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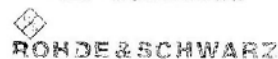## Moscow – Zvenigorod, Russia

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Superconductor – ferromagnetic control unit for superconducting memory compatible with RSFQ logic circuits

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We overview the current status of theoretical understanding and experimental realizations of superconducting spin valves, which can be used as control units for superconducting memory compatible with RSFQ logic circuits.

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 in SFF structures.

The recent status of experimental and theoretical achievements in developing SIsFS and SFFS Josephson control units 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.

1. D.S. Holmes, A.L.Ripple, and M.A. Manheimer, *IEEE Trans. on Appl. Supercond.*, **23**, 1701610, 2013; http://www.iarpa.gov/Programs/sso/C3/solicitation_c3.html

Josephson magnetic rotary valve

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Superconducting digital circuits based on Josephson junctions underwent significant progress in the last decades offering high frequency data receiving and processing (e.g. all-digital RF receiver with clock frequency of up to 30 GHz [1]). Magnetic flux quantization in a superconducting loop allowing representation of information bit as a flux quantum is one of the key features providing the superconducting technology advantages. Unfortunately, the reverse side of using this feature is a requirement to store the flux quantum in superconducting valves and memory cells that naturally limits possibilities of their miniaturization restraining progress of the technology.

Magnetic devices, which rely on manipulation of the local magnetizations, are well known for their applications in random access memory and recording heads. Recent advances in understanding of hybrid S-F structures operating at the interplay of generally mutually exclusive phenomena of superconductivity (S) and ferromagnetism (F) opened exciting opportunities to develop the new tunable Josephson junctions which characteristics are defined by properties of the F-layer(s) placed in the weak link area. For example, the junction ground-state phase difference can be π–shifted in comparison with that of conventional junction or even arbitrary φ-shifted ($0 < \varphi < \pi$) and doubly degenerated ($\varphi_0 = \pm \varphi$) by implementation of spatially inhomogeneous 0-π junction. A number of approaches were proposed for development of the Josephson valves relying on control of the induced superconducting pair states in the weak link area by directly changing the F-layer exchange field or changing the mutual orientation of magnetizations of multiple F-layers, or making use of the mentioned φ-junction ground-state bistability. However, experimental realizations revealed the drawbacks that depending on the used approach can be as follows: 1) the junction critical current is modulated in a very narrow range; 2) characteristic frequency of the junction is highly suppressed; 3) the critical current modulation requires application of strong magnetic fields; 4) the junction size cannot be reduced well below the Josephson penetration length which is larger by an order than characteristic dimension of modern junctions.

To circumvent the drawbacks we propose an approach that combines the advantages of some known Josephson valves in a single structure. We restrict ourselves by the single F-layer introducing a spatial 0-π inhomogeneity of the junction. Since the stable states of the 0- and π-parts are shifted in phase, their coupling provides the leveling of the phase across the junction (if the junction is small enough) corresponding to nearly unstable state that manifests itself via significant reduction of the total critical current I_c. The F-layer's magnetic field oriented parallel to the 0-π boundary can perform an "effective decoupling" providing the phase gradient across the junction, spreading the phase in the parts close to their initial ground states, and thus restoring the I_c. If the F-layer's magnetization is rotated perpendicularly to the junction's spatial inhomogeneity, the field is vice versa enhances the critical current suppression. We show that the 0-π inhomogeneity can be formed by introducing an additional thin normal (N) layer above some part of the F-layer. To provide the required high-frequency characteristics of the junction, the proposed S-F/FN-S valve can be used as a control element in the SIsFS junction which we proposed earlier [2]. In this case the $I_c R_n$ product which is proportional to characteristic frequency of a Josephson junction is determined by the SIs part while modulation of the junction critical current in a wide range corresponds to rotation of the F-layer magnetization in the s-F/FN-S part used instead of the sFS one. This rotation can be easily provided by application of reasonable mutually orthogonal magnetic fields. The using of the magnetization orientation for the critical current control provides non-volatility of the element and the ability of non-destructive read-out.

1. D. Gupta et al., IEEE Trans. Appl. Supercond., **21**, 1EB01, 2011.
2. S.V. Bakurskiy, N.V. Klenov, I.I. Soloviev, M.Yu. Kupriyanov, and A.A. Golubov, Phys. Rev. B, **88**, 144519, 2013.