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Abrikosov vortices in SF bilayers

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It is well known that the critical temperature, T_C, of superconductor-ferromagnetic (SF) sandwiches and critical current, I_C, of Josephson SFS junctions are non-monotonic functions of thickness, d_F, of the ferromagnetic layer [1–3]. It should be noted that these theoretical predictions were obtained in structures, which are homogeneous along SF interfaces. Should we expect similar effects in the two-dimensional case, when the superconducting correlations depend on the spatial coordinates along an SF interface is still an open question.

Abrikosov vortex is one of example providing such an inhomogeneity. The goal of this paper is to demonstrate that (by analogy with the oscillations of T_C and I_C) non-monotonic alterations in the structure of Abrikosov vortex in SF sandwich is indeed possible. We show that by varying the exchange field in an F-layer or by varying S/F interface transparency one can achieve vortex current reversal in the F-layer.

We consider SF bilayer in external magnetic field, H, oriented perpendicular to the plane of the bilayer. We assume that the conditions of dirty limit are valid for both films and pair potential Δ is zero in the F film. The F layer is supposed to be a single domain ferromagnet with out-of-plane direction of its easy axis. To define the coordinate dependence of the Green's function we use the Wigner-Seits approximation [4] for elementary vortex cell and replace hexagonal vortex unit cell on a circular one with radius $r_S = \sqrt{\Phi_0/\pi H}$, where Φ_0 is magnetic flux quantum.

Under the above assumptions we analyzed the problem in the frame of two-dimensional Usadel equations [5] with KL boundary conditions [6] at SF interface and Maxwell equation, $\operatorname{rot}\operatorname{rot}\mathbf{Q} = \kappa^{-2}\mathbf{J}$, which relates the vector potential $\mathbf{Q} = (0, Q, 0)$ with supercurrent $\mathbf{J} = (0, J_S, 0)$. To find the solution of the Maxwell equation we have supposed that the Ginzburg–Landau parameter $\kappa = \lambda_{S\perp}/\xi_S \gg 1$. This condition allows to neglect the magnetic field produced by current in comparison with the applied external field H and get $Q = (1 - r^2/r_S^2)/r$, where r is a radius from vortex center and Q is normalized on $\Phi_0/2\pi\xi_S$. The external field is constant inside a circular vortex cell provided that the cell radius r_S is less than $\lambda_{S\perp} = \max(\lambda_S, \lambda_S^2/d_S)$, where λ_S is the London penetration depth.

We demonstrate that the considered problem can be simplified in the limit of small F layer thickness $d_F \ll \xi_F/\mathrm{Re}(\sqrt{\widetilde{\Omega}})$, where $\widetilde{\Omega} = \Omega + iE$, $\Omega = (2n+1)t$ are Matsubara frequencies, E is normalized on πT_C exchange energy, $\xi_F = (D_F/2\pi T_C)^{1/2}$, D_F is diffusion coefficient in the F film, $t = T/T_C$, T is a temperature of the bilayer. We formulate the conditions that permit to find analytical relation between Usadel anomalous functions in the F, $\theta_F(r)$ and S, $\theta_S(r)$ layers and developed numerical code for calculation of $\theta_S(r)$.

Substitution of $\theta_F(r)$ into expression for the supercurrent density in the F-film results in

$$\frac{e\rho_F\xi_F J_S(r)}{2\pi T_C} = t\sum_{\Omega\geq 0}^{\infty} \frac{p}{\sqrt{p^2+q^2}} \sin^2\theta_S(r) Q, \qquad (1)$$

where $p = \left(1 + 2\gamma_{BM}\Omega\cos\theta_S(r) + \gamma_{BM}^2\Omega^2\right) - E^2\gamma_{BM}^2$, $q = 2\gamma_{BM}E\left(\cos\theta_S(r) + \Omega\gamma_{BM}\right)$, and suppression parameter $\gamma_{BM} = R_{BF}\mathcal{A}_B d_F/\rho_F\xi_F^2$, ρ_F is the normal state resistivitiy of the F metal, R_{BF} and $\mathcal{A}_B$ are, respectively, the resistance and the area of the FS interface. It follows from (1) that with an increase of E or γ_{BM} the transformation takes place when proximity induced vortex supercurrent around the core in the F-layer changes its direction compared to the current in the S-layer. To illustrate this effect, we performed numerical calculations of the supercurrent within the vor-

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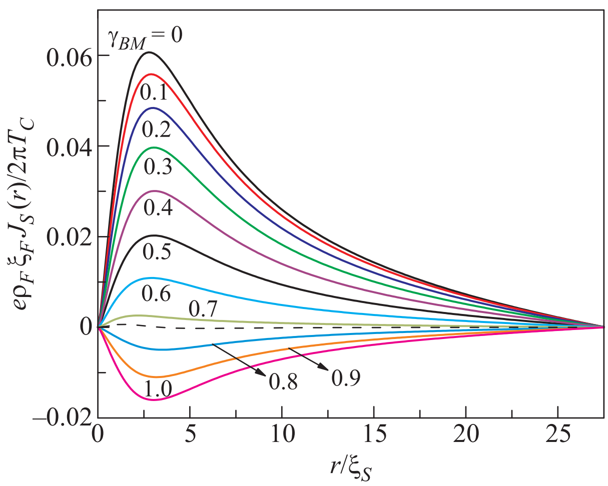

Fig. 1. (Color online)The spatial distribution of the supercurrent within the vortex unit cell in the F part of SF bilayer for $T = 0.2T_C$, $E = 2\pi T_C$ and for various values of the suppression parameter γ_{BM}. The dashed line corresponds to $\gamma_{BM} \approx 0.73$

tex unit cell in the F-layer (see Fig. 1) for different values of γ_{BM}, fixed exchange energy $E/\pi T_C = 2$, $t = 0.2$ and $H/H_{C2} = 0.01$, which corresponds to $r_S = 27.5\xi_S$. It is seen that for $\gamma_{BM} = 0$, the proximity-induced circulating supercurrent flows in the F-layer. The current density achieves its maximum value at $r \approx 2.5r_S$ and then goes to zero at $r \to r_S$. Increase of γ_{BM} results first in gradual suppression of this current and at $\gamma_{BM} \approx 0.73$ (the dashed line in Fig. 1) two regions are formed inside the cell with currents flow in opposite directions. Further increase of γ_{BM} leads to reversal of the supercurrent direction in the F-layer compared to that in the S-layer.

The physical mechanism of this transformation is the same as discussed previously for the formation of so-called π-junctions in SFS Josephson devices. Superconducting current in the SF structures has two contributions. The first one, defined by the singlet superconducting correlations, is always positive. The second, negative, contribution to the current is due to the triplet order parameter component. Such separation of the current into two components is realized in the present case, as follows from the expressions (1). In a certain range of parameters of the studied SF structures, the negative contribution to the current may prevail over the positive one thus resulting to the vortex current reversal discussed above.

It is necessary to mention that in our approximation the magnetic field is not a function of r and its integration over circular unit cell results in magnetic flux inside the cell exactly equal to Φ_0, independently on a direction of supercurrent circulating around the vortex core. In the next approximation with respect to the Ginzburg–Landau parameter $\kappa \gg 1$ there should be corrections to spatial distribution of the magnetic field inside the unit cell proportional to κ^{-2}. In the case of an SN bilayer ($E = 0$) or for $\gamma_{BM} \lesssim 0.7$ and $E = 2\pi T_C$ (see Fig. 1) the correction has maximum in the center of the vortex core and decreases monotonically with increase of r. Therefore the net magnetic field should exhibit small spatial modulation typical for an Abrikosov vortex: there is maximum of H in the core region ($r \lesssim \xi_S$) and monotonous decay to a constant value at $r = r_S$.

Contrary to that, for $\gamma_{BM} \gtrsim 0.75$ and $E = 2\pi T_C$ the correction to magnetic field generated by circulating supercurrent in the area $r \lesssim \xi_S$ should have direction opposite to that of external field H. As a result, the net magnetic field should have a minimum in the core region and should increase with r.

Note that magnetic flux per unit cell exactly equals to Φ_0 in both cases considered above. At the same time, the difference between magnetic field distributions can detected by means of magnetic force microscopy [7], by muon scattering experiments [8] or by means of nano-SQUID [9].

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