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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

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

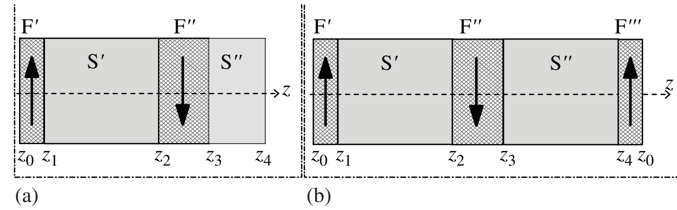

Fig. 1. The geometry of the F′/S′/F″/S″ tetralayer (a) and the F′/S′/F″/S″/F‴ pentalayer (b) in the AFM configuration. Vertical arrows show the directions of the (in-plane) magnetizations that play the role of the magnetic OP. Here $z_0 = -d_f/2$, $z_1 = 0$, $z_2 = d_s$, $z_3 = d_s + d_f$, $z_4 = 3d_s/2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

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

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

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 frequency ω. In this paper, the quantities related to the inner S′ layer or the outer F′ layer are denoted by *the prime*, the ones related to the S″ layer or the inner F″ layer are marked by *the double prime*, and the ones for the outer F‴ layer (Fig. 1b) are noted by the *triple prime*. In the *tetralayer* case we should remove the expression in Eq. (4) for $F'''_{\rm f}$ and put $C''=0$. The complex value of wave vectors $k_{\rm f}$ for the FM mutual alignment of magnetizations in the *adjacent* F layers and for the AFM one are defined as [1,10]

$$(k_{\rm f}')^2=(k_{\rm f}'')^2=-\frac{2I}{D_{\rm f}} \text{ for the FM configuration,}$$
$$(k_{\rm f}')^2=-\frac{2I}{D_{\rm f}},\quad (k_{\rm f}'')^2=\frac{2I}{D_{\rm f}} \text{ for the AFM one.} \tag{5}$$

The similar relations take place in the pentalayer case.

We derive the Abrikosov–Gor'kov-type equation [1]

$$\ln t'^{('')}=\Psi\left(\frac{1}{2}\right)-\mathrm{Re}\Psi\left(\frac{1}{2}+\frac{D_{\rm s}(k_{\rm s}'^{('')})^2}{4\pi T_{\rm cs}t'^{('')}}\right), \tag{6}$$

where $t'^{('')}=T_{\rm c}'^{('')}/T_{\rm cs}$ is the reduced superconducting transition temperature of the S′ and S″ layers, respectively; $\Psi(x)$ is the digamma function. The condition of nontrivial compatibility leads to Eqs. (7)–(12) for pair-breaking parameters $D_{\rm s}(k_{\rm s}')^2$ and $D_{\rm s}(k_{\rm s}'')^2$, which may differ not only for each of the possible phases, but for each superconducting layer (S′ and S″) as well.

The F′/S′/F″/S″/F‴ *pentalayer* may have only three nonequivalent configurations in which the S′ and S″ layers are in essentially different local environment. There are two *symmetrical* configurations: the completely FM one (we designate this case as ↑S′↑S″↑), and the AFM case (↑S′↓S″↑, Fig. 1b). For the third *nonsymmetrical* case (↑S′↑S″↓) we introduce the FMAFM designation.

In the ↑S′↑S″↑ case we have two sets FM($\underline{a}$) and FM($\underline{b}$) of solutions (2) *coinciding* for both S layers (the *pentalayer* states are denoted by *underlined* letters):

$$\begin{cases}\alpha'\gamma'+1=0 & (\underline{a}'\to 00),\\ \alpha''\gamma'+1=0 & (\underline{a}''\to 00),\end{cases}$$
$$\begin{cases}2\alpha'\beta'\gamma'\delta'+(\beta'-\alpha')(\gamma'+\delta')=2 & (\underline{b}'\to\widetilde{\pi 0}),\\ 2\alpha''\beta''\gamma'\delta'+(\beta''-\alpha'')(\gamma'+\delta')=2 & (\underline{b}''\to\widetilde{\pi 0}),\end{cases} \tag{7}$$

where, according to the first line of Eq. (5), $\gamma''=\gamma'$, $\delta''=\delta'$, and the following designations are introduced:

$$\alpha=\frac{4D_{\rm s}k_{\rm s}}{\sigma_{\rm s}v_{\rm s}}\tan\frac{k_{\rm s}d_{\rm s}}{2}-1,\quad \beta=\frac{4D_{\rm s}k_{\rm s}}{\sigma_{\rm s}v_{\rm s}}\cot\frac{k_{\rm s}d_{\rm s}}{2}+1,$$
$$\gamma=-\frac{4D_{\rm f}k_{\rm f}}{\sigma_{\rm f}v_{\rm f}}\tan\frac{k_{\rm f}d_{\rm f}}{2}+1,\quad \delta=\frac{4D_{\rm f}k_{\rm f}}{\sigma_{\rm f}v_{\rm f}}\cot\frac{k_{\rm f}d_{\rm f}}{2}+1. \tag{8}$$

The appropriate primes should appear at Greek symbols (α, β, γ, δ) on the left-hand side of expressions (8) and at corresponding wave vectors ($k_{\rm s}$ and $k_{\rm f}$) on the right-hand side according to sets (7) and (8). Note, in these sets only the equations are left that lead to a finite nonzero critical temperature.

The first solution (7) ($\underline{a}'\equiv\underline{a}''$) coincides with the known 00 solution for the F/S superlattice [1,15]. The second set of Eq. (7) determines a ***new*** solution for the *five-layered system* $\left(\underline{b}'=\underline{b}''=\widetilde{\pi 0}\right)$, corresponding to the π state on superconductivity and the 0 phase on magnetism. To distinguish all *new* solutions from the "*known*" superlattice ones we will designate the new ones with tilde. Their occurrence is connected with the outside boundary conditions because the corresponding pair amplitudes (4) contain only cosine functions.

In the ↑S′↓S″↑ case we also have two sets AFM($\underline{c}$) and AFM ($\underline{d}$) of solutions *coinciding* for both S layers:

$$\begin{cases}\alpha'\beta'|\gamma'|^2+(\beta'-\alpha')\mathrm{Re}\,\gamma'=1 & (\underline{c}'\to 0\pi),\\ \alpha''\beta''|\gamma'|^2+(\beta''-\alpha'')\mathrm{Re}\,\gamma'=1 & (\underline{c}''\to 0\pi),\end{cases}$$
$$\begin{cases}2\alpha'\beta'\gamma'\delta'^*+(\beta'-\alpha')(\gamma'+\delta'^*)=2 & (\underline{d}'\to\widetilde{\pi\pi}),\\ 2\alpha''\beta''\gamma'\delta'^*+(\beta''-\alpha'')(\gamma'+\delta'^*)=2 & (\underline{d}''\to\widetilde{\pi\pi}),\end{cases} \tag{9}$$

where $\gamma''=(\gamma')^*$, $\delta''=(\delta')^*$ and $\gamma'''=\gamma'$, $\delta'''=\delta'$ are used.

In the *nonsymmetrical* ↑S′↑S″↓ case we have two sets FMAFM($\underline{e}$) and FMAFM($\underline{f}$) of *nonequivalent* solutions:

$$\begin{cases}\alpha'\gamma'+1=0 & (\underline{e}'\to 00),\\ \alpha''\beta''|\gamma'|^2+(\beta''-\alpha'')\mathrm{Re}\,\gamma'=1 & (\underline{e}''\to 0\pi),\end{cases}$$
$$\begin{cases}2\alpha'\beta'\gamma'\delta'+(\beta'-\alpha')(\gamma'+\delta')=2 & (\underline{f}'\to\widetilde{\pi 0}),\\ 2\alpha''\beta''\gamma'^*\delta'+(\beta''-\alpha'')(\gamma'^*+\delta')=2 & (\underline{f}''\to\widetilde{\pi\pi}).\end{cases} \tag{10}$$

For the F′/S′/F″/S″ *tetralayer* we have the similar solutions as for the considered *pentalayer*. For the FM alignment of magnetizations there are the FM(a) ones, which completely coincides with the FM($\underline{a}$) pentalayer case (7), and FM(b) ones, that looks as

$$\begin{cases}2\alpha'\beta'\gamma'\delta'+(\beta'-\alpha')(\gamma'+\delta')=2 & (b'\to\widetilde{\pi 0}),\\ \alpha''\delta'+1=0, & (b''\to \pi 0),\end{cases} \tag{11}$$

where $\delta''=\delta'$ is used. For the AFM ordering, we have the other two cases AFM(c) and AFM(d):

$$\begin{cases}\alpha'\beta'|\gamma'|^2+(\beta'-\alpha')\mathrm{Re}\,\gamma'=1 & (c'\to 0\pi),\\ \alpha''\gamma'^*+1=0 & (c''\to 00),\end{cases}$$
$$\begin{cases}2\alpha'\beta'\gamma'\delta'^*+(\beta'-\alpha')(\gamma'+\delta'^*)=2 & (d'\to\widetilde{\pi\pi}),\\ \alpha''\delta'^*+1=0 & (d''\to \pi 0),\end{cases} \tag{12}$$

where $\gamma''=(\gamma')^*$, $\delta''=(\delta')^*$ are used.

Thus, the received expressions firstly include a competition between the 0 phase and the π phase types of superconductivity. Secondly, they take into account the interaction of the localized moments of the F layers through the superconducting layers.

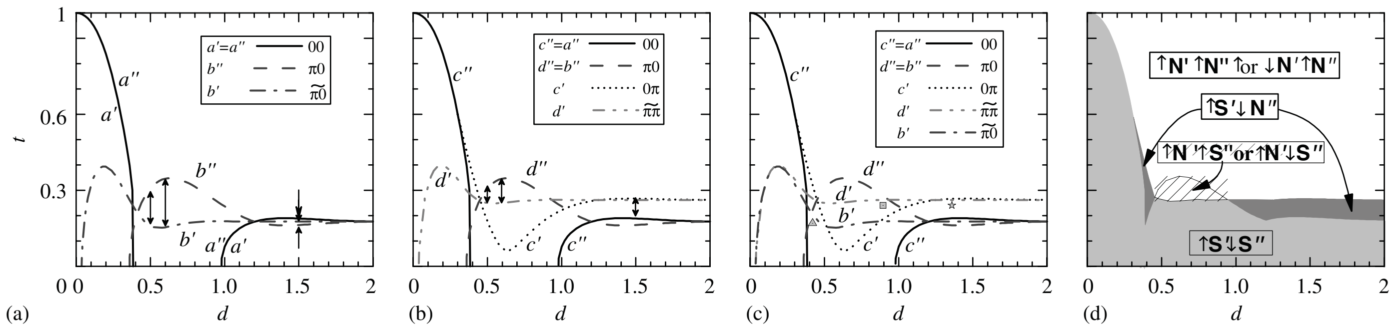

Fig. 2. (a, b) The dependences of the reduced critical temperatures t for the F′/S′/F″/S″ system versus the reduced F layer thickness d. The $t'(t'')$ curves are indicated by letters with *single (double) prime* according to the notation used in Eqs. (7)–(12). The following values of parameters are used: $\sigma_s = 15$; $2I\tau_f = 0.1$; $n_{sf} = 1.4$; $l_s = 0.25x_{s0}$; $d_s = 0.25x_{s0}$. The presented phase diagrams are for the FM (panel a) and the AFM (panel b) configurations. The arrows indicate the $(t'-t'')$ difference between the states; (c) The combined phase diagram of the four-layered F/S/F′/S′ system. The symbols indicate "working" points of imaginary control devices with various numbers of possible states. (d) The generalized phase diagram of the four-layered F′/S′/F″/S″ system. Vertical arrows indicate the direction of magnetization in the corresponding ferromagnetic layers. S and N designate the superconducting or normal states of the superconductor layers, accordingly. For simplicity we assume that the magnetization in the outer F′ layer is directed "upwards".

3. The phase diagrams and control devices

The set of Eqs. (5)–(12) allows us to investigate the dependence of critical temperatures (t' and t'') of the four- and five-layered nanostructures on the reduced thicknesses of the F layers ($d_f/a_f = d$). Let us discuss the tetralayer case more comprehensively since it has the extra π0 state in comparison with the pentalayer one.

A set of phase diagrams $t(d)$ at the *optimal* values of parameters is shown in Fig. 2a–c. In general case there are four various solution sets for the S′ and S″ layers (FM(a',a''), FM(b',b''), AFM(c',c'') and AFM(d',d'')), each of them completely defines the state of *both* layers. However, we have only *two dissimilar* states for layer S″: FM(a'') = AFM(c'') ≡ 00 and FM(b'') = AFM(d'') ≡ $\widetilde{\pi 0}$, see Fig. 2a,b. The latter can be easily understood from the physical point of view. Since only *one* ferromagnetic layer (F″) acts on the outer S″ layer, the S″ layer state depends only on the magnitude of the exchange field in the F″ layer and does not depend on its sign. In other words, the S″ layer is ***always*** situated in the ***local*** FM environment; therefore, the π magnetic solutions do not exist for this layer. We also have two known superlattice solutions for the inner S′ layer: FM(a')≡00 (7), and AFM(c')≡0π (12). Besides, two *new* solutions FM(b') ≡ $\widetilde{\pi 0}$; (11) and AFM(d') ≡ $\widetilde{\pi\pi}$ (12), which are not present in the superlattice case, correspond to the π states on superconductivity. The main distinction between the new $\widetilde{\pi\chi}$ and the known πχ states is the peak position (χ = 0 or π). For the inner S′ layer it is shifted to lower values of thickness d_f as compared with the superlattice case due to the appearance of the outside boundary conditions.

The above-stated peculiarities of the *four-layered system* lead to *different critical temperatures for different S layers* contrary to the *superlattice* case [1,15], for which all the S layers have the same critical temperature due to periodical boundary conditions. Note, the phase diagram for the corresponding F/S/F *trilayer* contains only the a' and c' solutions! Thus, the tetralayer has more physically different states than the F/S/F *trilayer* and even than the F/S *superlattice*.

At first we consider the FM configuration (Fig. 2a). If there is no difference between t' and t'' for the 00 state, the π phase superconductivity case is more interesting and t'' and t' differ from each other. For instance, $t'' - t' \approx 0.15$, 0.2, −0.02 at $d = 0.5$, 0.6, 1.5, correspondingly. Note, the switching of the ground state takes place between the 0 and π superconducting states (00 and π0) at $d \approx 0.4$ and $d \approx 1.2$. For the AFM configuration, the appropriate differences between transition temperatures for the S′ and S″ layers are also indicated by arrows in Fig. 2b. The arising *difference in critical temperatures* for the F′/S′/F″/S″ system is a manifestation of *decoupled* (*spatially separated*) *superconductivity* in its clearest form. This difference between critical temperatures t' and t'' could be observed in experiment with the special field-cooled four-layered samples prepared with the FM or the AFM alignment of magnetizations (see Ref. [16]).

Let the system choose its own state according to the theory of the second-order phase transitions. The state with higher critical temperatures wins, and one of the four states, defined by Eqs. (5)–(7), and (11), (12) (see also Fig. 2a,b), is realized in the system. A complete phase diagram for the tetralayer is presented in Fig. 2d. There are four different regions in this diagram: at high temperature both S′ and S″ layers are in normal state. Then, there are two AFM regions (dark grey). In this *decoupled* state the inner S′ layer is superconducting, and the outer S″ one is normal. The striped region also corresponds to the *decoupled* state with the superconducting outer S″ layer and the normal S′ layer. There is only the ground AFMS (light grey) state at low temperature and/or at small thicknesses d. It is significant, the *inverse* action of *superconductivity on magnetism* leads to the AFM alignment of magnetizations if the inner S′ layer is in the *superconducting* state. Note, the details of the phase diagram strongly depend on the choice of the system parameters and the above analysis was performed in the absence of an external magnetic field.

Our analysis of solutions (5)–(10) shows that the F/S pentalayer possesses simpler phase diagrams in comparison with the F/S tetralayer. Naturally, in the *symmetrical* cases both S layers have identical T_c. In the FM case (7) both S layers may be simultaneously either in the 00 state or in the $\widetilde{\pi 0}$ state (the a' and b' curves in Fig. 2a, respectively). In the AFM case (9) the states of both S layers are also determined simultaneously either the 0π one or the $\widetilde{\pi\pi}$; one (the c' and d' curves in Fig. 1b, accordingly). In the *nonsymmetrical* FMAFM case (10) each of the S layers is situated in different local magnetic surroundings: a competition arises between the e and f sets. For the S′ layer the 00 and $\widetilde{\pi 0}$ curves in Fig. 2a,b correspond to the e' and f' solutions, respectively. The 0π and $\widetilde{\pi\pi}$ lines correspond to the e'' and f'' solutions for the S″ layer. Thus, in only the nonsymmetrical case the decoupled superconductivity is possible for the F/S pentalayer.

Finally, we consider a conceptual scheme of the control device based on the F′/S′/F″/S″ structure according to the scheme proposed for the F/S superlattice [1]. For technical convenience [14], we add at the left the external magnetic insulator layer, whose role is to pin the direction of magnetization in the outer F′ layer. This does not practically influence the preceding computation for the tetralayer. The state of the F/S structure can be controlled by small external magnetic field **H**, which slightly changes the phase diagram [1,13,14]. Thus, we can change data recorded on the superconducting properties (the first channel) and orientation of magnetizations (the second channel). In our case, there are four specific values of the magnetic field [1]: coercive field H_{coer}; two critical fields H_c' and H_c'' for the S′ and S″ layer, correspondingly; and pinning field H_p.

Re-unite all the phase curves in one combined diagram (Fig. 2c). Let the system be in one of the indicated working points presented in diagram: the "triangle" point ($t \approx 0.17$, $d \approx 0.43$ in Fig. 2c). In this case it is possible to get up to ***seven*** logically various states. According to the second-order phase transitions theory at zero magnetic field the system is in the main AFMS state. When changing external magnetic field **H** at first along the direction of the pinning field, the transition from the ground AFMS state to the FMS one occurs at $H \approx H_{coer}$. If the orientation of magnetization of the F′ layer is pinned upwards (↑), this transition can be presented as ↑S↓S→↑S↑S (let $H_{coer} < H_c' < H_c'' < H_p$ for the FM configuration). One can say, the data written on the superconducting properties of the S layers are conserved but the information recorded on mutual directions of magnetizations is changed. At $H \approx H_c'$ the ↑S↑S→↑N↑S transition occurs, at $H \approx H_c''$ we have the ↑N↑S→↑N↑N transition: the data records on the supercurrent are changed. Applying the external magnetic field in the *opposite* direction one can gain other transitions chain from the ↑S↓S to the ↑S↓N at $H \approx H_c''$; then to the ↑N↓N at $H \approx H_c'$; and at last to the ↓N↓N at $H \approx H_p$. For other working points indicated in Fig. 2c we can get the chains with four (the star) and six possible ones (the square).

4. Conclusions

The F′/S′/F″/S″ tetralayer and F′/S′/F″/S″/F‴ pentalayer nanosystems have been consistently studied within the framework of the modern theory of the proximity effect taking into account the boundary conditions. It has been shown that simultaneous existence of the π phase superconductivity and nonequivalence of all layers results in considerably richer physics in comparison with the earlier studied three-layered F/S/F system [13,14] and even the F/S superlattices [1,15]. The new π phase superconducting states are found. The predicted *decoupled* superconductivity has been found to manifest itself in its most striking way through arising of different critical temperatures in different superconducting layers S′ and S″. The found optimal set of parameters should help experimentalists in choosing the materials and technology for preparation of the F/S systems with prescribed properties. We propose conceptual scheme of the nanoelectronics control device that combine in one sample the advantages of two different recording channels (superconducting and magnetic) and possesses up to *seven* different states, the transitions between them can be managed by a weak magnetic field. Thus, the four-layered systems are the most perspective candidates for use in superconducting spin nanoelectronics.

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