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Role of Interface Transparency and Exchange Field in the Superconducting Triplet Spin-Valve Effect

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Abstract. We study the superconducting transition temperature T_c of F2/F1/S trilayers (Fi is a metallic ferromagnet, S is a s-superconductor), where the long-range triplet superconducting component is generated at canted magnetizations of the F layers. In this paper we show that it is possible to realize different spin-valve effect modes - the standard switching effect, the triplet spin-valve effect, reentrant $T_c(\alpha)$ dependence or reentrant $T_c(\alpha)$ dependence with the inverse switching effect - by variation of the F2/F1 interface transparency or the exchange splitting energy. In addition, we show that position of the T_c minimum can be changed by joint variation of the F2/F1 interface transparency and the layer thicknesses.

Introduction

We study the superconducting transition temperature T_c of F2/F1/S structures (Fi is a metallic ferromagnet, S is a s-superconductor), where the long-range triplet superconducting component is generated at canted magnetizations of the F layers [1]. An asymptotically exact numerical method is employed to calculate T_c as a function of the trilayer parameters, in particular, mutual orientation of magnetizations and F2/F1 interface transparencies. Earlier, we demonstrated that T_c in such structures can be a nonmonotonic function of the angle α between magnetizations of the two F layers [2, 3]. The minimum is achieved at an intermediate α, lying between the parallel (P, $\alpha = 0$) and antiparallel (AP, $\alpha = \pi$) cases. This implies a possibility of a "triplet" spin-valve effect: at temperatures above the minimum T_c^{TR} but below T_c^{P} and T_c^{AP}, the system is superconducting only in the vicinity of the collinear orientations. At certain set of parameters, we predict a reentrant T_c behavior. At the same time, considering only the P and AP orientations, we find that both the "standard" ($T_c^{P} < T_c^{AP}$) and "inverse" ($T_c^{P} > T_c^{AP}$) switching effects are possible depending on parameters of the system. It was shown recently [4] the existence of the anomalous dependence of the spin-triplet correlations on the angle α in F/F/S structures. In this paper we show a possibility of the spin-valve effect mode selection (standard switching effect, the triplet spin-valve effect or reentrant $T_c(\alpha)$ dependence) by variation of the F2/F1 interface transparency or the exchange splitting energy. In addition, we show that position of the T_c minimum can be changed by joint variation of the F2/F1 interface transparency and the layer thicknesses.

Results and discussion

To solve this problem we calculate the superconducting transition temperature of F2/F1/S structure (see Fig. 1) for arbitrary values of the angle α, F2/F1 interface transparencies, and exchange field energies H_{F}. We suppose that F metals are single-domain ferromagnets with generically different

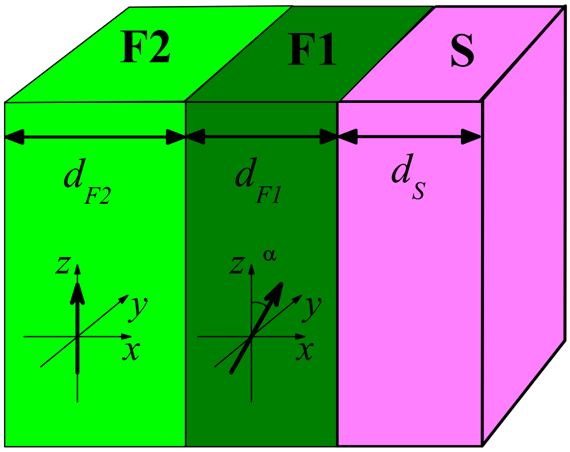

Fig. 1: F2/F1/S trilayer. The F1/S interface corresponds to $x = 0$. The thick arrows in the F layers denote direction of the exchange fields **h** lying in the (y, z) plane. The angle between the in-plane exchange fields is α.

values of the exchange field energy, H_{F1} and H_{F2}. We also assume that interfaces are not magnetically active and can be described by the spin independent suppression parameters γ and γ_{B} [5]:

$$\gamma_{\mathrm{BF1S}} = R_{\mathrm{BF1S}}\mathcal{A}_{\mathrm{B}}/\rho_{\mathrm{F1}}\xi_{\mathrm{F1}}, \quad \gamma_{\mathrm{F1S}} = \rho_{\mathrm{S}}\xi_{\mathrm{S}}/\rho_{\mathrm{F1}}\xi_{\mathrm{F1}}, \tag{1}$$

$$\gamma_{\mathrm{BF2F1}} = R_{\mathrm{BF2F1}}\mathcal{A}_{\mathrm{B}}/\rho_{\mathrm{F2}}\xi_{\mathrm{F2}}, \quad \gamma_{\mathrm{F2F1}} = \rho_{\mathrm{F1}}\xi_{\mathrm{F1}}/\rho_{\mathrm{F2}}\xi_{\mathrm{F2}}, \tag{2}$$

where R_{BF1S}, R_{BF2F1} and $\mathcal{A}_{\mathrm{B}}$ are the resistance and the area of the F1S and F2F1 interfaces; $\rho_{\mathrm{S(F1,F2)}}$ is the resistivity of the S(F1,F2) layer and the coherence lengths are related to the diffusion constants $D_{\mathrm{S(F1,F2)}}$ as $\xi_{\mathrm{S(F1,F2)}} = \sqrt{D_{\mathrm{S(F1,F2)}}/2\pi T_{\mathrm{cS}}}$ (T_{cS} is the superconducting transition temperature for an isolated superconductor).

We consider the F2F1S structure in the dirty limit, which is described by the linearized Usadel equations [1, 6, 7] for triplet condensate functions with 0 and ±1 spin projections and a singlet condensate function in the left F2 layer, in the right F1 layer, and in the S layer. The system of Usadel equations must be supplemented by relevant boundary conditions. Solving the system for F2 and F1 layers with proper boundary conditions we can reduce the problem of calculating T_{c} to an effective set of equations for the singlet component s_3 in the S layer: the set includes the self-consistency equation and the Usadel equation with effective boundary conditions. Now we have the "canonical form" of the problem that has been solved in [8]:

$$\Delta \ln \frac{T_{\mathrm{cS}}}{T_{\mathrm{c}}} = 2\frac{T_{\mathrm{c}}}{T_{\mathrm{cS}}} \sum_{\Omega>0} \left(\frac{\Delta}{\Omega} - s_3 \right), \tag{3}$$

$$\xi_{\mathrm{S}}^2 \frac{d^2}{dx^2} s_3 - \Omega s_3 + \Delta = 0, \tag{4}$$

$$\xi_S \frac{d}{dx} s_3(0) = W(\Omega) s_3(0), \quad \frac{d}{dx} s_3(d_S) = 0. \tag{5}$$

Here, $\Omega = \omega/\pi T_{cS}$, $h_{F1,F2} = H_{F1,F2}/\pi T_{cS}$, and $\Delta = \Delta_s/\pi T_{cS}$ are the Matsubara frequency, exchange field energy, and superconductor order parameter, respectively, normalized by πT_{cS} . The explicit expression for $W(\Omega)$ is presented in [3].

The results of numerical calculations of T_c as a function of the mutual orientation of magnetizations under the different F2/F1 interface transparencies, exchange field energies and layer thicknesses of the trilayer F2/F1/S are given in Figures 2-4 (see the Figures legends).

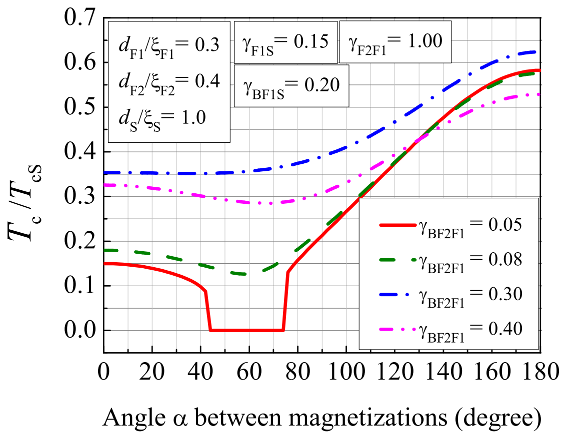

Fig. 2: Dependence of the critical temperature T_c on the angle α between magnetizations under the different F2/F1 interface transparencies.

The Figures 2-3 demonstrate a possibility of the spin-valve effect mode selection (the standard switching effect, the triplet spin-valve effect or the reentrant dependence) by variation of the F2/F1 interface transparency or exchange field energy.

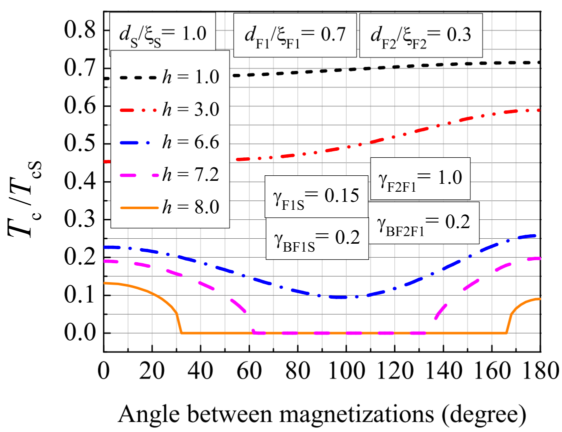

Fig. 3: Dependence of the critical temperature T_c on the angle α between magnetizations under the different $h_{F1} = h_{F2} = h$ exchange field energies.

Figure 4 demonstrates how a position of the T_c minimum can be changed by joint variation of the F2F1 interface transparency and the layer thicknesses (**1** - $d_{F1}/\xi_{F1} = 0.3$, $d_{F2}/\xi_{F2} = 0.3$, $\gamma_{BF2F1} = 0.1$; **2** - $d_{F1}/\xi_{F1} = 0.4$, $d_{F2}/\xi_{F2} = 0.3$, $\gamma_{BF2F1} = 0.4$; **3** - $d_{F1}/\xi_{F1} = 0.7$, $d_{F2}/\xi_{F2} = 0.3$, $\gamma_{BF2F1} = 0.2$).

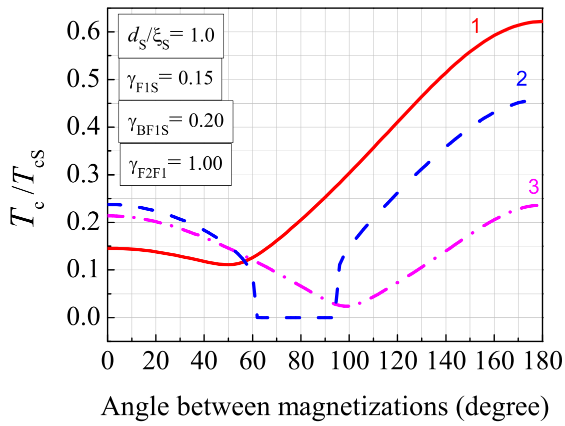

Fig. 4: Dependence of the critical temperature T_c on the angle α between magnetizations under the different F2F1 interface transparencies and layer thicknesses.

Summary

Thereby we show that the realization of one of the spin-valve effect modes can be realized not only by variation of the F layers thicknesses, but also by variation of the F2/F1 interface transparency or the exchange splitting energy. It is explained by changes in the interference conditions for the condensate functions. This interference depends on both the F layers thicknesses and the F2/F1 interface transparency or the exchange splitting energy. Experimentally, the interface transparency can be monitored not only by material choice in a couple, but also pausing of next layer deposition after the previous one (depends on vacuum conditions). The exchange field is intrinsic property of an F-material, however, NF composite ferromagnets were proposed recently [9] to ”dilute” exchange energy of a ferromagnet.

Acknowledgements

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References

[1] F.S. Bergeret, A.F. Volkov, K.B. Efetov, Reviews of Modern Physics 77 (2005) 1321-1373.

[2] Ya.V. Fominov, A.A. Golubov, T.Yu. Karminskaya, M.Yu. Kupriyanov, R.G. Deminov, L.R. Tagirov, JETP Letters 91 (2010) 308-313.

[3] R.G. Deminov, L.R. Tagirov, T.Yu. Karminskaya, M.Yu. Kupriyanov, Ya.V. Fominov, A.A. Golubov, Physical Review B (to be submitted).

[4] T.Yu. Karminskaya, A.A. Golubov, M.Yu. Kupriyanov, Physical Review B 84 (2011) 064531(5).

[5] J. Aarts, J.M.E. Geers, E. Brück, A.A. Golubov, R. Coehoorn, Physical Review B 56 (1997) 2779-2787.

[6] K.D. Usadel, Physical Review Letters 25 (1970) 507-509.

[7] R.G. Deminov, L.R. Tagirov, R.R. Gaifullin, T.Yu. Karminskaya, M.Yu. Kupriyanov, Ya.V. Fominov, A.A. Golubov, Journal of Magnetism and Magnetic Materials (2014). http://dx.doi.org/10.1016/j.jmmm.2014.02.033

[8] Ya.V. Fominov, N.M. Chtchelkatchev, A.A. Golubov, Pis'ma Zh. Eksp. Teor. Fiz. 74 (2001) 101-104 [JETP Letters 74 (2001) 96-99]; Physical Review B 66 (2002) 014507(13).

[9] T.Yu. Karminskaya, A.A. Golubov, M.Yu. Kupriyanov, A.S. Sidorenko, Physical Review B 81 (2010) 214518(13).