Superconducting Spin Switch Based on Superconductor-Ferromagnet Nanostructures for Spintronics

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***Abstract* – Very rapid developing area, spintronics, needs new devices, based on new physical principles. One of such devices – a superconducting spin-switch, consists of ferromagnetic and superconducting layers, and is based on a new phenomenon – reentrant superconductivity. The tuning of the superconducting and ferromagnetic layers thickness is investigated to optimize superconducting spin-switch effect for Nb/$Cu_{41}Ni_{59}$ based nanoscale layered systems.**

***Index Terms* – spin-switch, superconductivity, proximity effect, spintronics, nanotechnology**

I. INTRODUCTION

Fulde, Ferrell [1], Larkin and Ovchinnikov [2] predicted that an unconventional, nonuniform superconducting pairing (FFLO) with a non-zero momentum of a pair may occur in a ferromagnetic background, *i.e.* in the presence of an exchange field. In conventional (s-wave) superconductors such state can only be observed in a very small range of parameters and has not been realized up to now experimentally. However, Buzdin *et al*. [3] predicted FFLO-like pairing in S/F layered structures, where the pair amplitude in the F-material establishes due to penetration of the singlet electron pairs from the superconductor through the S/F interface. More advanced analysis was worked out by Tagirov [4] and Fominov *et al*. [5]. The most spectacular prediction of these theories is that not only T_c oscillations but also complete suppression of superconductivity may occur in a certain range of thicknesses of the F-layer followed by its unusual re-entrance with increasing of the F-layer thickness. Superconducting spin-switch based on proximity effect in Ferromagnet – Superconductor – Ferromagnet (F/S/F) layered system was investigated then theoretically in [6,7] using hypothetical materials and their thicknesses. The thicknesses tuning of the superconducting and ferromagnetic layers in SF -structures is the goal of the present work, to investigate and optimize superconducting spin-switch effect for Nb/$Cu_{41}Ni_{59}$ based nanoscale layered system.

II. FILMS DEPOSITION AND CHARACTERIZATION

We developed a special advanced technological process of superconducting layers preparation [8] for reliable fabrication of S/F structures with the layer thickness scale of several nanometers. The S and F layers were deposited by magnetron sputtering on commercial (111) silicon substrates at room temperature. The base pressure in the "Leybold Z400" vacuum system was about 2×10^{-6} mbar. Pure argon (99.999%, "Messer Griesheim") at a pressure of 8×10^{-3} mbar was used as sputter gas. A silicon buffer layer was deposited using RF magnetron. It produced a clean interface for the subsequently deposited niobium layer. To obtain flat and high-quality Nb layers with thickness in the range of 5-15 nm, the rotation of the target around the symmetry axis of the vacuum chamber was realized. A dc-motor drive moved the full-power operating magnetron along the silicone substrate of the 80×7 mm^2 size during the deposition. Thus, the surface was homogeneously sprayed with the sputtered material. The effective growth rate of the Nb film in this case was about 1.3 nm/sec. The deposition rate for a fixed, non-moving target would be about 4-5 nm/sec.

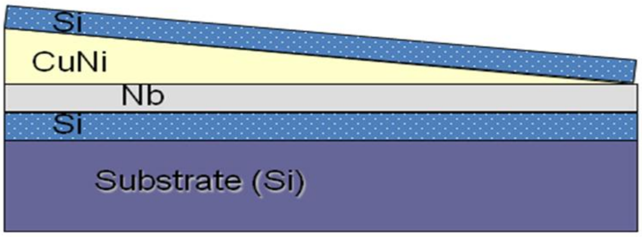

Fig.1. Sketch of the layers stack in the deposited S/F-specimen.

The next step of the procedure was deposition of a wedge-shaped ferromagnetic layer utilizing the intrinsic spatial gradient of the deposition rate of the sputtering material. The $Cu_{40}Ni_{60}$ target was RF sputtered with a rate of 3-4 nm/sec, resulting in practically the same composition ($Cu_{41}Ni_{59}$) of the alloy in the film. To prevent a destructive influence by the atmospheric conditions, the last deposited layers were coated by a silicon cap of about 5-10 nm thickness (see a sketch of the prepared samples in Fig. 1).

Samples of a width of about 2.5 mm were cut perpendicular to the wedge to obtain a set of S/F bilayer strips with varying $Cu_{41}Ni_{59}$ layer thickness d_F, for $T_c(d_F)$ measurements. Aluminum wires of 50 µm in diameter were bonded to the strips by ultrasonic bonder for four-probe resistance measurements.

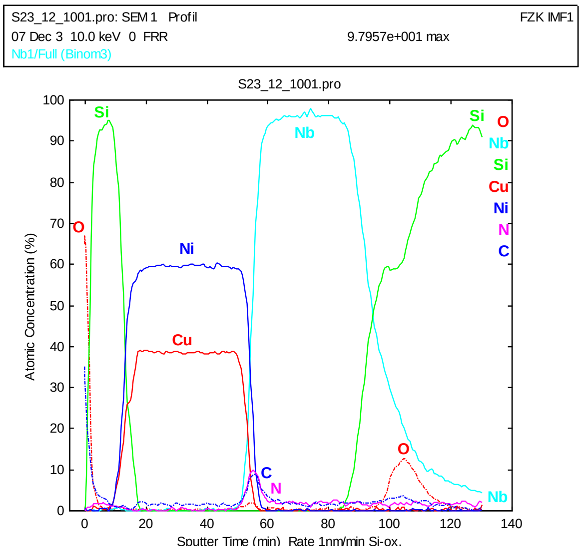

Fig. 2. Scanning Auger electron spectroscopy (AES) of a Si(substrate)/Si(buffer)/Nb/$Cu_{1-x}Ni_x$/Si(cap) sample, d_{Nb} =7.5 nm and d_{CuNi}=32.9 nm (thickness according to the RBS data).

To study the quality of interfaces between the layers we performed Auger electron spectroscopy (AES) measurements of specimens. A defocused Xe-ion beam erodes a crater into the film with inclination angles of the scarps of only a few degrees or below. An electron beam then scans the shallow crater. The emitted Auger electrons reveal the lateral distribution of elements. As a result, one reconstructs the elemental concentration as a function of the sample depth profile. The AES data for the Nb/$Cu_{1-x}Ni_x$ specimen are shown in Fig. 2. There are about 59 at.% Ni (in agreement with the RBS data) and 39.0 at.% Cu in the $Cu_{1-x}Ni_x$ film. There is a small concentration of O, C and N impurities at the Nb/$Cu_{1-x}Ni_x$ interface as a result of physical absorption of gases from the residual atmosphere of the vacuum chamber. The $Cu_{1-x}Ni_x$/Si(cap) interface is free of contaminations.

The samples for the $T_c(d_S)$ measurements were prepared with the same procedure, but with a $Cu_{41}Ni_{59}$ film of constant thickness on the top of a wedge-shaped Nb layer. In addition, single flat Nb films and single CuNi-wedge shaped layers were prepared in a similar way for materials characterization.

III. SUPERCONDUCTING PROPERTIES OF NB/$CU_{41}NI_{59}$ BILAYERS

Fig. 3 demonstrates the dependence of the superconducting transition temperature for SF samples on the thickness of the $Cu_{41}Ni_{59}$ layer. For specimens with $d_{Nb} \approx 14.1$ nm the transition temperature T_c reveals a non-monotonic behavior with a very shallow minimum at about $d_{CuNi} \approx 6.8$ nm, it is just the qualitative behavior. The transition temperature T_c reveals an expressed non-monotonic behavior with a deep minimum at d_{CuNi} about 7.9 nm. For the series of specimens with $d_{Nb} \approx 6.2$ nm the transition temperature T_c decreases sharply for increasing ferromagnetic $Cu_{41}Ni_{59}$ layer thickness, until $d_{CuNi} \approx 3.8$ nm. Then, for $d_{CuNi} \approx 3.8$-24 nm, the superconducting transition temperature vanishes (at least T_c <40 mK, which is the lowest temperature measured). For d_{CuNi} > 24 nm the transition into a superconducting state is observed again. Finally, T_c increases to a little bit above 1 K showing an outstanding reentrant superconductivity behavior with evidence for a second disappearance of the superconducting state at d_{CuNi} > 37.4 nm. Altogether, the $T_c(d_{CuNi})$ curves given in Fig. 3 represent all types of non-monotonic $T_c(d_{CuNi})$ behaviors predicted by the theory [4]. This phenomenon of the reentrant superconductivity in the S/F bilayer has been presented in our recent publications [9,10].

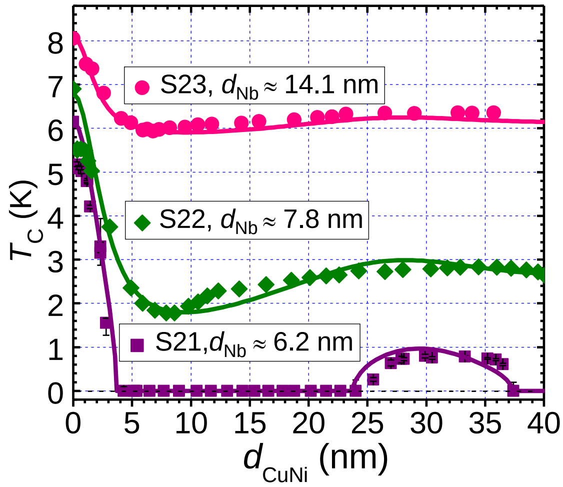

Fig.3 Non-monotonous T_c (d_F) dependence for Nb/$Cu_{41}Ni_{59}$ bilayers with the Nb layer thickness, $d_{Nb} \approx 6.2$ nm, $d_{Nb} \approx 7.8$ nm, and $d_{Nb} \approx 14.1$ nm. Solid lines are fits using the theory [4].

IV. SIMULATION AND DISCUSSION

To describe the experimental data we used the calculation procedure described in [9,10]. The results for superconducting critical temperature T_c calculations for parallel and anti-parallel directions of ferromagnetic layers magnetizations for a core-structure $Cu_{41}Ni_{59}$ /Nb/ $Cu_{41}Ni_{59}$ with superconducting layer thicknesses d_{Nb} = 12.5nm, 14 nm are presented in Fig. 4.

One can see that a maximal spin-switch effect value ΔT_c of the order of 1-2 K is achievable only in a very strict region of superconductor and ferromagnetic layer thicknesses. Otherwise one can expect only negligible value of ΔT_c.

V. CONCLUSION

It was found from the calculations, based on our experimental parameters that maximal spin-switch effect value with the order of magnitude 1-2 K is achievable only for the strict range of superconductor and ferromagnetic layers thicknesses. This range of controlled thicknesses is accessible using advanced vacuum technology [8-10] developed by us for preparation of the F/S/F-core structure for a superconducting spin-switch construction.

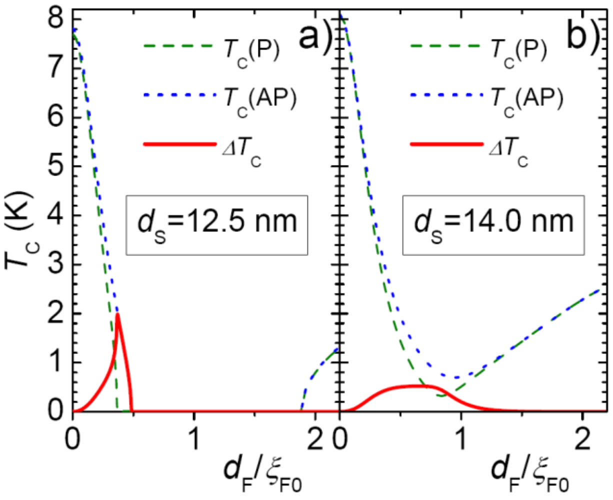

Fig.4. $T_c(d_F)$ curves of a superconducting F/S/F spin-valve core structure with $d_S = d_{Nb}$= 12.5 nm (a), $d_S = d_{Nb}$= 14 nm (b) calculated using the following set of parameters for (a) and (b) respectively: $T_{c0,Nb}(d_{CuNi} = 0$ nm) = 7.7, 8.1 K; in all cases ξ_S = 6.6 nm; $N_F v_F/N_S v_S$ = 0.22; T_F = 0.6; l_F/ξ_{F0} = 1.1; ξ_{F0} = 10.5 nm.

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REFERENCES

[1] P. Fulde and R. Ferrell, Phys. Rev. 135, A550 (1964).
[2] A.I. Larkin and Yu.N. Ovchinnikov, Zh. Eksp. Teor. Fiz. **47**, 1136 (1964) [Sov. Phys. JETP **20**, 762 (1965)].
[3] A.I. Buzdin and M.Yu. Kupriyanov, Pis'ma v ZhETF **52**, 1089 (1990) [JETP Lett. **52**, 487 (1990)].
[4] L.R. Tagirov, Physica C **307**, 145 (1998).
[5] Ya.V. Fominov, N.M. Chtchelkatchev, and A.A. Golubov, Phys. Rev. B **66**, 014507 (2002).
[6] L.R. Tagirov. Phys. Rev. Lett. **83**, 2058 (1999).
[7] A.I. Buzdin, A.V. Vedyayev, and N.V. Ryzhanova, Europhys. Lett. **48**, 686 (1999).
[8] A.S. Sidorenko, V.I. Zdravkov. R. Morari Device for preparation of superconducting layers, Patent of RM 175 (134) Y din 2010, Cl.Int. H01 L 21/00.
[9] V.I. Zdravkov, J. Kehrle, G. Obermeier, S. Gsell, M. Schreck, C. Müller, H.-A. Krug von Nidda, J. Lindner, J. Moosburger-Will, E. Nold, R. Moari, V.V. Ryazanov, A.S. Sidorenko, S. Horn, R. Tidecks, and L.R. Tagirov, Phys. Rev. B 82, 054517 (2010).
[10] A. S. Sidorenko, V. I. Zdravkov, J. Kehrle, R. Morari, E. Antropov, G. Obermeier, S. Gsell, M. Schreck, C. Müller, V. V. Ryazanov, S. Horn, R. Tidecks, and L. R. Tagirov. *in*: Nanoscale Phenomena - Fundamentals and Applications. H. Hahn, A. Sidorenko, and I. Tiginyanu, Eds. Springer-Verlag, Berlin-Heidelberg, 2009, p.3-11.