Evolution of superconducting critical temperature in asymmetrical $F_1/F_2/S$ trilayers due to singlet-triplet correlations and external magnetic field

Yu.N. Proshin and M.V. Avdeev

Kazan Federal university, Kremlevskaya, 18, Kazan, Russia

E-mail: `yurii.proshin@ksu.ru`

Abstract. We theoretically explore a competition between magnetism and superconductivity for the three-layered ferromagnet/superconductor (F/S) structures. The critical properties of $F_1/F_2/S$ trilayers in an external parallel magnetic field **H** are investigated. The different mutual orientations of the F layer magnetizations are examined. Under this condition the triplet component of the superconducting condensate is arisen. Assuming that all layers are dirty we solve boundary problem for the Usadel function. To find the critical parameters for trilayer as function of the F layers thicknesses we use Gor'kov's self-consistency equation. The results of numerical calculations for critical temperature T_c and critical magnetic field H_c at various parameters of F/S structure show that the external magnetic field and triplet correlations can essentially influence on the critical properties of considered systems. Unusual dependencies are discussed.

1. Introduction
It is well known that the singlet superconductor (S) and ferromagnet (F) order parameters are fundamentally incompatible and their coexistence in homogeneous materials is difficult to realize. However in the artificial layered heterostructures consisting of alternating F and S layers this is possible [1, 2] due to the proximity effect [3]. In the F/S structures the singlet superconducting correlations can penetrate from the S layer into the F layer on the depth of order of the coherence length $\sim \sqrt{a_F\, l_f}$ ($a_F = v_F/2I$ is spin stiffness length, I is exchange field value, velocity v_F is Fermi velocity and l_f is free path length in ferromagnet). Note that the penetration depth into the F is much smaller than that in the normal metal (N), since condition $I \gg T_c$ is satisfied in conventional ferromagnets. The features of interplay of the S and F ordering phases leads to interesting physical phenomena [1, 2, 4].

Recently, it was demonstrated that not only the singlet component of the superconducting condensate (correlations between quasiparticles with parallel spins) but also the triplet ones can be induced in the ferromagnet [5–9]. The triplet superconducting component is generated in case of nonhomogeneous magnetization of F layers. For the F/S structures the noncollinear orientation of magnetizations in the F layers may also give rise to the triplet superconductivity, in this case each magnetization may be homogeneous [8, 9]. The triplet component penetrates into F layer over more long distance compared to the singlet component. This circumstance may add new features to the proximity effect in the S/F structures.

Reach physics of the F/S system makes them attractive for technical applications. Thus the spin valve device based on the three layered FS systems switched by weak external magnetic field was proposed in works [10–12].

We study the $F_1/F_2/S$ structures in the presence of an external parallel magnetic field **H**. The different mutual orientations of the F layer magnetizations are examined. The triplet superconducting component is generated at noncollinear magnetizations of the F layers. Assuming that all S and F layers are dirty we solve boundary problem for the Usadel function. Then we use Gor'kov's self-consistency equation to find the critical parameters at various parameters F/S structure. The results of numerical calculations for critical temperature T_c and critical magnetic field H_c as function of thicknesses of both F_1 and F_2 layers are presented.

2. Theoretical background

The critical temperature T_c at the second order transition is obtained from the self-consistent equation for the superconducting gap $\Delta(\mathbf{r})$ [13]

$$\Delta(\mathbf{r}) \ln t = \pi T_{\mathrm{c}} \sum_{\omega > 0}^{\infty} \mathrm{Tr}\left(\hat{F}(\mathbf{r}, \omega) - \frac{\Delta(\mathbf{r})}{\omega}\right), \tag{1}$$

where $t = T_{\mathrm{c}}/T_{\mathrm{cs}}$ is the reduced critical temperature (T_{cs} is the superconducting critical temperature for the bulk material without spin exchange interaction), Tr means the trace function, the summation is performed over repeated spin indices, ω is the Matsubara frequency.

In presence of the external magnetic field $\mathbf{H} = \mathrm{rot}\mathbf{A}$ the pair amplitude $\hat{F}$ satisfies the Usadel-like equations [14–16]

$$\left[|\omega| - \mathrm{i}I(\hat{\sigma}_3)_{\alpha\beta} - \frac{1}{2}D_{\alpha\beta}\hat{\mathcal{L}}^2\right] F_{\alpha\beta}(\mathbf{r}, \omega) = \delta_{\alpha\beta}\Delta(\mathbf{r}),$$
$$D_{\alpha\beta} = \frac{D}{1 - \mathrm{i}2I\tau_f(\hat{\sigma}_3)_{\alpha\beta}}, \quad \hat{\mathcal{L}} = \nabla - \frac{2\pi\mathrm{i}}{\Phi_0}\mathbf{A}, \tag{2}$$

where Φ_0 is the magnetic flux quantum, D is the diffusion constant and τ_f is the elastic scattering time of non-magnetic impurities in F layer. Note that the diffusion constant $D_{\alpha\beta}$ in (2) is complex due to the presence of exchange interaction [1]. In case of the magnetization in F layer has the form $\mathbf{M}(0, M\sin\phi, M\cos\phi)$ then the solution of the (2) is $\hat{F}' = \hat{U}^\dagger\hat{F}\hat{U}$. Here $\hat{U}$ is unitary matrix, which has the form

$$\hat{U} = \begin{pmatrix} \cos\frac{\phi}{2} & \mathrm{i}\sin\frac{\phi}{2} \\ \mathrm{i}\sin\frac{\phi}{2} & \cos\frac{\phi}{2} \end{pmatrix}.$$

We use the boundary conditions derived by microscopic approach in the work [17]. For the SF interface, where F and S layers occupy the regions $x < 0$ and $x > 0$, respectively, they have the form

$$\frac{4D_s}{\sigma_s v_F^s}(\hat{\mathcal{L}}\mathbf{n})F_{\alpha\beta}^s = \frac{4D_f}{\sigma_f v_F^f}(\hat{\mathcal{L}}\mathbf{n})[\hat{U}^\dagger\hat{\mathcal{F}}^f\hat{U}]_{\alpha\beta} = F_{\alpha\beta}^s - [\hat{U}^\dagger\hat{F}^f\hat{U}]_{\alpha\beta}, \quad \mathcal{F}_{\alpha\beta}^f = \frac{F_{\alpha\beta}^f}{1 - \mathrm{i}2I\tau_f(\hat{\sigma}_3)_{\alpha\beta}}. \tag{3}$$

The boundary conditions at the outer surfaces have the form

$$(\hat{\mathcal{L}}\mathbf{n})F_{\alpha\beta}^{s,f} = 0. \tag{4}$$

Here $\mathbf{n}(1, 0, 0)$ is the unit vector normal to the S, F_1, F_2 planes; the indices s and f denote S and F layers; σ_s and σ_f are the transparencies from the S and F side, respectively [1]. Note that

the boundary conditions at the interface (3) take into account the fulfillment of the condition of detailed balance

$$\sigma_s v_{\mathrm{F}}^s N_s = \sigma_f v_{\mathrm{F}}^f N_f, \ \sigma_{f1} v_{\mathrm{F}}^{f1} N_{f1} = \sigma_{f2} v_{\mathrm{F}}^{f2} N_{f2}$$

where $N_{s,f}$ is the density of states on the Fermi surface for the S and F layers, respectively.

The set of the equations (1) and (2) and the appropriate boundary conditions (3), (4) are sufficient to calculate critical temperature T_c of the SF layered structures.

3. Results and discussion

We consider a $F_1/F_2/S$ system in presence of the external magnetic field **H** applied parallel to the plane of the contact. We choose the coordinate system so that the S layer occupies the region $0 < x < d_s$, F_1 and F_2 layers occupy the regions $-d_{f1} - d_{f2} < x < -d_{f2}$ and $-d_{f2} < x < 0$, respectively. The magnetization vector of the F_1 layer may be rotated $\mathbf{M}_1(0, M_1 \sin\phi, M_1 \cos\phi)$, while the magnetization of the F_2 layer is fixed $\mathbf{M}_2(0, 0, M_2)$. Following the work [18] we perform the numerical calculations of T_c for the $F_1/F_2/S$ trilayer in similar manner.
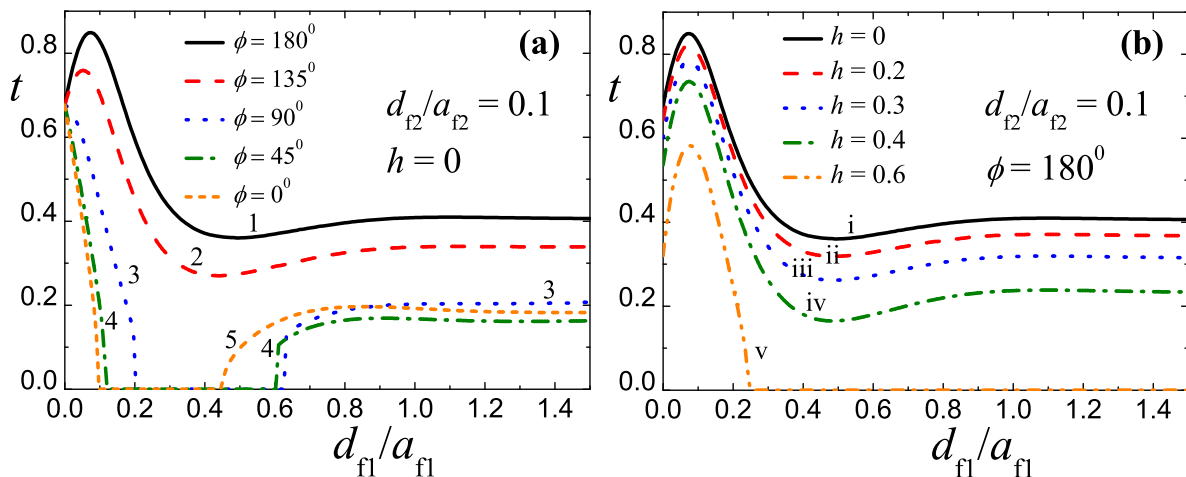

Figure 1. (Color online) (a) The phase diagram $t(d_{f1})$ at fixed thicknesses $d_{f2} = 0.1 a_{f2}$ without magnetic field ($H = 0$) at various values of the angle ϕ: (1) $\phi = 180^0$, (2) $\phi = 135^0$, (3) $\phi = 90^0$, (4) $\phi = 45^0$, (5) $\phi = 0^0$;
(b) The phase diagram $t(d_{f1})$ for the antiparallel state ($\phi = 180^0$) at various values of the h: (i) $h = 0$, (ii) $h = 0.2$, (iii) $h = 0.3$, (iv) $h = 0.4$, (v) $h = 0.6$;
Other parameters of the system are: $d_s/\xi_{s0} = 0.65$, $l_s/\xi_{s0} = 0.3$, $\sigma_s = 3$, $n_{sf} = 0.75$, $l_{f1}/a_{f1} = l_{f2}/a_{f2} = 0.25$, $\sigma_{f1} = \sigma_{f2} = 5$, $I_1/\pi T_{cs} = I_2/\pi T_{cs} = 15$, $d_{f2}/a_{f2} = 0.1$.

In figure 1(a) the reduced critical temperature t as function of the reduced F_1 layer thicknesses at fixed thicknesses $d_{f2} = 0.1 a_{f2}$ without magnetic field ($H = 0$) at various values of the angle ϕ is displayed. So we have an unusual dependence when a maximum corresponding to symmetrical case with $d_{f1} \approx d_{f2}$. It is caused by relatively small values of the $F_{1,2}$ layer thicknesses, when the antiparallel magnetizations compensate each other in most complete manner as in clean case [19], in which the solitary re-entrant superconductivity is predicted for clean $F_1/S/F_2$ trilayer. In common case a position of this peak strongly depends from the $F_1/S/F_2$ parameters (transparencies, etc). It is quite probably that the solitary re-entrant superconductivity may be realized in the dirty $F_1/S/F_2$ trilayer too.

The cases for $\phi = 180^0$ and $\phi = 0^0$ correspond to the antiparallel and parallel mutual orientation of the magnetizations respectively. It is seen, that the change of the angle from the

$\phi = 180^0$ to $\phi = 0^0$ leads to the suppression of the superconductivity. This is easy to understand. When the mutual orientation of the magnetization is antiparallel, the effective exchange field in the F layers is decreased and hence the critical temperature is maximal. Note that changing the angle ϕ varies qualitatively the dependence $t(d_{f1})$: a change of the mutual orientation of the magnetizations leads to the re-entrant superconductivity appearance.

The phase diagrams with the magnetic field influence are plotted in figure 1(b). The $t(d_{f1})$ curves for the antiparallel mutual orientation of the magnetizations are plotted under certain values of reduced magnetic field $h = H/H_c$ (H_c is critical field for isolated S metal). The thickness $d_{f2} = 0.1a_{f2}$ is fixed. The magnetic field variation leads to qualitative change of the $t(d_{f1})$ dependence. Without field this dependence has a maximum at the value $d_{f1} \approx 0.1a_{f1}$ and then it reaches a plateau. The magnetic field monotonically depresses the critical temperature, but it may also lead to qualitative change of dependence $t(d_{f1})$. Note that the dependence $t(d_{f1})$ at the value $h = 0.6$ has a clear pronounced peak and further ($d_{f1} > 0.1a_{f1}$) drops monotonically to zero.

4. Conclusions

In this work we consider the asymmetrical $F_1/F_2/S$ trilayers. Our theoretical approach is valid in the external magnetic field presence as in real experimental setup for the FS spin valve explorations [20, 21]. It is shown that the external magnetic field and triplet correlations can essentially influence on the critical properties of considered systems. In particular, the change of the magnetic field and mutual orientation of the magnetizations can lead to a qualitative modification of the phase diagrams of $F_1/F_2/S$ system.

Acknowledgments

References
[1] Izyumov Y A, Proshin Y N and Khusainov M G 2002 *Physics-Uspekhi* **45** 109–148
[2] Buzdin A 2005 *Rev. Mod. Phys.* **77** 935–976
[3] de Gennes P G 1964 *Rev. Mod. Phys.* **36** 225–237
[4] Efetov K B, Garifullin I A, Volkov A F and Westerholt K 2008 *Magnetic Heterostructures* (*Springer Tracts in Modern Physics* vol 227) (Springer Berlin / Heidelberg) chap Proximity Effects in Ferromagnet/Superconductor Heterostructures, pp 251–290
[5] Bergeret F S, Efetov K B and Larkin A I 2000 *Phys. Rev. B* **62**(17) 11872–11878
[6] Bergeret F S, Volkov A F and Efetov K B 2001 *Phys. Rev. Lett.* **86** 4096–4099
[7] Volkov A F, Bergeret F S and Efetov K B 2003 *Phys. Rev. Lett.* **90**(11) 117006
[8] Fominov Y V, Golubov A A and Kupriyanov M Y 2003 *JETP Letters* **77** 510–515
[9] Fominov Y V, Golubov A A, Karminskaya T Y, Kupriyanov M Y, Deminov R G and Tagirov L R 2010 *JETP Letters* **91** 308–313
[10] Oh S, Youm D and Beasley M 1997 *Appl. Phys. Lett* **71** 2376–2378
[11] Tagirov L R 1999 *Phys. Rev. Lett.* **83** 2058–2061
[12] Buzdin A I, Vedyayev A V and Ryzhanova N V 1999 *EPL (Europhysics Letters)* **48** 686
[13] Abrikosov A A and Gorkov L P 1961 *Sov. Phys. JETP* **12** 1243
[14] Usadel K D 1970 *Phys. Rev. Lett.* **25** 507
[15] Radović Z, Dobrosavljević-Grujić L, Buzdin A I and Clem J R 1988 *Phys. Rev. B* **38** 2388–2393
[16] Krunavakarn B and Yoksan S 2006 *Physica C: Superconductivity and its Applications* **440** 25–34
[17] Proshin Y N and Khusainov M G 1998 *JETP* **86** 930–942
[18] Avdeev M and Proshin Y 2012 *Journal of Physics: Conference Series* **394** 012015
[19] Khusainov M, Khusainov M, Ivanov N and Proshin Y 2009 *JETP Letters* **90** 359–364
[20] Leksin P V, Garif'yanov N N, Garifullin I A, Schumann J, Vinzelberg H, Kataev V, Klingeler R, Schmidt O G and Bchner B 2010 *Appl. Phys. Lett.* **97** 102505
[21] Leksin P V, Garif'yanov N N, Garifullin I A, Fominov Y V, Schumann J, Krupskaya Y, Kataev V, Schmidt O G and Büchner B 2012 *Phys. Rev. Lett.* **109**(5) 057005