Full spin switch effect for the superconducting current in a superconductor/ferromagnet thin film heterostructure

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Using the spin switch design F1/F2/S theoretically proposed by Oh *et al.*, [Appl. Phys. Lett. **71**, 2376 (1997)], that comprises a ferromagnetic bilayer as a ferromagnetic component, and an ordinary superconductor as the second interface component, we have realized a full spin switch effect for the superconducting current. An experimental realization of this spin switch construction was achieved for the CoO_x/Fe1/Cu/Fe2/In multilayer.
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The antagonism of superconductivity (S) and ferromagnetism (F) consists of strong suppression of superconductivity by ferromagnetism because ferromagnetism requires parallel (P) and superconductivity requires antiparallel (AP) orientation of spins. The exchange splitting of the conduction band in strong ferromagnets which tends to align electron spins parallel is larger by orders of magnitude than the coupling energy for the AP alignment of the electron spins in the Cooper pairs in conventional superconductors. Therefore the singlet pairs with AP spins of electrons will be destroyed by the exchange field. For this reason the Cooper pairs can penetrate into an F-layer only over a small distance ξ_F. For pure Fe the value of ξ_F is less than 1 nm (see, e.g., Ref. 1).

The physical origin of the spin switch effect based on the S/F proximity effect relies on the idea to control the pair-breaking, and hence the superconducting (SC) transition temperature T_c, by manipulating the mutual orientation of the magnetizations of the F-layers in a heterostructure comprising, e.g., two F- and one S-layer in a certain combination. This is because the mean exchange field from two F-layers acting on Cooper pairs in the S-layer is smaller for the AP orientation of the magnetizations of these F-layers compared to the P case. Historically, the first paper devoted to the realization of the spin switch effect by manipulating the mutual orientation of the magnetization of the F-layers has been published by Deutscher and Meunier in 1969.[2] They studied FeNi/In/Ni trilayer and obtained a surprisingly large difference in T_c between the AP and P orientations of the magnetizations $\Delta T_c = T_c^{AP} - T_c^{P}$. The reason for this effect has not been clarified up to now. Clinton and Johnson[3] have developed a SC valve which uses the magnetic fringe fields at the edges of the F film of a micrometer size. These fringe fields can be varied in magnitude by changing the mutual orientation of the magnetization of two F-layers separated by a nonmagnetic (N) spacer layer. In this experiment a direct contact between F- and S-layers was absent similar to the case studied in Ref. 2. The possibility to develop a real switch based on the S/F proximity effect has been theoretically substantiated in 1997 by Oh *et al.*[4] They proposed the F1/F2/S layer scheme where an S-film is deposited on top of two F-layers. The thickness of F2 should be smaller than ξ_F to allow the SC pair wave function to penetrate into the space between F1- and F2-layers. Two years later a different construction based on an F/S/F trilayer was proposed theoretically by Tagirov[5] and Buzdin *et al.*[6] Several experimental works confirmed the predicted influence of the mutual orientation of the magnetizations in the F/S/F structure on T_c (see, e.g., Refs. 7–10). However, the difference in T_c between the AP and P orientations ΔT_c turns out to be smaller than the width of the SC transition δT_c itself. Hence a full switching between the normal and the SC state was not achieved. Implementation of a design similar to the F1/N/F2/S layer scheme by Oh *et al.*[4] with a $[Fe/V]_n$ antiferromagnetically coupled superlattice instead of a single F1/N/F2 trilayer[11] is not actually the spin switch device because the system cannot be switched from the AP to P orientations of the magnetizations instantaneously. At the same time the analysis of the temperature dependence of the critical field has shown that implicitly ΔT_c of this system can reach up to 200 mK at $\delta T_c \sim 100$ mK.

Comparison of the results obtained for both proposed constructions of the spin switches gives grounds to suppose that the scheme by Oh *et al.*[4] may be more promising for the realization of the full spin switch effect. In this paper, we have fabricated a set of samples MgO(001)/CoO_x/Fe1/Cu/Fe2/In which show a full switching between the SC and normal states when changing the mutual orientation of the magnetizations of F1- and F2-layers. In this construction MgO(001) is a high quality single crystalline substrate, cobalt oxide antiferromagnetic layer plays a role of the bias layer which pins the magnetization of the F1-layer; Fe stands for the ferromagnetic F1- and F2-layers; Cu as a normal metallic N-layer which decouples the magnetizations of F1- and F2-layers; finally In is a S-layer.

The sample preparation was done by electron beam evaporation on room temperature substrates at the base pressure 2×10^{-8} mbar. The thickness of the growing films was measured by a quartz crystal monitor system. The Co oxide films were prepared by a two-step process consisting of the evaporation of a metallic Co film followed by the plasma

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TABLE I. Experimental parameters of the studied samples.

Sample	Layers' thickness (nm)					RRR	δT_c (mK)	ΔT_c (mK)
	CoO_x	Fe	Cu	Fe	In			
1					230	43	7	0 ± 2
2R				0.5	230	35	15	0 ± 3
3	4	2.4	4	0.5	230	47	7	19 ± 2
4	4	2.9	4	0.6	230	41	13	12 ± 2
5	4	2.6	4	2.6	230	44	50	-2 ± 8

oxidation converting Co into CoO_x layer. The residual resistivity ratio $\mathrm{RRR}=R(300\ \mathrm{K})/R(4\ \mathrm{K})$ is similarly high for all studied samples (see Table I) evidencing a high purity of the deposited In layers.

The indium film in our samples is a type I superconductor with parallel and perpendicular critical fields $H_c^{\parallel}\sim 220$ Oe and $H_c^{\perp}\sim 20$ Oe, respectively, at $T=2$ K. In view of this anisotropy we have taken care to avoid the appearance of the perpendicular component of an external field larger than 2 Oe. This means that we adjusted the sample plane position with an accuracy better than 2° relative to the direction of the dc external field. The easy axis of the magnetization which is induced by residual magnetic fields in our vacuum system was directed parallel to the long axis of the sample. The parameters of the studied samples are shown in Table I. Along with the spin switch samples nos. 3–5 we prepared for control purposes an indium thin film sample (no. 1) and a reference sample comprising an indium layer and only one F-layer (no. 2R).

In a first step the in-plane magnetic hysteresis loops of sample no. 3 in the direction of the magnetic field along the easy axis were measured by a superconducting quantum interference device (SQUID) magnetometer and is shown in Fig. 1(a). This step is necessary to obtain the Fe layers' magnetization behavior and to determine the magnetic field range where AP and P states can be achieved. The sample was cooled down in a magnetic field of +4 kOe applied parallel to the sample plane and measured at $T=4$ K. The magnetic field was varied from +4 kOe to −6 kOe and back again to the value of +4 kOe. Both limits correspond to the orientation of the magnetizations of the F1- and F2-layers parallel to the applied field. For the studied sample by decreasing the field from +4 kOe to the field value of the order of +50 Oe the magnetization of the free F2-layer starts to decrease. At the same time the magnetization of the F1-layer is kept by the bias CoO_x layer until the magnetic field of −4 kOe is reached. Thus, in the field range between −0.3 and −3.5 kOe the mutual orientation of two F-layers is antiparallel. Below $H=-3.5$ kOe the magnetization of the F1-layer starts to change its value and at the field of the order of −4.5 kOe magnetizations of both Fe layers become parallel. This corresponds to a further steplike decrease in the total magnetization. Qualitatively similar hysteresis loops were obtained for sample nos. 4 and 5. The minor hysteresis loops on the low field scale were obtained with decreasing the field from +4 kOe down to −1 kOe and increasing it again up to +1 kOe. An exemplary loop for sample no. 3 is shown in Fig. 1(b).

For the transport study we used another system which also enables a very accurate control of the real magnetic field acting on the sample. This field was generated by a high homogeneous electromagnet. The magnetic field value was measured with an accuracy of ±0.3 Oe using a Hall probe. The temperature of the sample was monitored by the 230 Ω Allen–Bradley resister thermometer which is particular sensitive in the temperature range of interest. In order to study the influence of the mutual orientation of the magnetizations on T_c we have cooled the samples down from room to a low temperature at the magnetic field of +4 kOe applied along the easy axis of the sample just as we did it when performing the SQUID magnetization measurements. For this field both F-layers' magnetizations are aligned (see the magnetic hysteresis loops shown in Fig. 1). Then at the in-plane magnetic field value of $H_0=\pm 110$ Oe the temperature dependence of the resistivity R was recorded. In the following we focus on the spin valve sample no. 3 (see Fig. 2). For this sample $\Delta T_c=T_c^{\mathrm{AP}}-T_c^{\mathrm{P}}=19$ mK [see Fig. 2(b) with an enlarged temperature scale]. We also performed similar resistivity measurements of the reference sample no. 2R with only one Fe layer (see Table I). For this sample we found $T_c=1.60$ K, which does not depend on the magnetic field direction [see

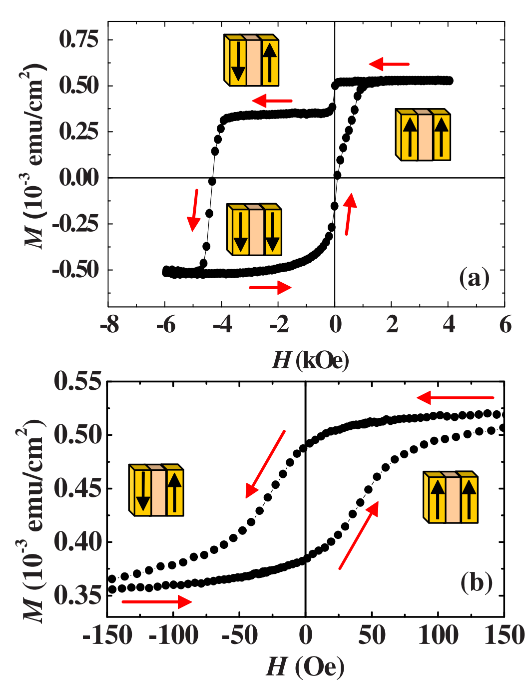

FIG. 1. (Color online) (a) Magnetic hysteresis loop for sample no. 3. Panel (b) shows part of the minor hysteresis loop for sample no. 3, obtained when decreasing the magnetic field from +4 kOe down to −1 kOe and increasing it up to +1 kOe. The amplitude of the minor hysteresis loops is proportional to the thickness of the free F2-layer. Coercive and saturation fields are the largest for the sample no. 3 and sharply decrease with increasing d_{Fe2}.

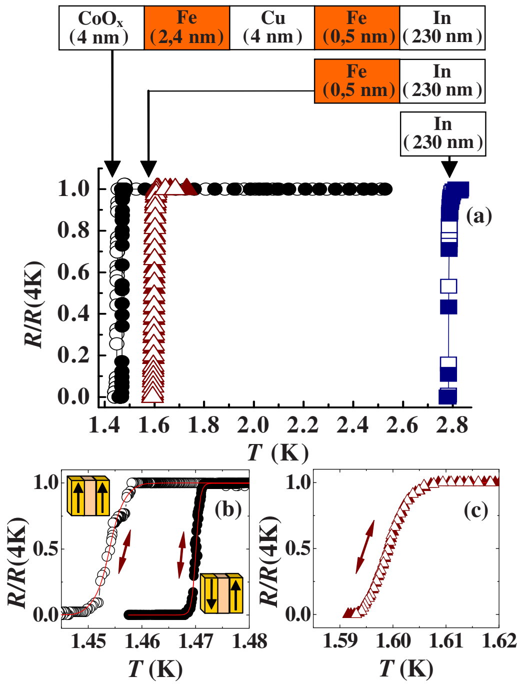

FIG. 2. (Color online) Overview of the resistivity transition curves. The spin valve sample no. 3 is shown by open (H_0=+110 Oe) and closed (H_0=−110 Oe) circles. For the reference sample no. 2R the data are depicted by open (H_0=+110 Oe) and closed (H_0=−110 Oe) triangles. For the pure In sample the data are presented by open (H_0=+110 Oe) and closed (H_0=−110 Oe) squares.

Fig. 2(c)]. This T_c value is lower than that for the In single layer film (sample no. 1) and higher than for sample no. 3 (Fig. 2). This means that T_c is suppressed by the F2-layer and in turn is sensitive to the influence of the F1-layer separated from the SC In layer by a 0.5-nm-thick F2 Fe layer and 4-nm-thick Cu layer. As can be expected from the S/F proximity theory, with increasing the thickness of the free F2-layer ΔT_c decreases and becomes practically zero at 2.6-nm-thick F2-layer (see Table I).

The observed shift ΔT_c=19 mK is not the largest one among the data published before (cf., e.g., Ref. 9, where $\Delta T_c \simeq 41$ mK at $\delta T_c \sim 100$ mK). However, very importantly it is substantially larger than δT_c which is of the order of 7 mK for sample no. 3 at H_0=110 Oe. This opens a possibility to switch off and on the SC current flowing through our samples *completely* within the temperature range corresponding to the T_c-shift by changing the mutual orientation of magnetization of F1- and F2-layers. To demonstrate this we have performed the measurements of the resistivity of sample no. 3 by sweeping slowly the temperature within the ΔT_c and switching the magnetic field between +110 and −110 Oe. This central result of our study is shown in Fig. 3.

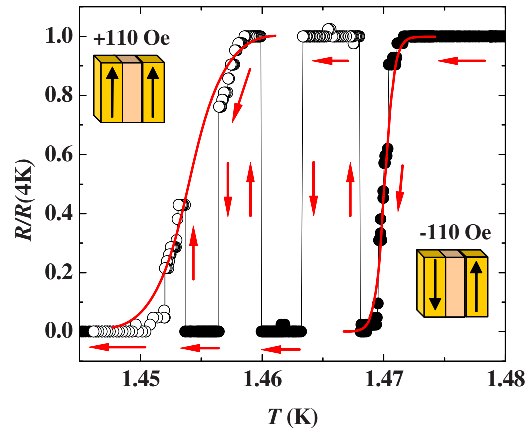

FIG. 3. (Color online) Switching between normal and SC states in the spin valve sample no. 3 during a slow temperature sweep by applying the magnetic field H_0=−110 Oe (closed circles) and H_0=+110 Oe (opened circles) in the sample plane.

It gives straightforward evidence for a complete on/off switching of the SC current flowing through the sample.

For sample no. 3 the obtained result is in agreement with the expectation based on the S/F proximity effect theory, namely, that $\Delta T_c > 0$. Indeed the main necessary prerequisite to realize the theoretical idea of Oh *et al.*[4] is fulfilled in this sample: d_{Fe2} is smaller than ξ_F. Finally, the high quality of the iron layers yields magnetization hysteresis curves with sharp well defined steps enabling a well controlled switching of the mutual orientation of the magnetization of the F-layers by application of relatively small magnetic fields.

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