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Controlling the proximity effect in a Co/Nb multilayer: the properties of electronic transport

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Abstract
We present both theoretical and experimental investigations of the proximity effect in a stack-like superconductor/ferromagnetic (S/F) superlattice, where ferromagnetic layers with different thicknesses and coercive fields are made of Co. Calculations based on the Usadel equations allow us to find the conditions at which switching from the parallel to the antiparallel alignment of the neighboring F-layers leads to a significant change of the superconducting order parameter in superconductive thin films. We experimentally study the transport properties of a lithographically patterned Nb/Co multilayer. We observe that the resistive transition of the multilayer structure has multiple steps, which we attribute to the transition of individual superconductive layers with the critical temperature, T_c, depending on the local magnetization orientation of the neighboring F-layers. We argue that such superlattices can be used as tunable kinetic inductors designed for artificial neural networks representing the information in a "current domain".

Introduction
Multilayer superconductor/ferromagnetic (S/F) heterostructures can be used for construction of tunable cryoelectronic elements, such as switches, Josephson junctions and inductors [1-8]. Here, we present theoretical and experimental investigations of an S/F "stranded wire" with a controllable proximity effect. The wire is composed of ferromagnetic (F) layers separated by thin super-

conducting layers, in which the superconducting order parameter is maintained due to the proximity to a thick superconducting bank (S-bank). Switching from the antiparallel (AP) to the parallel (P) alignment of neighboring F1 and F2 layers leads to a significant enhancement of the effective exchange field in this artificial ferromagnet. Previously, the properties of $[Co(1.5\ nm)/Nb(8\ nm)/Co(2.5\ nm)/Nb(8\ nm)]_6$ multilayer structures for cryogenic memory applications were studied using polarized neutron scattering and magnetometry techniques [9]. In particular, the parameter regions where the aforementioned switching between the P and AP orientations of the F1 and F2 layers is possible were found experimentally.

In this work, we perform theoretical and experimental analyses of electronic properties of Nb/Co multilayers with different F1 and F2 thicknesses and several stacking periods. It is demonstrated that the magnetization switching results in modulation of superconductivity in the superlattice with a corresponding change in the kinetic inductance of the superconducting parts of the wire core, due to the inverse proximity effect. We argue that this effect facilitates new possibilities for the development of tunable superconducting electronic components. For example, the considered "stranded wire" can be readily applied in a synaptic connection for a superconducting artificial neural network (ANN), where the information is represented in a "current domain" [10-21].

The paper is organized as follows. In the next section, we highlight how the proximity effect modulates hybrid S/F structures (the most interesting of the applications discussed), present the model and methods used in the theoretical research, and discuss the obtained results. In the "Experimental results" section, we analyze the transport measurements of the manufactured samples. At the end, we discuss possible applications of the results for the implementation of superconducting synapses and give a conclusion.

Results

Model and theoretical results

Contrary to traditional semiconductor basic elements (transistors), tunable kinetic inductors (TKIs), as well as nonlinear elements (Josephson junctions), are not fabricated in a substrate. This allows for 3D topology benefits, which are especially important for deep ANNs. The F1/s/F2/s superlattice, in which the thick S-bank acts as the source of induced superconductivity, is the simplest model of the 3D structure. Let us consider the applications that are possible due to the control over the order parameter in thin superconductor layers (s-layers) in such a structure.

The simplest cell for the current flow control using the TKI is a splitter. The input current, i_{in}, induced in the input inductance, l_{in}, splits between the two TKI elements. Figure 1b presents the principal scheme of a synaptic element in a superconducting ANN (with TKI elements instead of Josephson junctions, which were used previously [20]).

The synapse modulates the "weight" of an arriving signal, which corresponds to the input current. The transfer function of this current transformer can be described as follows:

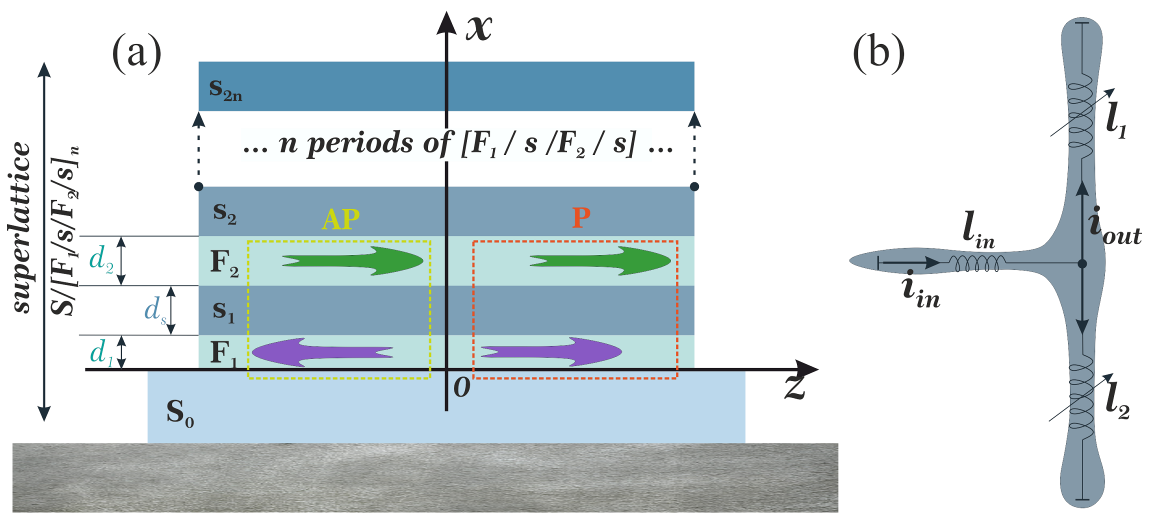

Figure 1: (a) Sketch of the investigated multilayer Co(1.5 nm)/Nb(6 nm)/Co(2.5 nm)/Nb(6 nm) structure. (b) The simplest splitter model based on this TKI.