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Determination of the critical thickness of Nb superconducting layers coupled proximiti with Co.

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***Abstract* - Contemporary technological progress is achieving new results due to current needs in microelectronics, superconductivity and nanotechnology. An important feature of high-speed, low-power microelectronics is the spin valve, which is made up of superconducting nanoscale layers such as niobium and cobalt. These two orders superconductivity and ferromagnetism, which at first sight have diametrically opposite tangents and in the natural state are virtually never next to each other - due to the Larkin - Ovchinnikov - Fulde - Ferrell (LOFF) state, demonstrate quantum phenomena quite exciting for further development with applications in: computer technology, chemistry, biology, pharmacology, artificial intellect etc. In this context of ideas we present research on Nb/Co hybrid structures with superconducting properties and the determination of the critical thickness of the superconducting Nb layer in contact with Co.**

Keywords: superconductor/ferromagnet proximity effect, FFLO pairing, critical thickness.

I. INTRODUCTION

Since the work of Ginzburg [1], the problem of the coexistence of two long-range orders - superconductivity (S) and ferromagnetism (F) - has been intensively discussed. Ginzburg concluded that the two antagonistic orders cannot coexist in a homogeneous material because superconductivity requires the conduction electrons to form Cooper pairs, i.e. pairs of electrons with antiparallel spins, while ferromagnetism forces the electron spins to align parallel. If superconductivity and ferromagnetism cannot exist in a homogeneous material, they can be spatially separated at the nanoscale, forming a natural or artificial layered material. This scenario has been realized in multicomponent magnetic superconductors [2] and in artificially created S/F bilayers and layered materials [3]. The latter system has the advantage that the thickness and/or sequence of the S and F layers can be modified during fabrication. Garifianov et al. [4] suggested the use of immiscible metal pairs, such as Pb and Fe, to avoid the diffusion problem. However, a detailed analysis showed [5] that in this case the transparency of the S/F interface is reduced due to the electrostatic potential barrier (band shift) created by adjusting the electrochemical potential of the contacting metals.

S/F pairs should not consist of immiscible metals to avoid the formation of islands due to lack of wetting at the interface. Rather, metals with limited solubility and narrow intermetallic compound formation intervals should be used.

Substrate type, surface quality and film growth regimes should ensure that the roughness of the F-layer interface is as low as possible compared to the F-layer thickness.

Measurement of F-layer thickness and roughness should provide accurate and reliable data within a thickness range of approximately (1 nm).

II. MAGNETRON DEPOSITION OF SUPERCONDUCTING STRUCTURES

The structure was deposited at a temperature of 200°C in the magnetron Z-400 sputtered on commercial silicon substrates (111). The sample size is: 80 mm × 10 mm. In the magnetron chamber, the base vacuum pressure was about 2 × 10-6 mbar. Three targets, Si, Nb and Co, with a diameter of 75 mm were used. Pure argon - 99.999%, "Messer Griesheim" - at a pressure of 8 × 10-3 mbar was used as the spray gas. Before the actual sputtering, all targets were pre-cleaned in Ar plasma for 2-3 minutes in a static position to remove any contamination. Then, without interrupting the vacuum, a wedge-shaped layer of Nb was deposited by moving the target 5 cm from the symmetry axis of the Nb substrate. To subsequently fabricate S/F samples with identical parameters - with varying thickness of the superconducting layer, so that the deposition conditions for all samples in the series are the same, we applied our deposition technique described in detail [6, 7, 8]. The growth rate of the Nb layer directly under the magnetron is about 3 - 4 nm /s. Thus, the silicon surface was sputtered homogeneously with superconducting material - the deposition time is 11.3 sec at a voltage of 380 V, DC.

Subsequently, the Nb wedge layer was coated with ferromagnetic material - Co with a thickness of about 2.5 nm. Cobalt was deposited at a cathodic current of 120 mA. After deposition of the Nb/Co double layer, it was encapsulated with an amorphous silicon layer to eliminate oxidation.

The figure below shows the Z - 400 magnetron at which the thin films were coated:

Fig 1. Magnetron type: Z - 400

To determine the critical thickness of Niobium in contact with Cobalt, an 80mm*10mm sample was coated on a Si substrate, which was placed asymmetrically to the magnetron target by 5 cm, and the superconducting layer (Nb) was deposited as a wedge as shown below:

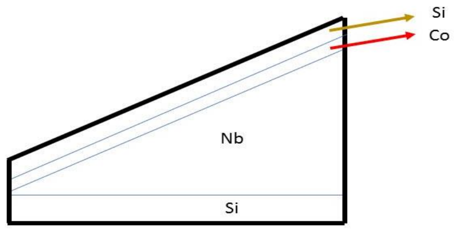

Fig 2. Profile diagram of the magnetron sputtered structure.

For hybrid S/F (Nb/Co) structures, the following issues persist:

a) in the magnetron sputtering process the possibility of island formation of the material must be excluded,
b) the energy of the Fermi levels must have approximately the same value,
c) high vacuum conditions.

The structure of dimensions: 80 mm * 10 mm is cut into 20 pieces. Each of these 20 pieces is measured by the 4-pin method and glued onto the printed circuit board for insertion into the cryostat. We follow figure 3 below:

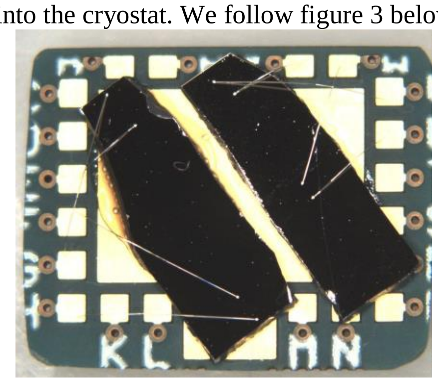

Fig 3. PCB plate, on which two samples are bonded before being inserted into the cryostat.

For this purpose, the PBC in Figure 4 is mounted on the rod that is fixed inside the cryostat:

Fig 4. PCB board, already mounted on the rod for insertion into the cryostat.

Placing samples in the 17 Tesla cryostat to measure superconducting properties:

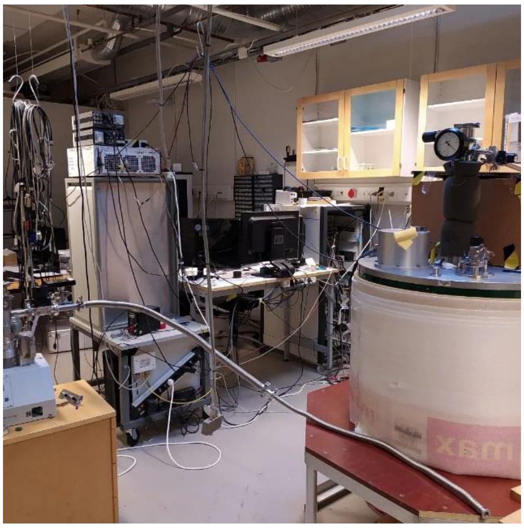

Fig 5. The 17 Tesla cryostat.

The experiment showed that at a constant thickness of 2.5 nm of Cobalt, coupled in close proximity to Niobium, as the thickness of the superconductor decreases - the critical temperature of the hybrid structure decreases. At a thickness less than 17.5 nm of Niobium coupled in proximity to Cobalt, whose critical temperature is 1.28 K, superconductivity disappears. The results are shown in the figure below:

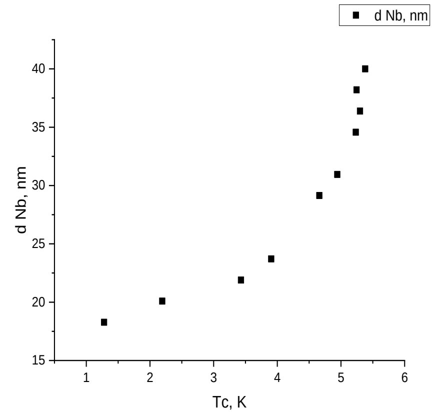

Fig 6. Critical temperature dependence of Niobium thickness.

Figure 6 shows that at 17.5 nm thickness of the Niobium layer the superconducting transition of Niobium in contact with Cobalt occurs.

An important characteristic of our magnetron sputtered nanometer layer samples is - the residual resistivity coefficient, and is shown by the following mathematical relation:

$$R_{300}/R_{10} = 2,5$$

where, R300 - sample resistance at room temperature (T = 300K), R10 - sample resistance at liquid helium temperature.

In figure 6 we can clearly see the transition from the normal state of a 100 nm Cobalt nanostrate to the superconducting state at a temperature of 8K

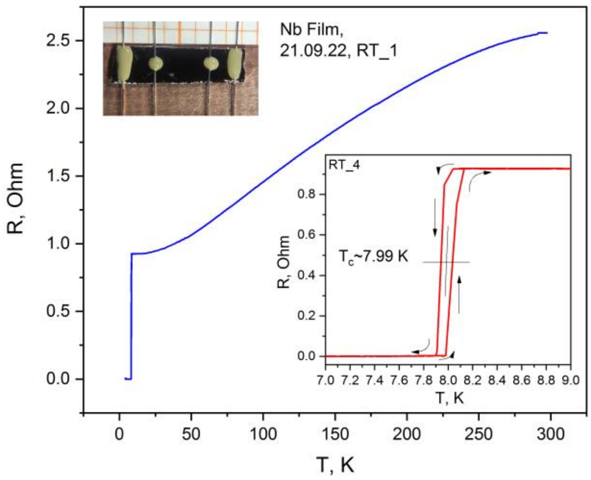

Fig 6. Conductive state transition of 100nm Co nanostrate.

Samples that for some reason are not of good quality - material impurities, or have not been cleaned well, because they do not register the ratio: Rn/Rs in the range of 2 - 2.5 have a low critical temperature, which is not interesting for practical applications because these samples require more cooling, but this is also due to higher economic costs, not being a prospective direction.

III. RESULTS AND DISCUSSION

We determined the superconducting coherence length ξ_S of the Nb layer, which is part of the proximity effect theory, from the linear dependence of $B_{c2\perp}(T)$ near the superconducting transition temperature. The representative slope value for the sample on the thick side of the Nb wedge (dNb ≈ 51 nm, Tc =6.6 K) is $-(dB_{c2\perp}(T)/dT)=0.58$ T/K. To obtain the coherence length ξ_S from the $B_{c2\perp}(T)$ data, we first determine the Ginsburg-Landau coherence length, $\xi_{GL}(0)$, using [9]:

$$\xi_{GL}(0) = \left[-\left(dB_{c2\perp}(T)/dT\right)\left(2\pi T_c/\phi_0\right)\right]^{-1/2}, \quad (1)$$

where $\varphi_0 = 2.07 \times 10^{-15}$ T*m2 is the magnetic flux quantum. Calculation of the parameter $\xi_{GL}(0) \approx 9.3$ nm. For a "dirty" superconductor (short free electron path, $l_S << \xi_{BCS}$, with Bardin-Cooper-Schriffer coherence length $\xi_{BCS} = \hbar\gamma/(\pi 2 k_B T_{c0})$, where $\gamma \approx 1{,}781$ is the Euler constant and is the Fermi velocity) the coherence length ξ_S is defined as follows [10, 11]:

$$\xi_S = \left({}^{\hbar D_S}/_{2\pi k_B T_{c0}}\right)^{1/2} = \sqrt[2]{{}^{\pi}/_{6\gamma}} * \sqrt[2]{l_S \xi_{BCS}} \quad (2)$$

where Ds = $l_S v_S/3$ is the electron diffusion coefficient in the superconductor. Comparison with the Ginsburg-Landau theory allows the relationship to be established [12]:

$$\xi_S = (2/\pi)\xi_{GL}(0) \quad (3)$$

from which we obtain $\xi_S \approx 5.9$ nm.

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