagnetic layer. The superconducting transition width was \( \sim 0.3K \). The curve shows the \( T_{c, SF} \) values corresponding to the onset of transition, its middle part, and completion. It is seen that the dependence of \( T_{c, SF} \) on \( d_F \) is nonmonotonic and has minimum at a ferromagnet thickness of 5 - 8 nm. Such a dependence was predicted in [3] and first observed for a bilayer \( Nb/Gd \) structure in [10]. This phenomenon is caused by the appearance of superconducting electron pairs with the nonzero net momentum in the presence of the exchange field that gives rise to the specific LOFF-state with the inhomogeneous sign-reversal order parameter, as was predicted in 1964 by Larkin and Ovchinnikov [11] and Fulde and Ferrel [12]. The induced superconductivity in a ferromagnet near the SF-interface proved to be a quite realizable LOFF modification [5, 6, 13]. It was shown in [14, 15] that the spatial oscillations of the order parameter in an SF-bilayer with the thickness \( d_F \) on the order of coherence length \( \xi_F \) in the ferromagnet give rise to the oscillations of the SF-interface transparency, providing the simplest explanation for the nonmonotonic dependence of \( T_{c, SF} \) on \( d_F \). Simple considerations suggest that the lowest barrier at the SF-interface (lowest \( T_{c, SF} \)) corresponds to the thickness \( d_F \) close to 1/4 of the period \( \lambda_{LOFF} \) of spatial oscillations of the induced superconducting order parameter in the \( F \)-layer [16]. A comparison of the curve in Fig. 1 with the results of a detailed theoretical analysis was carried out in [16, 17]. We also had a chance of comparing the period of spatial oscillations with the results obtained in the experiments with the Josephson SFS sandwiches, in which the same composition of \( Cu/Ni \) alloy was used as a Josephson interlayer and the same sputtering technique was applied (for the details of preparation and study of the Josephson SFS junctions, see [3]). The transition to the \( \pi \)-state [3, 5, 16, 18], in which the order parameter has different signs on different banks of the SFS sandwich, occurs for the ferromagnetic interlayer thickness close to a half-period of spatial oscillations of the order parameter. In the \( Nb - Cu_{0.43}Ni_{0.57} - Nb \) sandwiches, we observed this transition [19] for the \( F \)-layers with a thickness of 15 nm, i.e., twice the thickness corresponding to the minimal \( T_{c, SF} \) of the bilayer SF-structure, in agreement with the theoretical estimates [3, 16].
discussed for "superconducting ferromagnets" and multilayer SF-structures in [20, 21].

The appearance of the vortex phase lines in the superconducting layer near the domain walls of the ferromagnetic layer with in-plane magnetic anisotropy is shown in the inset in Fig. 4. The correlation between the flux-flow resistance and the number of domains (domain walls) is confirmed by the magnetic field measurements (Fig. 4). Magnetic field was applied parallel to the bilayer plane. The observed symmetric (i.e., even with respect to the field sign) behavior of \( R(H) \) is caused by the direct action of the field on the superconducting film. The curves also show positive magnetoresistance peaks at the "magnetization reversal" fields corresponding to the sample coercive field (the hysteresis loop \( M(H) \) is schematically drawn above the \( R(H) \) curve; coercive fields were measured in the magnetic and Hall experiments). In the step region on the \( R(T) \) curve (Fig. 2b), i.e., at temperatures \( T \) slightly above \( T^* \) and currents \( I \geq I_c \), the magnetoresistance coefficient can be rather large and exceed 100%.

We now discuss the conditions for the appearance of spontaneous vortex phase in the SF-bilayer and the value of critical temperature \( T^* \) for transition to the "Meissner" phase. The lower critical field for the penetration of a perpendicular magnetic field into the film is determined by the effective penetration depth \( \lambda_\perp = \lambda^2/d_\perp \) and its temperature dependence (\( \lambda \) is the field penetration depth into a thick film). Using the parameters of our film, one can estimate \( H_{c1}(0) \sim 10 - 20G \). This is comparable with the estimates of stray fields in the domain structure of our weak ferromagnet, if one assumes that the domain wall width is on the order of the domain size (~0.2 – 0.5\( \mu m \)). Therefore, \( T^* \) is the temperature for which the stray field becomes comparable with \( H_{c1}(T) \). Below this temperature the field of ferromagnetic film does not pierce the superconducting film through, and the flux-flow regime ceases. This model is additionally confirmed by the fact that the constant differential resistance disappears from the CVCs of \( S - SF - S \) bridges with the \( F \)-island sizes on the order of 0.2 \( \times \) 0.5\( \mu m \). The ferromagnetic islands with this area are, in fact, single-domain, so that the stray field in the region of such domain is appreciably weaker than the field produced by the domain wall.

We undertook attempt to connect the neighboring SF-regions in a one-dimensional chain of \( S - SF - S \) bridges with each other using spin-polarized quasiparticles injected into the ferromagnet-free sections of the superconducting film. As is illustrated in the inset in Fig. 5, a section of the initial SF-bilayer was "cut" at a length of 50\( \mu m \) so as to form SF-bridges separated by the sections of the Nb-film. Since the length \( L_F = 0.2\mu m \) of the ferromagnetic island remained constant, the spacing between the islands was varied by changing their number \( N \) in the structure. The results obtained for three structures with the superconducting sections \( L_S = 1, 0.5, \) and 0.2 \( \mu m \) and, correspondingly, the number of SF islands \( N = 30, 70, \) and 100 are presented in Fig. 5. In all cases, the bridge width was equal to 0.5 \( \mu m \). The resistive transition curves are given in the \( T/T_{c,SF} \) coordinates, because the critical temperatures of the free \( Nb \)-sections were slightly different due to the fact that the instant of time the \( Cu/Ni \)-layer etching was completed could not be controlled accurately, so that the niobium layers were slightly different in thickness. In addition to this transition and a rather smeared resistive transition for the \( SF \)-islands, a new step, associated with the resistance caused by the nonequilibrium quasiparticle injection into the superconducting sections, evolves in the mid-transition region starting at \( L_S = 1 \) \( \mu m \). At \( L_S = 0.2 \) \( \mu m \) (\( N=100 \)), this contribution becomes dominant. The estimate of the penetration depth of nonequilibrium quasiparticles (charge-imbalance relaxation length \( \lambda_Q \)) into superconducting \( Nb \) at temperatures \( T_{c,Nb} \) close to gives a value comparable to 0.2 \( \mu m \). For the case of spontaneous antiparallel alignment of the magnetizations in the neighboring \( F \)-islands, one could expect noticeable magnetoresistive effects in a magnetic field applied perpendicular to the bridge chain in the layer plane. Nevertheless, no appreciable effects were observed, most probably, because of the absence of antiferromagnetic alignment and the weak spin polarization of quasiparticles in our system.

In summary, the proximity effect in the SF-system have been studied in this work: it is shown that, due to the spatial oscillations of the induced superconducting order parameter in a ferromagnet, the critical temperature \( T_{c,SF} \) of a bilayer has a minimum when the thickness of the ferromagnetic layer is close to a quarter of the period of spatial oscillations. The occurrence of a spontaneous vortex state caused by the proximity of the domain magnetic structure of a ferromagnet has been observed in a superconductor. In this state, the magnetoresistive effects are quite appreciable.

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Fig. 1. Critical temperature of a bilayer $Nb – Cu_{0.43}Ni_{0.57}$ structure vs. the thickness of ferromagnetic layer.

Fig. 2. Resistive transition of the $S – SF – S$ bridge: (a) full curve for a current of $0.5 \mu A$ and (b) a part of the transition corresponding to the $SF$ bilayer for currents 0.5, 1, 10, 30, 80, and 110 $\mu A$.

Fig. 3. Current-voltage characteristics of the $S – SF – S$ bridge at temperatures 3.47, 3.2, 2.89, 2.66, 2.6, and 2.49 K.

Fig. 4. Resistance of the $S – SF – S$ bridge vs. longitudinal magnetic field at $T = 2.66 \text{K}$ and a current of $50 \mu A$. Arrows indicate the field-scan direction. The magnetization curve for a $Cu/Ni$ layer is schematically shown at the top.

Fig. 5. Resistive transitions of a one-dimensional chain of $S – SF – S$ bridges: $N = (1)$: 30, (2): 70, and (3): 100.

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