

# The spin valve device based on asymmetrical ferromagnet-superconductor trilayer in an external magnetic field

Yu Proshin and M Avdeev

Kazan Federal University, 18 Kremlevskaya, Kazan, Russia

E-mail: yurii.proshin@kpfu.ru

**Abstract.** We theoretically explore superconducting proximity effect for the three-layered ferromagnet/superconductor (FS) heterostructures. We consider the boundary value problem for the Usadel-like equations in the case of so-called “dirty” limit. The different mutual orientations of the F layers magnetizations are examined in presence of the external magnetic field. The results of numerical calculations for critical temperature  $T_c$  at various parameters of FS structures are presented. The appearance of solitary superconductivity is predicted for the  $F_1F_2S$  system. We also discuss possible spin valve applications for  $F_1F_2S$  trilayers.

## 1. Introduction

In recent years the study of layered heterostructures consisting of alternating layers of ferromagnetic (F) and superconducting (S) metals is attracted a keen interest. This is primarily due to the fact that in artificial layered structures the interplay between the S and F order parameters can lead to several striking phenomena (see reviews [1–3] and references therein).

These FS layered heterostructures are also interesting due to possible spin valve applications. Thus the spin valve device based on the three layered FS systems switched by weak external magnetic field was proposed for “asymmetrical” FFS trilayer [4] and for “symmetrical” FSF case [5,6]. Changing the mutual orientation of the F layers magnetizations can control the critical temperature  $T_c$  of these systems, and, therefore, the switching between two different states, i.e. the superconducting state with antiparallel (AP) orientation of the F layers magnetizations and the resistive state with parallel (P) one. Note that the superconducting switch based on the four-layered FSFS system can have up to seven different states [7]. A more detailed implementation of the spin valve is described in the works [8–10] (see also references therein) and in reviews [1–3].

The large set of effects is connected with the nonmonotonic behavior of the critical temperature and the Josephson current as a function of the F layers thickness [1–3]. Thus, the re-entrant and periodically re-entrant superconductivity was predicted in works [11–13]. Later the re-entrant superconductivity experimentally was discovered in bilayers V/Fe [14] and Nb/Cu<sub>1-x</sub>Ni<sub>x</sub> [15]. Recently the re-entrant superconductivity with increasing magnetic field, predicted in theoretical work [16], was observed in symmetrical Cu<sub>41</sub>Ni<sub>59</sub>/Nb/Cu<sub>41</sub>Ni<sub>59</sub> trilayers [17]. Note, a solitary superconductivity was also recently theoretically proposed for clean FS system [18,19]. Lately the appearance of peculiar solitary re-entrant superconductivity caused by external magnetic field is predicted for the  $F_1F_2S$  system [20].



These phenomena are closely related to one another. In this paper we present and discuss the numerical results of the phase diagrams for FSF and FFS trilayers in the presence of external magnetic field  $H$  applied parallel to the plane of the contact. In particular, we calculate the difference  $\Delta T_c = T_c^{AP} - T_c^P$  as function thicknesses of the F layers. The asymmetry ( $d_{f1} \neq d_{f2}$ ) in some cases can lead to the increase of this value  $\Delta T_c$  in comparison with symmetrical samples. Note, that obtaining the higher magnitude of the difference  $\Delta T_c$  is very important for stable operation of the spin valve device.

Basing on the method proposed in work [20], we solve the boundary value problem for the Usadel function and, using self-consistent equation, we calculate the critical temperature for the  $F_1F_2S$  system as function of the F layers thicknesses  $d_f$  in external magnetic field  $H$ .

## 2. Main equations

Let us shortly describe our approach [20]. The critical temperature  $T_c$  at the second order transition is obtained from the self-consistent equation for the superconducting gap  $\Delta(\mathbf{r})$  [21]

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

where  $t = T_c/T_{cs}$  is the reduced critical temperature ( $T_{cs}$  is the superconducting critical temperature for the bulk superconductor),  $\omega$  is the Matsubara frequency, and  $\hat{F}$  is the pair amplitude in spin space including singlet and triplet parts [20].

In presence of the external magnetic field  $\mathbf{H} = \text{rot} \mathbf{A}$  (we use the Coulomb gauge  $\nabla \mathbf{A} = 0$  and  $\mathbf{A} = \frac{1}{2}[\mathbf{H}\mathbf{r}]$ ) and triplet correlations the pair amplitude  $\hat{F}$  satisfies the Usadel-like equations [20, 22–24]

$$\left[ |\omega| - i\mathbf{I}\hat{\sigma} - \frac{1}{2}D\hat{\mathcal{L}}^2 \right] \hat{F}(\mathbf{r}, \omega) = \Delta(\mathbf{r}), \quad \hat{\mathcal{L}} = \nabla - \frac{2\pi i}{\Phi_0} \mathbf{A}, \quad (2)$$

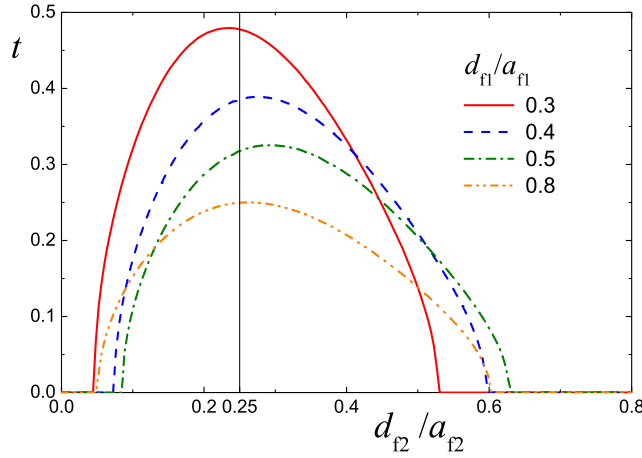
where  $\Phi_0$  is the magnetic flux quantum,  $\mathbf{I}$  is the exchange field in ferromagnet,  $\hat{\sigma}$  is Pauli matrix and  $D$  is the diffusion constant. The Kupriyanov-Lukichev [25] type boundary conditions derived by approach [13] including triplet correlations [20] are

$$\frac{4D_i}{\sigma_i v_F^i} (\hat{\mathcal{L}}\mathbf{n}) \hat{F}^i = \frac{4D_j}{\sigma_j v_F^j} (\hat{\mathcal{L}}\mathbf{n}) \hat{F}^j = \hat{F}^i - \hat{F}^j, \quad (\hat{\mathcal{L}}\mathbf{n}) \hat{F}^{i,j} = 0, \quad i, j = (s, f1, f2), \quad (3)$$

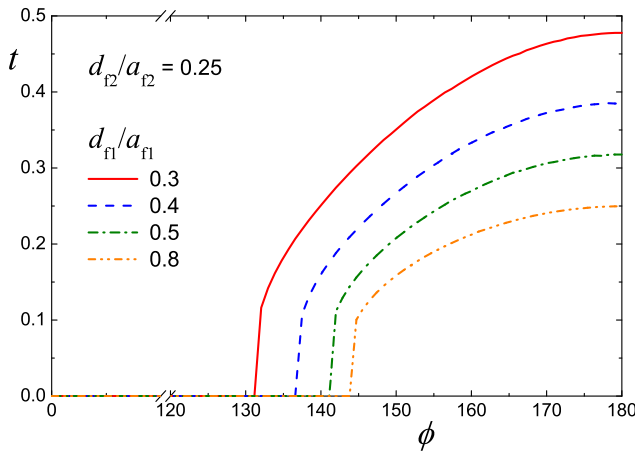
for the inner interfaces and the outer surfaces, correspondingly. For inner interfaces the detailed balance condition [1] ( $\sigma_s n_{sf} = \sigma_f$  where  $n_{sf} = v_F^s N_s / v_F^f N_f$ ) is fulfilled. Here  $\mathbf{n}$  is the unit vector normal to boundary planes, the indices  $s$  and  $f$  denote S and F layers,  $\sigma$  is the boundary transparency,  $N$  and  $v_F$  are the density of states and electron velocity on the Fermi surface [1]. The equations (1)-(3) are sufficient to calculate the critical temperature  $T_c$  of the SF structures.

## 3. Results and discussion

In this paper we explore the appearance of the *solitary* superconductivity and discuss its application to spin valve problem. We use the numerical approach proposed in our recent work [20] where we obtained a good agreement with the experimental data for the symmetrical CuNi/Nb/CuNi trilayer in external magnetic field [17]. In last work the re-entrant superconductivity was observed with the magnetic field increase. In present paper we used the same fitting procedure as in [20] for symmetrical FSF trilayer and evaluated the parameters values which we will use further for asymmetrical  $F_1F_2S$  system. The obtained parameters are close to ones found in paper [20]. For brevity, we will not describe here this fitting procedure.



**Figure 1.** (Color online) The reduced critical temperature  $t = T_c/T_{cs}$  ( $T_{cs}$  is critical temperature for bulk superconductor) as function of the thicknesses  $F_2$  layer  $d_{f2}$  for the AP state. The  $F_1$  layer thicknesses is fixed  $d_{f1} = 0.3a_{f1}$ ; Other parameters of the system are  $d_s/\xi_{s0} = 0.6$ ,  $l_s/\xi_{s0} = 0.2$ ; boundary transparencies  $\sigma_s = 3$  and  $\sigma_f = 100$ , respectively; parameter  $n_{sf} = 0.9$ ,  $l_f/a_f = 0.5$ ,  $I/\pi T_{cs} = 4$ .

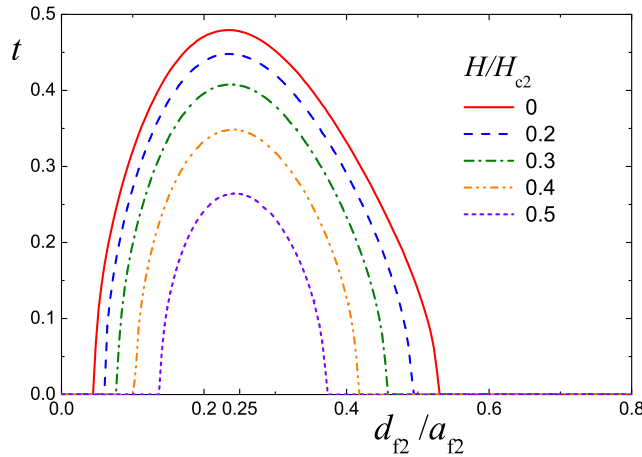


**Figure 2.** (Color online) The angular dependence of the reduced critical temperature  $t$  at various thicknesses of the  $F_1$  layer and at fixed thicknesses  $d_{f2} = 0.25a_{f2}$  (see thin vertical line in figure 1). Other parameters are same as in figure 1).

Note, that the theoretical approach and fit procedure in work [17] also gave good description of the experimental points.

In figure 1 the phase diagrams of the asymmetrical  $F_1F_2S$  trilayer are shown without magnetic field. In this figure the dependencies  $T_c(d_{f2})$  are plotted at various fixed values of the  $F_1$  thicknesses. The superconductivity appears only in finite range of the  $F_2$  layer thickness and furthermore, starting at some finite thickness of the  $F_2$  layer. Note that the mutual orientation of the F layers magnetizations is antiparallel (AP) for this case. This condition is very important for the appearance of solitary superconductivity. This phenomenon is easy to understand due to partial compensation of the effective exchange interactions of the adjacent ferromagnets at the antiparallel mutual orientation of the magnetizations. At the same time, it is important that the  $F_2$  interlayer has the thin thickness i.e.  $d_f \sim \xi_I = \sqrt{l_f a_f / 3} = \sqrt{D / 2I}$  ( $l_f$  and  $a_f = v_F / 2I$  are the mean free path length and spin stiffness length in F layers, respectively), because the pair amplitude decays into F layer on the  $\xi_I$  length. It should also be noted that the maximum of the function  $T_c(d_{f2})$  corresponds to the asymmetrical case with different  $F_1$  and  $F_2$  thicknesses (i.e.  $d_{f1} \neq d_{f2}$ ), that distinguishes this dirty  $F_1F_2S$  system from the clean  $F_1SF_2$  trilayer [18], when the maximum of solitary peak was observed at  $d_{f1} = d_{f2}$ .

The angular dependence  $T_c(\phi)$  (where  $\phi$  is the angle between the magnetization  $\mathbf{M}_1$  and  $\mathbf{M}_2$ ) is shown in figure 2 at various thicknesses of the  $F_1$  layer. The values  $\phi = 180^\circ$  and  $\phi = 0^\circ$  correspond to the AP and P state, respectively. It is clearly seen that the critical temperature  $T_c$  strongly depends on mutual orientation of the magnetizations. Thus, the maximum  $T_c$



**Figure 3.** (Color online) The influence of the magnetic field on the critical temperature at fixed thicknesses  $d_{f1} = 0.3a_{f1}$ . Other parameters are same as in figure 1.

corresponds to the AP state ( $\phi = 180^\circ$ ) and drops sharply to zero with a further change of the mutual orientation of the magnetizations. So, at the angle  $\phi \simeq 130^\circ$  superconductivity is completely absent. So, we may conclude that the solitary superconductivity appears as a result of partial compensation of effective exchange field in F layers at  $\phi = 180^\circ$  (AP state).

It is important to note, that the difference  $\Delta T_c = T_c^{AP} - T_c^P$  for the case of the solitary superconductivity is equal to  $T_c^{AP}$ . As discussed above, the magnitude of the difference  $\Delta T_c$  is important characteristic for the spin valve devices. In this regard, we believe that the search for such exotic solitary superconductivity is very actual for possible spin valve applications.

The influence of the magnetic field on the phase diagrams of the solitary superconductivity is plotted in figure 3 at five different values of the reduced magnetic field  $h = H/H_{c2}$  (where  $H_{c2}$  is upper critical field of the isolated S layer). The thickness of the  $F_1$  layer is fixed  $d_{f1} = 0.3a_{f1}$ . In particular, it is seen that the magnetic field monotonically suppresses superconductivity and the critical temperature decreases, which agrees with both experiments and theory. However we note that the superconductivity is present even at comparatively high value of the magnetic fields  $H \simeq 0.5H_{c2}$ . Such stability of the critical temperature relative to the external magnetic field magnitude is very important, since real experimental setup for the FS spin valve involves explorations in external magnetic field.

On the basis of the phase diagrams in figure 3, we can consider the simple model of the spin valve. Actually, the external magnetic field can change the mutual orientation of the magnetizations from the AP state ( $\uparrow_1\downarrow_2S$ ) to the P state ( $\uparrow_1\uparrow_2S$ ). The magnetization of the  $F_1$  layer is fixed by an additional layer of antiferromagnetic insulator (e.g., cobalt oxide) [10, 26]. For definiteness, we set the coercivity field for the  $F_2$  layer as  $H_{coer} = 0.2H_c$ . As is easy to see in figure 3, the curve  $T_c(d_{f2})$  has a maximum at  $d_{f2} = 0.25a_{f2}$ . Thus we consider a  $F_1F_2S$  system with fixed thicknesses  $d_{f1} = 0.3a_{f1}$  and  $d_{f2} = 0.25a_{f2}$  and at a fixed temperature  $T = 0.4T_{cs}$ . So, without magnetic field the system  $\uparrow_1\downarrow_2S$  is in the superconducting state since in this case  $T < T_c$ . With increasing magnetic field to the value of the coercive field  $H = H_{coer}$  the system switching from superconducting to the resistive state  $\uparrow_1\uparrow_2S$  with  $T_c^P = 0$ . Finally we note once more that for the considered case of the solitary superconductivity the difference  $\Delta T_c = T_c^{AP}$ .

#### 4. Conclusions

In this work we consider the asymmetrical  $F_1SF_2$  trilayers. The values of parameters are found from comparison our theory and real experimental data for symmetrical CuNi/Nb/CuNi trilayer [17]. It is shown that asymmetry and external magnetic field can essentially influence on the critical properties of considered systems. We show that the solitary superconductivity can occur both in the presence of magnetic field and in its absence. We conclude that the states are

important for spin valve applications. The simple model of the spin switch based on the FFS system with solitary superconductivity is proposed taking into account the external magnetic field.

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