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Decoupled superconductivity in the four- and five-layered ferromagnet–superconductor nanostructures and control devices

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Abstract

The ferromagnet/superconductor (F/S) tetra- and pentalayer consisting of rather dirty metals are considered with regard for the boundary conditions. The dependences of critical temperatures T_c versus the thicknesses of the F layers are investigated. The clearest manifestation of *decoupled superconductivity* for the $F'/S'/F''/S''$ *tetralayer* is the rise of a *hierarchy* of transition temperature T_c, and *different* S' and S'' *layers* can have *different critical temperatures*. The same is valid for *nonsymmetrical* case of the $F'/S'/F''/S''/F'''$ *pentalayer*. The complicated phase diagram of the tetralayer is discussed. The *inverse* action of *superconductivity on magnetism* leads to preferable mutual *antiferromagnetic* orientation of magnetizations of the F' and F'' layers, if the inner S' layer is in the *superconducting* state. Conceptual scheme of the new nanoelectronics control device, that has up to *seven* different states and combine in one sample the advantages of two different recording channels, is proposed.

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1. Introduction

For the ferromagnet/superconductor (F/S) heterostructures consisting of alternating ferromagnetic metal (F) and superconducting (S) layers, the superconducting order parameter (OP), owing to the proximity effect, can be induced in the F layer; on the other hand, the neighbouring pair of the F layers can interact with one another via the S layer. One can control properties of such systems varying the thicknesses of the F and S layers (d_f and d_s) or changing external magnetic field **H**. Numerous experiments on the F/S *structures* revealed nontrivial dependences of superconducting transition temperature T_c on the thickness d_f (see reviews [1,2] and references therein).

The first solution [3,4] of the boundary value problem (BVP) for pair amplitude in the dirty F/S superlattices led to the possibility of the nonmonotonic dependence $T_c(d_f)$ which was related to periodically switching the ground superconducting state between the 0 and π phases. Later the boundary conditions valid for arbitrary transparency of the F/S interface were deduced from the microscopic theory [1]. An additional mechanism of nonmonotonic dependence $T_c(d_f)$ [1,5–8] has been revealed due to modulation of the pair amplitude flux from the S layer to the F layer by thickness d_f. The reentrant superconductivity predicted by us [1] has been recently observed in the Fe/V/Fe trilayer [9].

The superconductivity in the F/S systems [1,10] is a combination of the BCS pairing in the S layers and the Larkin–Ovchinnikov–Fulde–Ferrell (LOFF) [11] pairing with a nonzero three-dimensional (3D) momentum of pairs in the F layers. Nevertheless, usually it is assumed [3–8,12]

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that momentum of the LOFF pairs is directed across the F/S interface (the 1D case [1,10]).

Basically, the F/S structures possess two data-record channels: on the superconducting properties and the mutual ordering of the F layers magnetizations. A sketch of "spin-switch" device of current based on the F/S/F *trilayer* was proposed in Refs. [13,14]. This F/S/F device operates only on transition between the superconducting (S) and normal (N) states controlled by external magnetic field H. In this valve regime the data stored on the superconducting current and mutual orientation of magnetizations change *simultaneously*, the magnetic order completely determines the superconducting properties.

The *multilayered* F/S systems have additional competition between the 0 and π phase types of superconductivity. Our detailed analysis [1,15] has shown that the F/S superlattice possesses four different states: two ferromagnetic superconducting (FMS) ones (00, π0), and two antiferromagnetic superconducting (AFMS) ones (0π and ππ). They are distinguished by the phases of the superconducting (the first symbol) and magnetic (the second one) OPs. In the AFMS states the pair-breaking effect of exchange field I of the F layers in the S layers is significantly attenuated, and the transition temperature is higher than in the FMS case. This theoretical prediction of ours has been experimentally confirmed for the Gd/La *superlattice* [16]. We have also proposed the principal scheme of the device that allows to *separate* the superconducting and magnetic data-record channels for the F/S *superlattice* [1]. However, both from the point of view of manufacturing and the "layer-by-layer" control by a weak magnetic field, the "superlattices" with a limited number of layers are more interesting objects.

Below we solve the Usadel equations for the four-and five-layered F/S systems taking into account the boundary conditions. Then, the phase diagrams with an optimal set of parameters are constructed, and some applications for nanoelectronics are discussed.

2. The theory

The studied systems are shown in Fig. 1. To calculate T_c we use our 1D theory [1] with the dirty limit conditions ($l_s \ll \xi_s \ll \xi_{s0}$, $l_f \ll a_f \ll \xi_f$) and usual relation between the energy parameters ($\varepsilon_f \gg 2I \gg T_{cs}$). ε_f is the Fermi energy; $l_{s,f} = v_{s,f}\tau_{s,f}$ is the mean free path length for the S(F) layer; $\xi_{s,f} = (D_{s,f}/2\pi T_{cs})^{1/2}$ is the superconducting coherence length; ξ_{s0} is the BCS coherence length; $D_{s,f} = v_{s,f} l_{s,f}/3$ is the diffusion coefficient; T_{cs} is the critical temperature of the S material; $v_{s,f}$ is the Fermi velocity; $a_f = v_f/2I$ is the spin stiffness length.

The BVP [1] for each layer is reduced to the Gor'kov self-consistency equations for $F(z,\omega)$ (the Gor'kov function or the "pair amplitude") and to the Usadel equations

$$\Delta_{s,f}(z) = 2\lambda_{s,f}\pi T \mathrm{Re}\sum_{\omega>0} F_{s,f}(z,\omega), \quad (1)$$

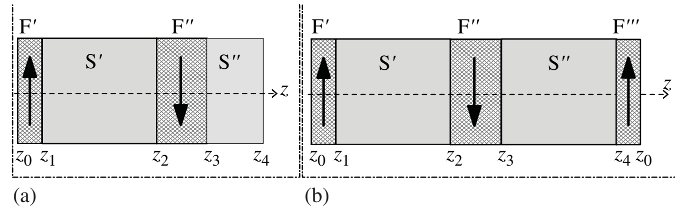

Fig. 1. The geometry of the F′/S′/F″/S″ tetralayer (a) and the F′/S′/F″/S″/F‴ pentalayer (b) in the AFM configuration. Vertical arrows show the directions of the (in-plane) magnetizations that play the role of the magnetic OP. Here $z_0 = -d_f/2$, $z_1 = 0$, $z_2 = d_s$, $z_3 = d_s + d_f$, $z_4 = 3d_s/2 + d_f$ for the tetralayer (panel a); for the pentalayer $z_4 = 2d_s + d_f$ and $z_5 = 2d_s + 3d_f/2$ (panel *b*).

$$\left[\omega - \frac{D_s}{2}\frac{\partial^2}{\partial z^2}\right] F_s(z,\omega) = \Delta_s(z),$$

$$\left[\omega + iI(z) - \frac{D_f}{2}\frac{\partial^2}{\partial z^2}\right] F_f(z,\omega) = \Delta_f(z), \quad (2)$$

$$\frac{4D_s}{\sigma_s v_s}\frac{\partial F_s(z,\omega)}{\partial z}\bigg|_{z=z_i\pm 0} = \frac{4D_f}{\sigma_f v_f}\frac{\partial F_f(z,\omega)}{\partial z}\bigg|_{z=z_i\mp 0} = \pm[F_s(z_i \pm 0,\omega) - F_f(z_i \mp 0,\omega)]. \quad (3)$$

In the boundary conditions (3) an index i numbers the *inner* interfaces (see Fig. 1). The upper signs are chosen at $i = 1$, 3, the lower signs are chosen at $i = 2$ (and $i = 4$ for pentalayer). $\partial F_{s,f}(z,\omega)/\partial z$ equals zero at the *outer* boundaries. $\Delta_{s,f}$ and $\lambda_{s,f}$ are the superconducting OP and the electron–electron coupling constant in the S(F) layers, correspondingly; $\omega = \pi T(2n+1)$. $\sigma_{s(f)}$ is the boundary transparency at the S(F) side correspondingly ($0 \leqslant \sigma_{s,f} < \infty$). They satisfy the detailed balance condition: $\sigma_f/\sigma_s = v_s N_s/v_f N_f = n_{sf}$ [1], where $N_{s(f)}$ is the Fermi level density of states. Since below we use $2I\tau_f \ll 1$, the diffusion coefficient D_f is real [1,10].

The powerful pair-breaking action of exchange field I is the basic mechanism for the destruction of superconductivity in the F/S systems. For simplicity we put $\lambda_f = 0$ ($\Delta_f = 0$) [1], and we will look for the solutions of Eqs. (1)–(3) in the single-mode approximation [1], which is valid [1,6,7] at the thicknesses $d_{s,f} \ll \xi_{s,f}$. This permits the analytical solution of the complicated BVP and qualitative study of the physical properties of the studied systems. Thus, for the *pentalayer* case we have

$$F'_f = B' \cos k'_f(z - z_0), \quad F'''_f = B''' \cos k'_f(z - z_5),$$

$$F'_s = A' \cos k'_s\left(z - \frac{z_2}{2}\right) + C' \sin k'_s\left(z - \frac{z_2}{2}\right),$$

$$F'_f = B'' \cos k''_f\left(z - \frac{z_2 + z_3}{2}\right) + D'' \cos k''_f\left(z - \frac{z_2 + z_3}{2}\right),$$

$$F''_s = A'' \cos k'_s\left(z - \frac{z_3 + z_4}{2}\right) + C'' \sin k'_s\left(z - \frac{z_3 + z_4}{2}\right). \quad (4)$$

Here $k_{s(f)}$ is the components of the wave vector describing spatial changes of the corresponding pair amplitudes across the layers (along the z-axis) independent of the