Quasi-one-dimensional FFLO state in the Nb/Ni layered system

A.S. Sidorenko [a,b], V.I. Zdravkov [b], A.A. Prepelitsa [b], C. Helbig [a], Y. Luo [c], S. Gsell [a], M. Schreck [a], S. Klimm [a], S. Horn [a], L.R. Tagirov [a,d,1], R. Tidecks [a]

[a] *Institut für Physik, Universität Augsburg, D-86159 Augsburg, Germany*
[b] *Institute of Applied Physics, MD-2028 Kishinev, Moldova*
[c] *I. Physikalisches Institut, Universität Göttingen, D-37073, Göttingen, Germany*
[d] *Kazan State University, 420008 Kazan, Russia*

Abstract

We investigated Nb/Ni bilayers prepared by DC magnetron sputtering on glass subtrates. The quality of the films was characterized by small-angle X-ray diffrraction analysis. The thickness of the layers was determined by the Rutherford Back Scattering (RBS) technique. We observed distinct oscillations of the superconducting critical temperature for specimens with constant Nb layer thickness upon increasing the thickness of the Ni layer. The results are interpreted in terms of Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) like inhomogeneous superconducting pairing in the ferromagnetic Ni Layer.

Key words: Superconductor/ferromagnet proximity, FFLO pairing

1. Introduction

Two antagonistic long-range orders, superconductivity (S) and ferromagnetism (F), can not coexist in a homogeneous material, because superconductivity requires conduction electron spins to form singlet (spinless) Cooper pairs, whereas the ferromagnetism forces the electron spins to align parallel. However, superconductivity and ferromagnetism can be reconciled, if they are spatially separated in the nanoscale range to form an artificially layered material [1].

Buzdin *et al* [2,3] predicted a realization of a Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) [4,5] like inhomogeneous pairing in the ferromagnetic layers of S/F structures, leading to oscillating behavior of T_c. This prediction stimulated intense studies of artificially layered S/F systems to observe oscillations of T_c. The results appeared to be controversial: in some investigations T_c oscillations were observed, but in others not (see, for example, in [1]), even using the same S/F couples. From the analysis of all published experiments we have drawn the following conclusions:

(1) The sputtering technique has an advantage in comparison with MBE to fabricate S/F samples showing oscillating behavior of superconducting $T_c(d_F)$;

(2) The S/F couples should not consist of immiscible metals. Rather, metals with restricted solubility and narrow composition ranges of intermetallic compound formation should be used;

(3) The substrate type, the quality of the surface, and the film growth regimes should ensure an interface roughness of F-layers as small as possible compared to the F-layer thickness, at which a non-monotonic $T_c(d_F)$ dependence is expected;

(4) The thickness and roughness measurement of the F-layers should give correct and reliable data in the range of thickness around 10Å.

In this investigation we tried to fulfil the above requirements choosing the Nb/Ni couple to observe and characterize oscillating behavior of the superconducting critical temperature.

[1] Corresponding author. Present address: Theoretical Physics Department, Kazan State University, Kremlevskaya str. 18, 420008 Kazan, Russia. E-mail: lenar.tagirov@ksu.ru

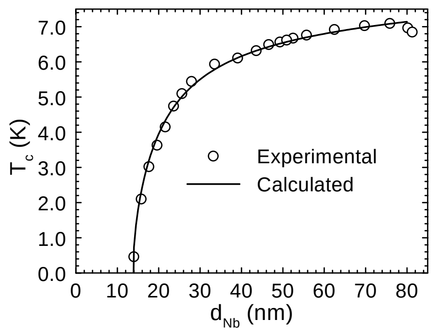

Fig. 1. The dependence of superconducting T_c on the thickness of Nb layer at constant thickness of Ni layer (d_{Ni}=7 nm).

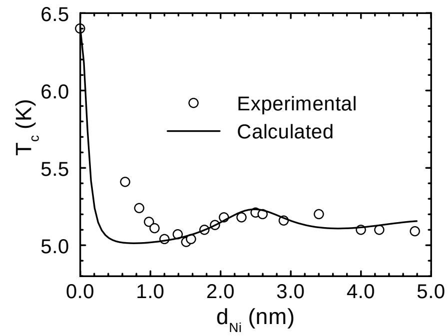

Fig. 2. The dependence of superconducting T_c on the thickness of Ni layer at constant thickness of Nb layer (d_{Nb}=31nm, the coherence length in Ni, ξ_{Ni} $\simeq$0.85 nm).

2. Sample preparation and characterization

The samples were prepared by DC magnetron sputtering on a glass substrate kept at room temperature in Ar atmosphere, at $p_{Ar}= 8{\times}10^{-3}$ mbar. Flame polished glass substrates 8×75 mm^2 was used to prepare bilayers with constant thickness of the one material, and wedge-shaped layer of the second material. The optimal deposition rate was 0.7 nm/s for Nb and 0.5 nm/s for Ni layers. The resulting wedge sample was cut into 1.5 mm wide strips using a diamond cutter. Platinum 50 μm wires were attached by silver paste for four-contact resistance measurements.

Small angle $\theta - 2\theta$ X-ray reflectivity scans were used to determine the Nb films thickness and the interface quality. A big number of oscillations (more than 20 periods) indicated a small roughness of the layers interface (rms less than 0.3 nm). RBS has been used to measure precisely the thickness of Nb and Ni layers. For this purpose an additional sample with identical thickness was prepared on Si substrate at the same run. The advantage of RBS is the possibility to determine the absolute thickness of Ni layers at the level of 10Å with accuracy $\pm$0.2 Å.

3. Results and discussion

Figure 1 shows the dependence of the superconducting T_c on the thickness of Nb at constant thickness of a thick (7 nm) Ni layer deposited on top of the Nb wedge. The critical thickness, $d_{Nb}^{cr} \simeq 139$Å, allows us to determine some of the physical parameters which enter in the theory. Figure 2 displays the dependence of the superconducting T_c on the thickness of the Ni layer at constant thickness of the Nb layer. It shows distinct oscillatory behavior which we refer to the realization of FFLO-like inhomogeneous pairing in the Ni layer.

The physics of oscillations can be explained as follows. When the thickness of the F-layer is smaller or comparable to the decay length of pairing, the pairing wave function being incident on the S/F interface interferes with the wave reflected from the outer surface of the F-layer. Using the analogy with the interference of light, one may say that the F-layer acts like a Fabri-Perot interferometer, which is highly reflective or almost transparent depending on the relation between the wavelength of the light and the thickness of the interferometer. Thus, the pairing function flux is modulated as a function of the F-layer thickness d_F. As a result, the coupling between S and F layers is modulated, and the superconducting T_c oscillates as a function of d_F.

The results of calculations using the theory of Ref. [6] are shown in Figs. 1 and 2 by the solid lines. The discrepancy between the theory and the experiment for $T_c(d_{Ni})$ at small thickness of the Ni layer is probably caused by oxidation. It is well known that the oxidation of Ni stops at a thickness of order of 1-2 nm, depending on temperature and exposition time in air. The thickness at which the theory deviates from the experiment in Fig. 2 correlates well with the oxidation hypothesis.

This work was partially supported through the INTAS Project Nr. 99-00585 (A.S.S. and V.I.Z.), and through the RFBR grant Nr. 00-02-16328 and BRHE grant REC-007 (L.R.T.).

References

[1] C.L. Chien and D.H. Reich, JMMM **200** (1999) 83.

[2] A.I. Buzdin, M.Yu. Kupriyanov, JETP Lett. **52** (1990) 487.

[3] Z. Radović, *et al.,* Phys. Rev B **44** (1991) 759.

[4] P. Fulde and R. Ferrell, Phys. Rev. **135** (1964) A550.

[5] A.I. Larkin and Yu.N. Ovchinnikov, ZhETF **47** (1964) 1136; JETP **20** (1965) 762.

[6] L.R. Tagirov, Physica C **307** (1998) 145.