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Josephson effect in laterally inhomogeneous structures with ferromagnetic materials

T. Karminskaya, M. Kupriyanov, N. Pugach

1. Institute of Nuclear Physics, Moscow State University, Moscow, Russia, mskupri@pn.sinp.msu.ru 2. Physics Department of Moscow State University, Moscow, Russia, pugach@imag.ru

Utilization of Josephson junctions with ferromagnetic (F) materials into practical devices is limiting now by small values of superconducting decay length in F interlayes and by a possibility of nucleation a inhomogenous superconducting state in the direction perpendicular to the current flow. In this paper we rack both of these problems. In the frame of microscopic theory of superconductivity we have analyzed the Josephson coupling in three generic structures. They are S-(FN)-S and S-(FNF)-S devices and tunnel SIFS structures with inhomogeneous transparency of SF interface.

The first two structures consists of superconducting (S) banks coupled by a ferromagnetic/normal (N) metal multilayer providing a possibility for a supercurrent to flow in the direction parallel to NF interfaces. The main disadvantage of previously studded SFS structures comes from the fact that a supercurrent in them has been applied in the direction perpendicular to the planes of interfaces. This in combination with small value of decay length $\xi_F=1,2\ldots 4,6$ nm and period of oscillations $\xi_F=0,3\ldots 2$ nm of thickness dependence of a junction critical current $I_C$ make difficult the fabrication of SFS junctions with reproducible parameters. Small values of $\xi_F$ and $\xi_F$ also lead to suppression of $I_C R_N$ product thus limiting the cut off frequency of the junctions. In this range of $\xi_F$ and $\xi_F$ it is also difficult to realize an effective control of $I_C$ by changing the mutual orientation of magnetization of the F layers.

In this study we have shown that this difficulties can be overcome in S-(FN)-S Josephson junctions in the geometry of the structure providing the supercurrent flow in the direction parallel to FN interfaces. In the frame of Usadel equations we have demonstrated that the interaction between F and N films may result in significant increase of effective $\xi_F$ and $\xi_F$ up to the scale of $\xi_N$. We also have studied the dependence of the critical current of the structure on the value of exchange energies $H_1$ and $H_2$ in the bottom and upper F films.

We have shown that the transition from parallel to anti parallel orientations of F films magnetization results ether in transition from 0 to $\pi$ states or in essential increase of the value of the critical current.

The next advantage of considered S-(FN)-S Josephson junctions is that they are free from a nucleation of point contacts with inhomogeneous distribution of critical current density $J_c(y)$ inside them. The last effect can take place in a traditional geometry in which the direction of the current flow is perpendicular to the interfaces, while the junction itself is close to the point of “0” to “$\pi$” transition and there are fluctuations ether of layer thickness or transparency of interfaces. In recent experiments [1,2] with SFS and SIFS junctions the lack of uniformity of $J_c(y)$ had been achieved by making a step like changes of the thickness of the ferromagnetic (F) or normal layer inside a junction.

We model this step by supposing that one of S/F interfaces of a structure possesses a step like change of its transparency. In the framework of the Usadel equations we have shown that at certain thickness of F-layer the inhomogeneity of the transparency leads to a formation of a nonuniform point contact inside the structure. This may lead to the dependence of the junction critical current on external magnetic field essentially different from the Fraunhofer pattern typically observed in usual Josephson contacts. Namely, the value of critical current grows up with the increase of magnetic field achieving the maximum value in the field of the order of a second critical magnetic field of superconducting electrodes.

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Fluctuations of the thin diffusive metal film under the influence of microwave radiation

I. Devyatov¹, M. Kupriyanov¹, D. Goncharov¹

1. Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 1 - 2, Leninskie Gory, GSP-2, Moscow, Russia, 119992, E-mail address:igor-devyatov@yandex.ru.

The purpose of this paper is the study of nonequilibrium fluctuations originating of expose of the thin low temperature diffusive metal resistor by high-frequency electromagnetic radiation. This problem is important for the correct account of fluctuations in modern Josephson self-selecting detector based on LTS materials and operating in GHz frequency range. This problem also important for the design of the RSFQ circuits interface of the quantum computer.

The nonequilibrium fluctuation related with nonequilibrium electron distribution function in the metal diffusive resistor by the relation, obtained in [1]. With the aim to calculate this nonequilibrium distribution function we used the semiclassical quantum kinetic equation, which has in a spatially homogeneous case the following form:

$$I^{\text{elas}} = I^{\text{coll}}.$$  (1)

In (1) term $I^{\text{coll}}$ describes processes of an inelastic relaxation of electrons, and term $I^{\text{elas}}$ describes connection with an external electromagnetic field (source term). We considered the case of rather high-frequency field, with frequency $\omega$ satisfying to a quantum condition of absorption of an electromagnetic field [2]:

$$\tau_{\text{e}}^{-1} \gg \omega \gg \tau_{\text{n}}^{-1}.$$  (2)

In (2) $\tau_{\text{e}}^{-1}$, $\tau_{\text{n}}^{-1}$ are velocities of an inelastic and elastic relaxation accordingly. In this case source term $I^{\text{elas}}$ in (1) has the following form [2]:

$$I^{\text{elas}}(\epsilon) = \tau_{\text{e}}^{-1}\left[f(\epsilon + h\omega) + f(\epsilon - h\omega) - 2f(\epsilon)\right].$$  (3)

In (3) $f(\epsilon)$ is the distribution function of electrons on energies. The form of the source term (3) differs from the classical form of the source function, used in [3] appropriate to a low-frequency signal. Source term (3) describes process of absorption of photons of an electromagnetic field by electrons of a diffusive film, when the momentum conservation law during absorption of a photon by an electron is ensured with scattering of an electron on impurity. In this case the velocity of absorption of photons is equal: $\tau_{\text{e}}^{-1} = e^2 Da^2/(\hbar c)^2$,

where $A_0$ is the amplitude of a vector potential of a high-frequency harmonic electromagnetic signal, $D$ is the diffusivity of a film, $c$ is the speed of light, $e$ is the charge of an electron. The used form of a source term (3) takes into account a single photon absorption, and also sequential absorption of photons.

We considered various models of an inelastic relaxation appropriate to the scattering term $I^{\text{elas}}$ in (1). We considered both electron - phonon and electron - electron interactions appropriate to a "pure" limit [4], and also considered the "dirty" limit. For "dirty" case we considered phenomenologically introduced kernels with power degree dependence "-2" [5], and "-3/2" [6]. For all mentioned above cases the non-equilibrium distribution function were calculated and the dependence of a noise spectral density of fluctuations on a power of a high-frequency signal was found.

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