Journal of Magnetism and Magnetic Materials 373 (2015) 18–22

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

The superconducting spin valve and triplet superconductivity

I.A. Garifullin [a,*], P.V. Leksin [a], N.N. Garif'yanov [a], A.A. Kamashev [a], Ya.V. Fominov [b,c], J. Schumann [d], Y. Krupskaya [d], V. Kataev [d], O.G. Schmidt [d], B. Büchner [d,e]

[a] *Zavoisky Physical-Technical Institute, Kazan Scientific Center of Russian Academy of Sciences, 420029 Kazan, Russia*
[b] *L. D. Landau Institute for Theoretical Physics RAS, 119334 Moscow, Russia*
[c] *Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia*
[d] *Leibniz Institute for Solid State and Materials Research IFW Dresden, D-01171 Dresden, Germany*
[e] *Institut für Festkorperphysik, Technische Universität Dresden, D-01062 Dresden, Germany*

ARTICLE INFO

Article history:
Received 30 November 2013
Received in revised form
28 February 2014
Accepted 1 April 2014
Available online 19 April 2014

Keywords:
Superconductor
Ferromagnet
Proximity effect

ABSTRACT

A review of our recent results on the spin valve effect is presented. We have used a theoretically proposed spin switch design F1/F2/S comprising a ferromagnetic bilayer (F1/F2) as a ferromagnetic component, and an ordinary superconductor (S) as the second interface component. Based on it we have prepared and studied in detail a set of multilayers CoO_x/Fe1/Cu/Fe2/S (S=In or Pb). In these heterostructures we have realized for the first time a full spin switch effect for the superconducting current, have observed its sign-changing oscillating behavior as a function of the Fe2-layer thickness and finally have obtained direct evidence for the long-range triplet superconductivity arising due to noncollinearity of the magnetizations of the Fe1 and Fe2 layers.

1. Introduction

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. Considering the S layer in the “dirty” limit, i.e. in the regime when the mean free path of conduction electrons in a superconductor l_s is much smaller compared to the Bardeen–Cooper–Schrieffer (BCS) coherence length ξ_0, the characteristic depth of the decay of the pairing function in the F layer $\xi_F = (4\hbar D_F/I)^{1/2}$ is given by the diffusion coefficient D_F and the exchange splitting I of the conduction band in the F layer [1]. For pure Fe the value of ξ_F is less than 0.8 nm (see, e.g., [2]).

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 Copper pairs in the S layer is smaller for the AP orientation of the magnetizations of these F-layers compared to the P case. The possibility to develop a switch based on the S/F proximity effect has been theoretically substantiated in 1997 by Oh et al. [3]. They proposed the F1/N/F2/S layer scheme where an S film is deposited on top of two F layers, F1 and F2, separated by a thin metallic N layer. The thickness of F2 should be smaller than ξ_F to allow the SC pair wave function to penetrate into the N-layer. Two years later a different construction based on a trilayer F/S/F thin film structure was proposed theoretically by Tagirov [4] and Buzdin et al. [5,6]. According to the above theories the SC transition temperature for the AP mutual orientation of the magnetizations of the F layers T_c^{AP} should be always higher than T_c for P of their orientation T_c^P [7]. 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., [9–12]). However, the difference in T_c between the AP and P orientations $\Delta T_c = T_c^{AP} - T_c^P$ 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. [3] with a $[Fe/V]_n$ antiferromagnetically coupled superlattice instead of a single F1/N/F2 trilayer [13] 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

---

[*] Corresponding author.
E-mail address: ilgiz_garifullin@yahoo.com (I.A. Garifullin).

http://dx.doi.org/10.1016/j.jmmm.2014.04.002
0304-8853/© 2014 Elsevier B.V. All rights reserved.

analysis of the temperature dependence of the critical field has shown that implicitly ΔT_c of this device can reach up to 200 mK.

Having compared the results obtained for both proposed constructions of the spin switches we have chosen the scheme by Oh et al. [3] as a most promising basic design of all our spin valve samples.

In the following we review the results of our recent studies of the spin valve effect [14–17].

2. Full spin valve effect for the superconducting current in a superconductor/ferromagnet thin film heterostructure

The spin valve has been studied for a set of samples MgO(001)/CoO_x/Fe1/Cu/Fe2/In which shows 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 (AFM) 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 an S-layer. The sample preparation was done by electron beam evaporation on room temperature substrates at the base pressure of 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 oxidation converting Co into CoO_x layer. In a first step of our work the in-plane magnetic hysteresis loops in the direction of the magnetic field along the easy axis were measured by a SQUID magnetometer and are shown in Fig. 1a. 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. The minor hysteresis loop on the low field scale obtained with decreasing the field from +4 kOe down to −1 kOe and increasing it again up to +1 kOe is shown in Fig. 1b for sample #3. For other samples the amplitude of the minor hysteresis loops is proportional to the thickness of the free F2 layer.

In order to study the influence of the mutual orientation of the magnetizations on T_c we have cooled down the samples 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 $\pm H_0 = \pm$ 110 Oe the temperature dependence of the resistivity R was recorded. In the following we focus on the spin valve sample # 3 (see Fig. 2a). For this sample the difference in T_c for different magnetic field directions is clearly seen (see Fig. 2b with an enlarged temperature scale). The SC transition temperature for the AP orientation of the magnetizations occurs at a temperature exceeding the T_c for the P orientation of the sample by 19 mK. We also performed similar resistivity measurements of the reference sample #2R with only one Fe layer. For this sample we found T_c=1.60 K, which does not depend on the magnetic field direction (see Fig. 2c). This T_c value is lower than that for the In single layer film (sample #1) and higher than for sample #3 (Fig. 2a). 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 superconducting In layer by a 0.5 nm thick F2 Fe layer and a 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. The observed shift of the SC transition temperature $\Delta T_c = 19$ mK is not the largest one among the data published before (cf., e.g., Ref. [11]). However, very important is that it is larger than the SC transition width δT_c which is of the order of 7 mK for sample #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 #3 by sweeping slowly the temperature within the ΔT_c and switching the magnetic field between +110 and −110 Oe. The result of our study is shown in Fig. 3. It gives straightforward evidence for a complete on/off switching of the SC current flowing through the sample. To the best of our knowledge, this is the first ever example of the realization of a full spin switch design for an SC current in F/S structures with a perfect contact at each interface.

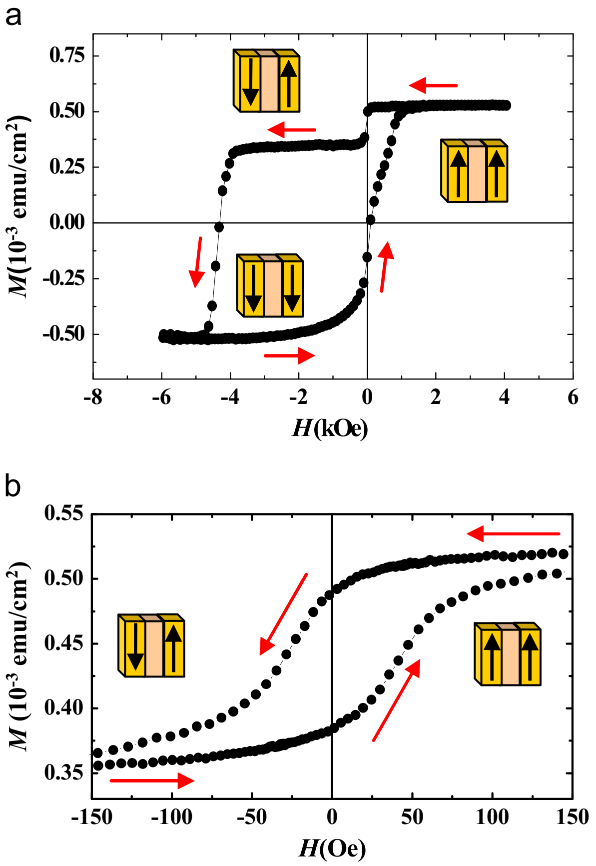

Fig. 1. (a) Magnetic hysteresis loop for sample #3 (CoO_x(4 nm)/Fe1(2.4 nm)/Cu (4 nm)/Fe2(0.5 nm)/In(230 nm)). Panel (b) shows part of the minor hysteresis loop for sample #3, obtained when decreasing the magnetic field from +4 kOe down to −1 kOe and increasing it up to +1 kOe [14,16].

3. Interference effects

We have also investigated in detail the dependence of ΔT_c on the thickness d_{Fe2} of the intermediate Fe2 layer on an extensive set of spin valve samples CoO_x(4 nm)/Fe1(3 nm)/Cu(4 nm)/Fe2(d_{Fe2})/In(230 nm) with the value of d_{Fe2} lying in the range between 0.4 and 5.2 nm [16,15]. We obtained the oscillating behavior of the