CHERNOGOLOVKA LDM & SCS 2009

I. F. Schegolev Memorial Conference "Low-Dimensional Metallic and Superconducting Systems"

Chernogolovka, October 11-16, 2009.

Double Re-Entrant Superconductivity in SF-Hybrids

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Superconducting hybrids based on thin films are the object for intense investigations for recent decades as a base element for superconducting electronics [1]. The investigations of proximity effect at Superconductor-Normal metal (S/N) and Superconductor-Ferromagnet (S/F) interfaces require technological approach yields high quality superconducting films with constant thicknesses and enhanced superconducting properties. We developed technological approach yields significant improvement of superconducting properties of large area Nb films of nanoscale thickness, in comparison with common methods based on DC-magnetron deposition. The thickness deviation of Nb layer along the sample with length of 80 mm does not exceed 5–6%, that is promising for superconducting spintronics applications.

In superconductor-ferromagnet metallic (S/F) contacts the superconducting condensate penetrates through the S/F interface into a ferromagnetic layer, and the pairing wave function not only decays deep into the F metal, but simultaneously oscillates. Based on these oscillations various new physical effects were predicted ([1] and references therein), some of them have been observed experimentally: a non-monotonous superconducting T_c behavior as a function of the F -layer thickness, Josephson junctions with intrinsic π shift across the junction, capsized differential I-V characteristics.

We report on the first experimental observation of the double suppression of superconductivity in Nb/$Cu_{1-x}Ni_x$ bilayers as a function of the ferromagnetic layer thickness d_{CuNi}. The superconducting T_c drops sharply with increasing d_{CuNi} till total suppression of superconductivity at $d_{CuNi} \approx 2.5$ nm occurs. At further increase of the $Cu_{1-x}Ni_x$ layer thickness, the superconductivity restores at $d_{CuNi} \geq 24$ nm. Then, with the subsequent increase of d_{CuNi} the superconductivity vanishes again at $d_{CuNi} \approx 38$ nm.

The theoretical curves were fitted following the strategy described in [3,4]. Throughout, the improved range for the superconducting coherence length ξ_S between 6.2 nm and 6.7 nm was applied instead of $\xi_S \sim 10$ nm, as used in our previous publications on Nb/$Cu_{41}Ni_{59}$ bilayers. In detail, the fitting parameters are as follows for curves S15, S21, S22, and S23, with $T_{c0,Nb}(d_{CuNi} = 0\text{nm}) = 6.67$, 6.2, 6.85, and 8.0 K, respectively: $\xi_S = 6.3$, 6.1, 6.5, and 6.6 nm; $N_F v_F / N_S v_S = 0.22$ for all; $T_F = 0.67$, 0.65, 0.61, and 0.44; $l_F/\xi_{F0} = 1.3$, 1.1, 1.1, and 1.1; $\xi_{F0} = 9.5$, 11.2, 10.7, and 10.8 nm. Here, ξ_S is the superconducting coherence length, $N_F v_F / N_S v_S$ the ratio of the Sharvin conductances at the S/F interface, T_F the interface transparency parameter, l_F, the electron mean free path of conduction electrons in the ferromagnet, and ξ_{F0} the magnetic coherence length.

Our investigation clearly show the existence of the quasi-one-dimensional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) like state [2] in the Nb/$Cu_{41}Ni_{59}$ bilayers. The non-monotonic behavior of the critical temperature predicted by theory, including the phenomenon of reentrant superconductivity with evidence for a multiple reentrant state, could be demonstrated experimentally.

The authors are grateful to A. Golubov, J. Aarts, C. Attanasio, and M. Eschrig for stimulating discussions. The work was partially supported by RFBR grants No. 07-02-00963-a and 08-02-90105_Mol-a.

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Spin valve effects in superconductor/ferromagnetic devices

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The current status of investigation of spin valve effects in structures composed from superconducting (S), normal (N) and ferromagnetic (F) layers are briefly reviewed. The main difficulties on the way of realization of SF spin valve devices are outlined. Several types of spin valves have been considered.

It is demonstrated that to implement the effective T_C ([1, 2]) or I_C ([3–5]) modulation it is necessary to fit two alternative conditions. On the one hand, thickness of S layer in FSF part of the spin valve devices must be large enough in order to have a reasonable critical temperature [6]. On the other hand, to provide the connectedness of the magnetization directions of the F films this thickness must be small. The same problems occur in realization of FSF spin valve devices (see e.g. [7]). Small scale (of the order of 1 nm) of propagation of singlet superconducting correlations into F metals also provides a set of severe technological limitations on quality of interfaces as well as on the degree of uniformity and geometrical factors of F layers. We have shown that these difficulties may be overcomed by using FNF control unit instead of traditional FIF or FSF control elements [8–11]. It has several strong advantages.

In S-FNF-S Josephson spin valve devices the superconducting correlations in N layer exist due to proximity effect with S electrodes rather than to its own superconductivity. Consequently the limitation on the thickness of N layer is not too strong and it can be small enough to provide the necessary interaction between F layers. The next distinction is that for generation of the odd triplet component it is enough slightly (on the angle $\alpha \lesssim 10^o$) deflect the direction of magnetization of one of F layers from initial antiferromagnetic configuration of F films magnetization vectors. It is also necessary to point out that in this domain of α decay lengths of both singlet and odd triplet superconducting components into FNF weak link region are real, they decay on ξ_N scale without any oscillations, and odd triplet superconducting components falls down more slowly compare to singlet one. At a given distance between superconducting electrodes $L \gtrsim \xi_N$ the last fact leads to transition of S-FNF-S spin valve from 0 to π state with α increase and it was demonstrated that the magnitude of I_C in this π state can be essentially larger than that for ferromagnetic configuration of magnetization.

In FSF spin valve devices the maximum shift $T_C^{AP} \approx 40$ mK was reported in [12] for a Ni/Nb/Ni trilayer. Superconducting transition temperature of this structure $T_C \approx 0.4$ K and a resistive transition width of about 0.3 K. Only recently [7] an anomalous shift $\Delta T_C \approx 200$ mK of T_C, which is accompanied gradual rotation of magnetization vector of one of F film in S-FNF spin valve had been observed. We argue that the effect observed in [7], can be considered as the first experimental confirmation of existing of so-called long range proximity effect occurred in structures with nonuniform magnetization [5].

The work was partially supported by RFBR grants Nos. 07-02-00963-a, 08-02-90105-Mol_a, 09-02-12176-ofi_m and 09-02-12260-ofi_m.

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Properties of superconductor-normal metal/ferromagmet-superconductor Josephson variable thickness bridges.

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The novel S-FN-S and S-FNF-S types of Josephson junctions (S - superconductor, F - ferromagnet, N - normal metal) suggested in [1-4] provide the opportunity for solution of several challenging problems, which still exists in SFS spin valve devices. They are the problem of enhancement of the decay length of critical current, and the problem of realization of control upon the junction parameters by changing the mutual orientation of magnetization vectors of ferromagnetic films.

In all these junctions S electrodes are adjoined to the left and right end-walls of FN sandwich. From technological point of view it is more easy to fabricate junctions having only parallel interfaces between S, N and F films. In this work we have considered junctions in which S electrodes are located on the top of FN bilayer. Three different geometries has been considered. They are SN-NF-NS junctions, which consists of two SN electrodes linking by NF weak region. The SNF-N-FNS structures, in which N film interconnect SNF multilayers and SNF-NF-FNS junctions with S electrodes located on the top of FN bilayer. The critical currents of these Josephson variable thickness bridges have been calculated in the framework of linearized Usadel equations in the assumption of arbitrary length of S electrodes. We compare obtained results with each other and with them obtained in [1-4].

The work is supported by RFBR grants 08-02-90105-Mol_a, 09-02-12176-ofi_m.

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