Superconducting Spin Valve Corn Element Based on S/F Nanostructures

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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-valve, consists of ferromagnetic and superconducting layers, is based on a novel phenomenon – reentrant superconductivity. The tuning of the superconducting and ferromagnetic layers thickness is investigated for optimization of superconducting spin-switch effect for Nb/$Cu_{41}Ni_{59}$ based corn structure.**

Index Terms **— spin-valve, 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.

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).

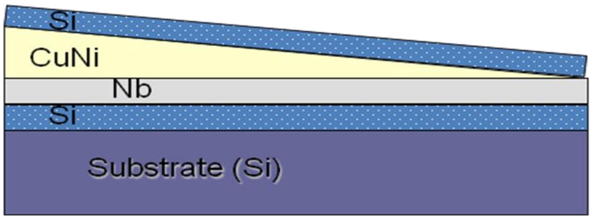

Fig.1. Sketch of the layers stack in the deposited S/F- specimen.

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.

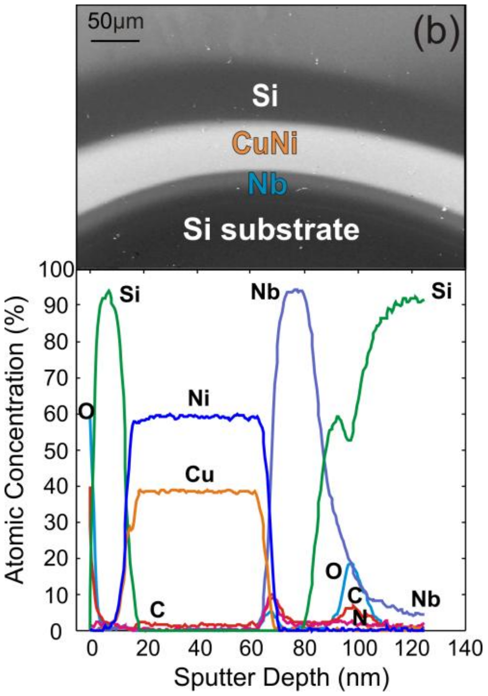

Fig. 2. Scanning Auger electron spectroscopy (AES, the bottom part of the Figutre) of a Si(substrate)/Si(buffer)/Nb/$Cu_{1-x}Ni_x$/Si(cap) sample, d_{Nb} =7.5 nm and d_{CuNi}=32.9 nm (thickness according to the RBS data).The upper part (marked as b) demonstrates the image of the crater, sputtered by Xe ions at low angle during the sample profiling in the AES-spectrometer [10].

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 dependences of the superconducting transition temperature for SF samples on the thickness of the $Cu_{41}Ni_{59}$ layer.

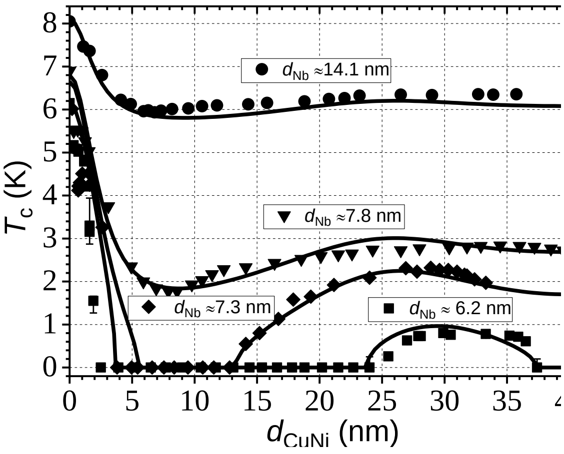

Fig.3 Non-monotonous T_c (d_F) dependence for Nb/$Cu_{41}Ni_{59}$ bilayers with the Nb layer thickness, d_{Nb}≈ 6.2 nm, d_{Nb} ≈ 7.3 nm, d_{Nb} ≈ 7.8 nm, and d_{Nb} ≈ 14.1 nm. Solid lines are fits using the theory [4].

For specimens with d_{Nb} ≈ 14.1 nm the transition temperature T_c reveals a non-monotonic behavior with a very shallow minimum at about d_{CuNi} ≈ 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} ≈ 6.2 nm and d_{Nb} ≈ 7.3 nm at increase of the $Cu_{1-x}Ni_x$ layer thickness, the superconductivity restores at d_{CuNi} ≈ 14 nm for the re-entrant behavior (d_{Nb} ≈ 7.3 nm), and d_{CuNi} ≈ 24 nm for the doubly suppressed re-entrant behavior (d_{Nb} ≈ 6.2 nm). The transition temperature T_c decreases sharply for increasing ferromagnetic $Cu_{41}Ni_{59}$ layer thickness, until d_{CuNi} ≈ 3.8 nm. Then, for d_{CuNi} ≈ 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].

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.

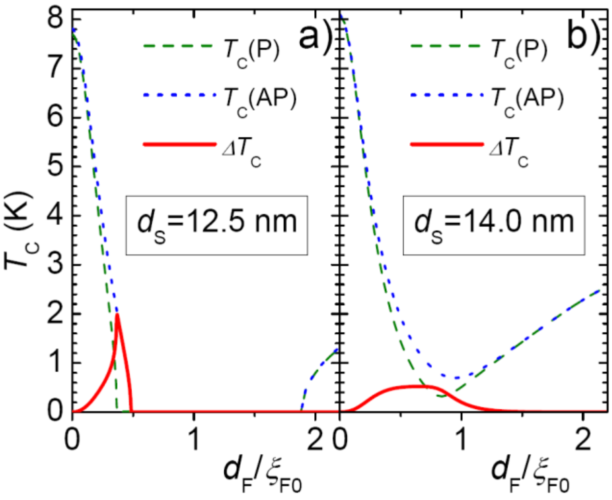

Fig.4. $T_c(d_F)$ curves of a superconducting F/S/F spin-valve core structure with $d_S = d_{Nb}$= 12.5 nm (a), $d_S = d_{Nb}$= 14 nm (b) calculated using the following set of parameters for (a) and (b) respectively: $T_{c0,Nb}(d_{CuNi} = 0$ nm) = 7.7, 8.1 K; in all cases ξ_S = 6.6 nm; $N_F v_F/N_S v_S$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

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.

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