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Nucleation of Superconducting Domains in Thin s-layers of S-F/N-sIS Josephson Devices

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Josephson junctions containing normal (N) and ferromagnetic (F) materials in the weak link region are currently the subject of intense research. The interest in such structures is due to the possibility of their use as control elements of superconductor memory compatible with the SFQ logic. At present there are many implementations of such controls. Among them, the tunnel structures containing one ferromagnetic layer in the weak link region are of greatest interest. Anisotropy of their properties necessary for operation of the cell is achieved in such devices by complicating the structure of the weak-coupling area.

In this work we study theoretically the properties of S-F/N-sIS tunnel devices in the frame of the quasiclassical Usadel formalism. This structure consists of two superconductive electrodes (S), two areas of weak link with tunnel (I) and metallic (N/F) types of superconductivity. (N/F) part includes longitudinally oriented normal (N) and ferromagnetic (F) layers. We choose thickness of F-layer such that related SFs junction occurs in the π state. The weak link areas are separated by thin superconductive s-layer. We assume that the scale of the structure is much less than the Josephson penetration depth and all materials are in the dirty limit, so we can use Usadel equations. We consider this system numerically as a two-dimensional self-consistent boundary problem with Kupriyanov-Lukichev boundary conditions and focus on the state of the intermediate thin superconductive s-layer.

This system exists in the competition between three different terms, which determine the properties (pair amplitude and phase) of the s-film. The first two terms are the Josephson energies of SNs and SFs junctions, respectively. SNs junction forces the s-layer to exist with 0-phase in the ground state, while SFs one tries to force π-phase. The stronger term wins the competition and sets its preferable state. However, while the s-film has a finite thickness, there is one other possible option: the superconductivity in a certain volume disappears and the s-film exhibits two separate superconductive domains with 0- and π- phase. Numerical solutions confirm this model.

When the s film is thicker than the critical value (ds = 4 and ds = 5), the single domain exists. Thin s films (ds = 3 and ds =3.5) include two domains s_0 and s_π, separated by certain volume of suppressed superconductivity.

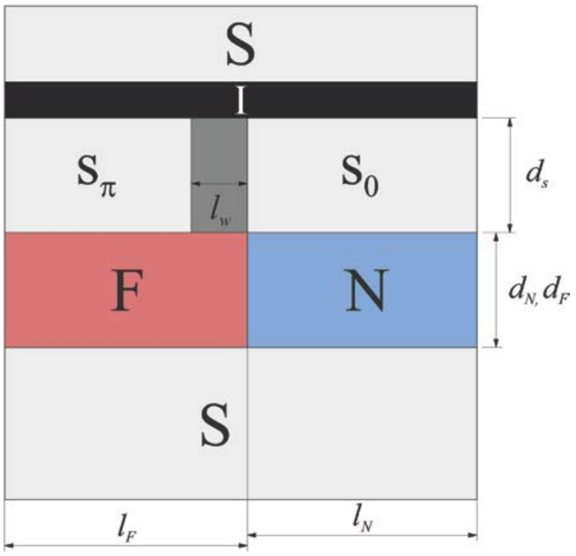

Fig.1. Schematic picture of S-N/F-s-I-S structure with superconducting 0- and π- domains in the thin s-layer. Thickness of the superconductive, ferromagnetic and normal metal films are denoted as *ds*, d_N and d_F, respectively. Cross-sectional lengths of ferromagnetic and normal metal films are denoted as l_F and l_N.

We demonstrate that the system with critical thickness ds can exist in both states: with separation of domains and without it. These states are metastable and can be switched. We propose to switch this system between two states defined above by Josephson current injected trough different electrodes. Consider injection of the current through the bottom S electrode and thin s-film. In the case of s-film without separate domains, the system operates like a conventional double channel 0-π junction: currents through N and F parts have opposite directions and decrease the total critical current. The energy of this state increases with the current's magnitude. However, if the s-layer is separated into domains, the current distribution strongly depends upon which domain is chosen as an electrode. If the current flows to s_0 electrode, than the main impact on this current is provided by N channel, while the SFs junction is suppressed by additional domain junction connected in series with it. This is most energy efficient current state. In contrast, if the current flows to s_π electrode, it is a π - junction with additional suppressed normal channel. In this case, for chosen parameters, it has the lowest value of critical current and the highest energy of the state. Thus, the injected current can switch the system into two different states: from separated domains to homogeneous state and back.

Read operation can be implemented by vertical current through top and bottom S electrodes. In this case, weak link of the Josephson junction is located on tunnel barrier I and the critical current is much smaller than in previously discussed cases. Hence, it can't change the initial state of the system. The magnitude of critical current is determined only by superconductive order parameters in the vicinity of insulator I. In the state with homogeneous s-layer, the current is distributed evenly over the whole tunnel barrier, while in the case of separate domains, the current through the tunnel barrier consist of two channels with opposite directions of flow. Total current in the latter state is much smaller than in the former. Thus, the system significantly changes critical current by switching and can be used as a key or memory element.

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