Low-Field Superconducting Spin Switch Based on a Superconductor/Ferromagnet Multilayer

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The principle of a novel device, which is called a superconducting spin switch or a spin valve for supercurrent, is proposed and theoretically justified. It is based on a four-layer antiferromagnet/ferromagnet/superconductor/ferromagnet spin-valve-like structure. Calculations show that this structure has either zero value or lower superconducting transition temperature for the parallel alignment of magnetizations in the ferromagnetic layers as compared with an antiparallel alignment of magnetizations. Thus, the supercurrent flowing through the superconducting layer can be switched by rotating the magnetization of the top free ferromagnetic layer by a weak external magnetic field.

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The superconductor/ferromagnet (SC/FM) artificial superlattices provide the possibility of controlled studies of interplay between superconductivity and ferromagnetism. The work by Wong *et al.* [1], where the indications of nonmonotonic dependence of superconducting transition temperature T_c on the thickness of ferromagnetic layers had been observed in SC/FM multilayers, triggered the investigations of the proximity effect between superconductor and ferromagnet. Buzdin *et al.* [2–5] and Radović *et al.* [6,7] have suggested that superconductivity in SC/FM multilayers is suppressed because of the large conduction-band exchange splitting in FM layers, which extends into a superconductor via the proximity effect. At the same time, the Cooper pairs leaking from SC into FM acquire a spatially dependent phase, because the partners in a Cooper pair belong to the different spin subbands of a ferromagnet, split by the exchange energy $2I \gg k_B T_{c0}$ (T_{c0} is the superconducting transition temperature of an isolated SC layer). The quantum interference of the incident on the SC/FM interface pairing wave function with the wave reflected from the opposite side of a FM layer leads to the oscillating and reentrant behaviors of superconducting transition temperature T_c in SC/FM bi-, tri-, and multilayers upon changing the thickness of FM layers, as can be seen from a careful reading of Refs. [3–7]. Shortly afterwards the oscillations of T_c were observed experimentally in Nb/Gd multilayers [8,9], Nb/CuMn multilayers [10], Nb/Gd/Nb trilayers [11], and Fe/Nb/Fe trilayers [12,13].

The above physical picture proposes the idea that, if the interference of the spin-dependent pairing function is influenced by an external perturbation, the transition temperature will change in a controlled way. At the proper choice of operation temperature the SC/FM structure can be switched from the superconducting state to the normal one and vice versa, thus valving the supercurrent flow through the superconducting layer.

The proposed device structure is a four-layer thin-film structure on a relevant substrate: the first layer is an insulating antiferromagnet (AFM), whose role is to pin the (in-plane) direction of magnetization of the second layer (FM1), made of a metallic ferromagnet of the thickness d_F. The third layer (SC) is a superconductor of the thickness d_S, and the fourth, top layer (FM2) is again a metallic ferromagnet of the thickness d_F. The sketch of this structure is depicted in Fig. 1; it looks similar to the spin-valve structure proposed in the physics of giant magnetoresistance by Dieny *et al.* [14]. The direction of magnetization of the top FM layer (FM2 on Fig. 1) is rotated in the film plane by a weak external magnetic field. This structure can exist in two distinctively different states with magnetizations of FM layers being aligned parallel (P case) or antiparallel (AP case). We assume the dirty limit condition for both SC and FM metals: $l_{S(F)} \ll \xi_{S(F)}$, where $l_{S(F)}$ and $\xi_{S(F)}$ are the electron mean free paths and the coherence lengths in the SC (FM) layers, respectively. Near T_c the proximity effect in the above system can be described by linearized equations for the Usadel's anomalous Green functions $\Phi_{\alpha\beta}$. They can be derived from the linear Gor'kov equation for the order

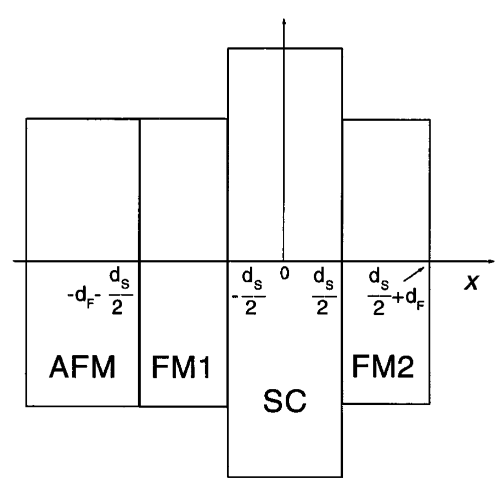

FIG. 1. Schematic picture of the superconducting spin-switch structure.

parameter by a method close to [15] ($\hbar = 1 = k_B$):

$$\left\{|\omega| \pm iI - \frac{1}{2} D_F^{\pm} \frac{d^2}{dx^2}\right\}\Phi_F^{\pm}(x,\omega) = 0 \qquad (1)$$

in the FM layers ($d_S/2 < |x| < d_S/2 + d_F$), and

$$\left\{|\omega| - \frac{1}{2} D_S \frac{d^2}{dx^2}\right\}\Phi_S^{\pm}(x,\omega) = \Delta_S \qquad (2)$$

in the SC layer ($-d_S/2 < x < d_S/2$). In (1) and (2) $\Phi_\alpha^{+}(\Phi_\alpha^{-}) \equiv \Phi_{\uparrow\downarrow\alpha}(\Phi_{\downarrow\uparrow\alpha})$, $\omega = \pi T(2n + 1)$ is the Matsubara frequency, n is an integer; $D_S = \frac{1}{3}v_S l_S$ and $D_F^{\pm}$ are the diffusion coefficients for electrons,

$$D_F^{\pm} = \frac{1}{3}\frac{v_F l_F}{[1 \pm i\,\mathrm{sgn}(\omega) l_F/\xi_F)]}, \qquad \xi_F = v_F/2I, \quad (3)$$

v_S and v_F are the Fermi velocities in SC and FM layers, respectively, and the order parameter in the FM layers is assumed to be zero. Equations (1) and (2) should be supplemented with the self-consistency equation for the order parameter in the SC layer [16]

$$\Delta_S(x) = \frac{\lambda}{2}\pi T \sum_{\omega} [\Phi_S^{+}(x,\omega) + \Phi_S^{-}(x,\omega)], \quad (4)$$

where λ is the dimensionless BCS coupling constant, and with the boundary conditions at the outer surfaces of FM layers $x = \pm(d_S/2 + d_F)$ (no supercurrent through FM1/AFM and FM2/vacuum interfaces)

$$\frac{d}{dx}\Phi_F^{\pm}(x,\omega) = 0, \qquad (5)$$

as well as at the SC/FM interfaces $x = \pm d_S/2$ [17], rewritten in the form of the linear hydrodynamic boundary conditions:

$$N_S D_S \frac{d}{dx}\Phi_S^{\pm} = N_F D_F^{\pm}\frac{d}{dx}\Phi_F^{\pm}, \qquad (6)$$

$$-D_F^{\pm}(\mathbf{n}_F \cdot \nabla_x \Phi_F^{\pm}) = \frac{v_F T_F}{2}(\Phi_S^{\pm} - \Phi_F^{\pm}), \qquad (7)$$

where N_S (N_F) is the electronic density of states of SC (FM), $\mathbf{n}_F$ is a vector of the outward unit normal, and T_F is the dimensionless interface transparency parameter ($T_F \in [0,\infty]$).

The solution of Eqs. (1) and (2) can be found in the *single-mode* approximation [6], which is proved to be accurate for $d_S \geq \xi_S$. In this approximation the self-consistency equation (4) at $T \to T_c$ becomes the equation for finding the reduced transition temperature $t_c = T_c/T_{c0}$:

$$\ln t_c = \Psi\left(\frac{1}{2}\right) - \mathrm{Re}\Psi\left(\frac{1}{2} + \frac{2\phi^2}{t_c(d_S/\xi_S)^2}\right). \quad (8)$$

In (8) $\Psi(x)$ is the digamma function, $\xi_S^2 = D_S/2\pi T_{c0}$, $\phi = k_S d_S/2$, where k_S is the propagation momentum of the pairing function in the SC layer. Before proceeding further let us assume that the conduction band splitting parameter I is *positive* in the pinned ferromagnetic layer FM1. Then it is also *positive* for the parallel alignment (P case) and *negative* for the antiparallel alignment of magnetization in the layer FM2 (AP case). Then the coefficients in solutions can be eliminated making use of the boundary conditions (5)–(7), thus giving the equation for finding k_S^{P} in the P case:

$$\phi^{\mathrm{P}}\tan\phi^{\mathrm{P}} = R \equiv \frac{N_F D_F^{+}}{2N_S D_S}\frac{k_F^{+} d_S \tanh k_F^{+} d_F}{1 + \frac{2D_F^{+}k_F^{+}}{T_F v_F}\tanh k_F^{+} d_F}, \quad (9)$$

and k_S^{AP} in the AP case:

$$(\phi^{\mathrm{AP}}\tan\phi^{\mathrm{AP}} - R')(R'\tan\phi^{\mathrm{AP}} + \phi^{\mathrm{AP}}) - (R'')^2\tan\phi^{\mathrm{AP}} = 0. \qquad (10)$$

In the above two equations $R = R' + iR''$, $\phi^{\mathrm{P(AP)}} = k_S^{\mathrm{P(AP)}} d_S/2$ and $(k_F^{\pm})^2 = \pm 2iI/D_F^{\pm}$. The set of equations (8) and (9) solves the problem for the parallel alignment, and the set of equations (8) and (10) solves the problem for the antiparallel alignment. We expect that these solutions give, in general, different t_c, which will be denoted t_c^{P} and t_c^{AP}, respectively.

The above expectation can be qualitatively justified in the Cooper limit $d_S/\xi_S \ll 1$ for the SC layer, in which the pairing function is nearly homogeneous across this layer. The series expansion of the left-hand parts of Eqs. (9) and (10) immediately gives

$$(\phi^{\mathrm{P}})^2 \simeq R' + iR'', \qquad (11)$$

$$(\phi^{\mathrm{AP}})^2 \simeq R' + \frac{(R'')^2}{R' + 1}. \qquad (12)$$

In the case of low interface transparency ($T_F \ll 1$) the analysis can be done for the arbitrary FM-layer thickness d_F. The unity in the denominator of Eq. (9) may be dropped with the result for R:

$$R \simeq T_F \frac{N_F}{N_S}\frac{d_S v_F}{4D_S} = R', \qquad R'' = 0. \qquad (13)$$

Equation (13) shows us that R is real valued. Then making use of (11) and (12) we have

$$(\phi^{\mathrm{P}})^2 \simeq R' \simeq (\phi^{\mathrm{AP}})^2, \qquad (14)$$

from which we conclude that at the low transparency limit, T_c of the structure does not depend on the mutual alignment of magnetizations of FM layers.

In the perfect transparency limit ($T_F \to \infty$) the denominator of R reduces to unity, and the series expansion of hyperbolic cotangent in the Cooper limit for the FM layers, $d_F/\xi_F \ll 1$, gives

$$R \simeq i\left(\frac{N_F d_F}{N_S d_S}\right)\left(\frac{d_S}{\xi_S}\right)^2\left(\frac{I}{2\pi T_{c0}}\right) = iR'', \qquad R' = 0. \qquad (15)$$

From (15), (11), and (12) we immediately obtain

$$(\phi^{\mathrm{P}})^2 \simeq iR'', \qquad (16)$$

$$(\phi^{\mathrm{AP}})^2 \simeq (R'')^2, \qquad (17)$$

which definitely give different transition temperatures; in particular, because of $R'' \ll 1$, $t_c^{\mathrm{AP}} > t_c^{\mathrm{P}}$. Substituting ϕ's (16) and (17) into (8) we obtain the following equations:

$$\ln t_c^{\mathrm{P}} = \Psi\left(\frac{1}{2}\right) - \mathrm{Re}\Psi\left(\frac{1}{2} + i\,\frac{2R''}{(d_S/\xi_S)^2 t_c^{\mathrm{P}}}\right), \quad (18)$$

$$\ln t_c^{\mathrm{AP}} = \Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2} + \frac{2(R'')^2}{(d_S/\xi_S)^2 t_c^{\mathrm{AP}}}\right). \quad (19)$$

The solutions of Eqs. (18) and (19) are displayed in Fig. 2. The clearly visible back turn of the t_c^{P} curve indicates the intersection with the curve of tricritical points at $t_c^{\mathrm{P}} \sim 0.47$, below which the transition becomes of the first order (see details in [7]). From Fig. 2 we learn that there exists a wide window in the values of R'' at which the superconductivity is completely destroyed for the parallel alignment and only weakly suppressed for the antiparallel magnetizations alignment. This means that, if the structure is used as a cryogenic device, the superconductivity or the superconducting current flowing along the superconducting layer can be switched on and off turning the direction of the top free FM2 layer. The physical origin of the predicted effect is rather transparent: pair-breaking spin polarizations, extending into a SC layer from the antiparallel aligned FM layers, are of opposite signs and cancel each other, provided that perturbations of the pairing function in the Cooper limit are homogeneous in space. Alternatively, at the parallel alignment of magnetizations the spin-polarized perturbations of the pairing function from both layers are of the same sign; they enhance each other quenching superconductivity for an appropriate choice of other parameters.

In the case of no restrictions on the thicknesses of both the SC and FM layers Eqs. (8)–(10) have to be solved numerically. The representative curves of the dependence of t_c on the thickness d_F of FM layers are displayed in Fig. 3 for the few values of the interface transparency parameter T_F. Calculations show that the finite transparency of the SC/FM interface does not destroy the operation of the device: until the hysteresis of T_c for P and AP alignments holds, the spin switch will operate at temperatures $T_c^{\mathrm{P}} < T < T_c^{\mathrm{AP}}$. Parameters of the proposed device can be optimized by changing the values of the quantities: d_S/ξ_S, d_F/ξ_F, l_F/ξ_F, T_F, and ε. The latter one is given by

$$\varepsilon^{-1} = \frac{1}{2}\sqrt{\frac{2}{3}}\left(\frac{N_F}{N_S}\right)\left(\frac{\xi_F}{\xi_S}\right)\left(\frac{I}{2\pi T_{cS}}\right). \quad (20)$$

The detailed numerical investigation of the general problem with finite interface transparency and spin-orbit scattering of electrons [18] will be given elsewhere.

In the Cooper limit it is possible to estimate the ratio of the critical current that the proposed device can switch at low temperatures, to the critical current of the isolated film of the same geometry: $R_c \simeq \beta^{3/2}(T_c^{\mathrm{AP}}/T_{c0})^{3/2}$, where the numeric factor $\beta \in [1, 2]$ depends on transition temperature of the open valve T_c^{AP}. As the ratio T_c^{AP}/T_{c0} decreases, β increases reaching its maximum value at $T_c^{\mathrm{AP}}/T_{c0} \sim 0.36$. For example, at $T_c^{\mathrm{AP}}/T_{c0} = 0.4$ the estimation gives $R_c \simeq 0.48$, and we may conclude that the switch can operate with the critical currents of the same order of magnitude as the critical current of the isolated SC film. Comparison with the fringe fields controlled superconducting switch of Clinton and Johnson [19] (which actually works at the SC layer thickness close to the Cooper limit) shows that both devices can operate with critical currents of the same order of magnitude. The fringe fields themselves are of little importance for the proximity-effect valve, because the FM layers are about 2 orders of magnitude thinner. The typical thicknesses of the layers in the experiments [8–13] are 250–600 Å for SC layers and 3–40 Å for FM layers.

Finally, let us discuss the magnitude of magnetic field, which may be used for quenching of superconductivity in the proposed structure. It is simply the in-plane coercive field H_c of the top layer FM2, which can be measured

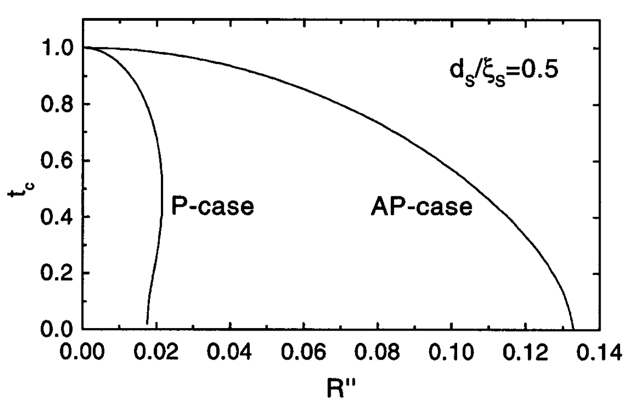

FIG. 2. The dependence of the reduced superconducting transition temperature t_c on the pair-breaking parameter R''.

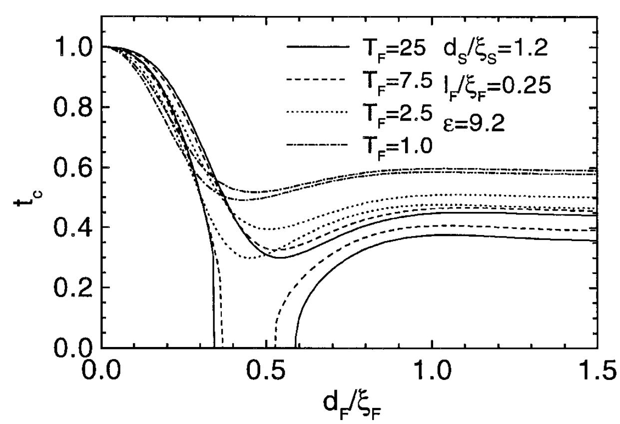

FIG. 3. The reduced superconducting transition temperature t_c as a function of the reduced ferromagnetic layer thickness d_F/ξ_F. The lower curves of every style are drawn for the P case; the upper ones are for the AP case.

by SQUID, VSM, or MOKE. The typical values of H_c lie in the range from a few oersteds for magnetically soft ferromagnets, like permalloy, to a few tens or hundreds of oersteds for the elemental ferromagnets, like Fe ($H_c \sim$ 35 Oe for the 22 Å thick Fe layer on top of the Nb layer [13]). Thus, we conclude that the switching field may be very small, so we can call the proposed structure a low-field superconducting spin switch or a spin valve for supercurrent.

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