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Book of Abstracts

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Main Topics

- Spintronics and Magnetotransport
- Magnetophotonics (linear and nonlinear magnetooptics, magnetophotonic crystals)
- High Frequency Properties and Metamaterials
- Diluted Magnetic Semiconductors and Oxides
- Magnetic Nanostructures and Low Dimensional Magnetism
- Magnetic Soft Matter (magnetic polymers, complex magnetic fluids and suspensions)
- Soft and Hard Magnetic Materials
- Magnetic Shape-Memory Alloys and Magnetocaloric Effect
- Multiferroics
- Magnetism and Superconductivity
- Magnetism in Biology and Medicine
- Theory

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TRIPLET PAIRING EFFECTS IN SUPERCONDUCTOR-FERROMAGNET NANOLAYERED HETEROSTRUCTURES

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The theory of superconductor-ferromagnet (S-F) heterostructures with two and more ferromagnetic layers predicts generation of long-range, odd-in-frequency triplet pairing at non-collinear alignment of magnetizations of the F-layers ([1] and references therein). As a consequence, the triplet spin-valve effect has been predicted in [2]. To observe this effect experimentally we realized Nb/$Cu_{41}Ni_{59}$/Nb/Co/CoO_x and Co/CoO_x/$Cu_{41}Ni_{59}$/Nb/$Cu_{41}Ni_{59}$ superconducting spin-valve type proximity-effect heterostructures [3,4].

In the first, adjacent type spin-valve structure, a weak ferromagnet – $Cu_{41}Ni_{59}$ alloy was used as a propagator layer adjacent to the bottom niobium layer – a conventional S-wave superconductor. An antiferromagnetic cobalt oxide layer provided the exchange bias of the in-plane magnetization of the underlying cobalt layer, which played a role of mixer of the triplet and singlet pairing channels.

In the second, interleaved type spin-valve structure, the functional superconducting Nb layer was sandwiched between two ferromagnetic copper-nickel alloy layers. The auxiliary Co/CoO_x bilayer served for exchange biasing the adjacent $Cu_{41}Ni_{59}$ alloy layer to create non-collinear magnetic configurations in the system in the external magnetic field.

Our FMR and SQUID measurements confirmed that the $Cu_{41}Ni_{59}$ layer has easy magnetization axis perpendicular to the film plane, while the metallic Co layer always has in-plane alignment of the magnetization.

The magnetoresistance measurements in Nb/$Cu_{41}Ni_{59}$/Nb/Co/CoO_x system at temperatures close to the superconducting (SC) transition temperature T_c, and magnetic field applied in the in-plane direction, have shown a sequence of transitions from the normal to the SC state and vice versa when sweeping the magnetic field. We refer this unusual magnetoresistance behavior to the indication of the triplet pairing generation at the non-collinear alignment of magnetizations in the Nb/$Cu_{41}Ni_{59}$/Nb/Co/CoO_x heterostructure [3]. A memory effect, *i.e.* zero-field resistance, depending on a magnetic pre-history, has been observed experimentally in Co/CoO_x/$Cu_{41}Ni_{59}$/Nb/$Cu_{41}Ni_{59}$ heterostructure [4] which is also referred to generation of the triplet pairing at non-collinear magnetic configurations.

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30OR-LT-4

ROLE OF NORMAL INTERLAYER IN FERROMAGNETIC JOSEPHSON JUNCTIONS

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The coexistence and competition of ferromagnetic (F) and superconducting (S) ordering leads to a rich spectrum of unusual physical phenomena, intensively studied during the recent years. One of the consequences is the so-called π Josephson junction with phase shift π in the ground state. One or two insulating (I) barriers may be introduced at the SF interfaces as well, in order to enlarge the product $J_c R_N$ in the π-phase. Here J_c is the critical current density of the junction and R_N is its normal resistance.

Nowadays, the development of magnetic memory cells for rapid single flux quantum (RSFQ) logics becomes more and more actual. Only recently, a new type of magnetic memory element based on a junction with a complex ferromagnet-superconductor-insulator weak link (SIsFS) was proposed. One of the aims of our calculation is to study the behaviour of such SIsFS junctions when their middle superconducting layer is in the normal state. Introducing a normal metal (N) layer between the F layer and the S electrode into a ferromagnetic Josephson junction (FJJ) is technologically necessary. Such an additional N layer was used in many FJJs. However, it was not taken into account by any theoretical explanation of these experiments [1].

We calculate the critical current density J_c of FJJs containing ferromagnetic, normal, and insulating layers in the weak link region. We determine the Green's functions with the help of the Usadel equations, which we use in theta parametrization. The Kupriyanov-Lukichev boundary conditions at all interfaces were used.

It was shown earlier that insulating barriers decrease the critical current density and shift the 0-π transitions to smaller values of the ferromagnet thickness d_F [2,3]. A thin N layer inserted between S and I layers does not significantly influence the Josephson effect. However, if the N layer is inserted between I and F layers, it can have a large effect on the Josephson current. The presence of the N layer may increase the amplitude of $J_c(d_F)$ and shift the first 0-π transition to larger d_F. The oscillation period of $J_c(d_F)$ is still determined by the relation of the magnetic exchange energy H and the diffusion coefficient in the dirty limit.

It is shown that even a thin additional N layer may change the boundary conditions at the IF boundary depending on the value of its conductivity. We conclude that it effectively mitigates the effect of the insulating barrier on the decaying oscillations of the critical current density $J_c(d_F)$. Even technological thin N layers, which almost do not suppress the superconducting correlation, have to be taken into account for the explanation of experimental results concerning the Josephson effect in FJJs. For example, the 0 and π states of multilayered FJJs containing few normal layers, proposed recently as basis for a cryogenic magnetic memory, should be determined very carefully. Using the developed approach we explain the existing experiments on SIFS and SINFS FJJs [1].

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30PO-I2-17

MAGNETIC JOSEPHSON JUNCTIONS FOR REVERSIBLE COMPUTATIONS

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We present the possibilities to construct principal logic cell for reversible (adiabatic) computing by implementation of magnetic Josephson junction in usual dc-SQUID.

The interest to this problem is motivated by extremely small energy dissipation per operation in the mentioned reversible SQUID-based logic circuits. The currently demonstrated specific energy dissipation per elementary operation for semiconductor technology is of the order of 10^6 kT, where k is the Boltzmann constant and T is the temperature. However, the thermodynamic threshold per logic operation, known as the Landauer limit, is equal to $kT \ln 2$ [1, 2]. And this limit can be achieved and outperformed due to *reversible* controllable evolution of current states in arrays of magnetically coupled pi-shifted bi-SQUIDs.

The suggested bi-SQUID is a two-junction interferometer, where geometric inductance is shunted with Josephson π-junction in superconducting state. This shunt is based on a heterostructure with *negative critical current*, which consists of superconductor (S), insulator (I), and ferromagnetic (F), and normal (N) metal (e.g. SFS, SIsFS, SINFS et cetera). Fabrication and utilization of the suggested structure proved to be much more easier, then for the known Josephson reversible cells (based on SQUIDs with negative inductances and quantum parametron) [2, 3].

We start with the brief discussion of impact of magnetic Josephson junction on dc-SQUID potential energy. Then we present the analysis of reversible dynamics in single cell, in the cells, coupled in the transition line and in simple shift register. As a conclusion, we compare main characteristics (such as energy dissipation per operation and size) of the bi-SQUID-based adiabatic circuits with the same characteristics of the mentioned competing structures.

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1TL-LT-4

SUPERCONDUCTING SPIN VALVES, CURRENT STATUS

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We discuss the current status of theoretical understanding and experimental realizations of superconducting spin valves.

The interest to this problem is motivated by the recent developments, which clearly demonstrated that the achieved background in this field provides the opportunity for finding solutions for elaboration of superconducting memory cells, which can be integrated with RSFQ logic circuits. These cells are based on heterostructures, which consist of superconducting (S) materials, insulator (I), ferromagnetic (F) and normal (N) metals. Fabrication and study of such heterostructures is one of the components of the new U.S. program, providing for the next 4 years the establishment of production for the manufacture of working model of a prototype superconducting computer [1].

We start with the brief discussion of peculiarities of proximity effect in SF and SFF multilayers and their manifestation in spin valve devices controlling critical temperature of S film or conductance of one of the F layers.

The recent status of experimental and theoretical achievements in developing SIsFS and SFFS Josephson devices, which are considered as the control unit of superconducting memory cell will be discussed. Special attention will be given to the effect of formation of domain walls and normal phase inclusions in the F films on the junction critical current.

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http://www.iarpa.gov/Programs/sso/C3/solicitation_c3.html

1OR-LT-7

CURRENT PROPERTIES OF JOSEPHSON SISFS JUNCTIONS

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In recent years Josephson junctions with ferromagnetic F layers became one of the most desirable and actively developed devices in superconductive electronics. The oscillating nature of superconductive proximity effect in the magnetics leads to appearance of π state and provides opportunities to develop a wide range of applications. Among them there are memory elements, improved RSFQ circuits and metamaterial elements.

Unfortunately, characteristic voltage, $I_C R_N$, of conventional SFS junctions is much smaller than that of tunnel SIS devices, which are widely used in superconductive electronics. This leads to deficient value of characteristic frequency and to difficulties in integration with other circuits.

As possible way to solve this task we considered Josephson SIsFS structures with complex interlayer consisting of tunnel barrier ‘I’, ferromagnetic layer ‘F’ and thin superconductor layer ‘s’ and we outlined operational modes of these junction. Due to superconductive support inside weak link this structure achieves both high frequency and has magnetic properties. Thus SIsFS can be used as high-speed π junction or memory element [1-2].

However pairing in the thin middle superconductive film ‘s’ suffers from proximity effect with ferromagnetic layer and stays in the critical regime. It means that state of that layer significantly depends from inhomogeneities in ferromagnetic layer. We study impact on current properties of different types of inhomogeneities including domains walls and normal phase inclusions.

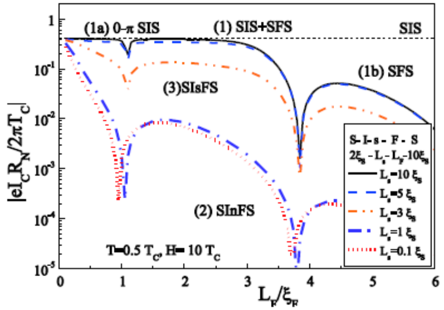

Fig. 1 Operational Modes of SIsFS structure: Characteristic voltage $I_C R_N$ versus thickness of F-layer L_F for the set of different s-layer thickness L_s

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1OR-LT-9

PROXIMITY EFFECTS IN SUPERCONDUCTING TRIPLET SPIN-VALVE F2F1S STRUCTURES

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We investigate critical temperature T_c of F2F1S trilayers (S is a singlet superconductor, Fi is a ferromagnetic metal), where the long-range triplet superconducting pairing component is generated at noncollinear magnetizations of the F layers [1]. Earlier we demonstrated that T_c in such structures can be non-monotonic function of the angle α between magnetizations of the two F layers [2,3]. It was shown recently [4] that anomalous dependence of the spin-triplet correlations on the angle α in FFS structures can be realized.

We demonstrate that it is possible to realize different spin-valve effect modes - the standard switching effect, the triplet spin-valve effect, reentrant $T_c(\alpha)$ dependence or reentrant $T_c(\alpha)$ dependence with the inverse switching effect - by variation of the F2/F1 interface transparency or the exchange splitting energy.

Moreover, we show that position of the T_c minimum can be changed by joint variation of the F2/F1 interface transparency and the layer thicknesses.

Thereby we demonstrate that the realization of one of the spin-valve effect modes can be done not only by variation of the F layers thicknesses, but also by varying the F2/F1 interface transparency or the exchange field energy. It is explained by changes in the interference conditions for the condensate functions. This interference depends on the F layers thicknesses, the F2/F1 interface transparency, and the exchange splitting energy.

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3RP-B-5

MEMORY EFFECT IN SUPERCONDUCTOR/FERROMAGNET NANOSTRUCTURES Co/CoO$_x$/CuNi/Nb/CuNi

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The theory of superconductor-ferromagnet (S-F) heterostructures with two and more ferromagnetic layers predicts generation of long-range, odd-in-frequency triplet pairing at non-collinear alignment of magnetizations of the F-layers ([1] and references therein). Based on ideas of the superconducting triplet spin-valve [2,3] we observed switching of the Co/CoO$_x$/Cu$_{41}$Ni$_{59}$/Nb/Cu$_{41}$Ni$_{59}$ proximity type heterostructures between normal and (almost) superconducting states [4].

The Co/CoO$_x$/Cu$_{41}$Ni$_{59}$/Nb/Cu$_{41}$Ni$_{59}$ ultrathin heterostructure was prepared by magnetron sputtering on a commercial silicon substrate covered by a silicon buffer layer prior the heterostructure deposition. The Co/CoO$_x$ composite layer provided strong exchange biasing (~ 1800 Oe) of the adjacent hard ferromagnetic Cu$_{41}$Ni$_{59}$ alloy layer, while the outer soft Cu$_{41}$Ni$_{59}$ alloy layer could be remagnetized by a weak external magnetic field creating controllable alignments with respect to the hard interior Cu$_{41}$Ni$_{59}$ alloy layer and the metallic Co layer as well. The thickness of the Cu$_{41}$Ni$_{59}$ alloy layers was varied between 0 and 25 nm, the Nb layer thickness was about 12 nm.

Upon cycling the in-plane magnetic field in the range ± 6 kOe and the temperature close to the superconducting transition a memory effect has been observed [4]. If the magnetic field was dropped to zero from the initial field-cooling direction at 10 kOe, the system resistance dropped down to the almost superconducting low-resistive state. Changing polarity of the field, raising its magnitude to -6 kOe and dropping the field to zero again brought the system to the resistance at the normal conducting state. The bistability was repeatedly reproduced upon further cycling along the full magnetic hysteresis loop of the heterostructure. The both low- and high-resistive states at zero magnetic field were determined solely by pre-history of the field cycling and did not need biasing field to keep them steady.

We refer the observed memory effect to generation of the triplet pairing at non-collinear magnetic configurations in the studied system.

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