Ferromagnetic Josephson junctions with steplike interface transparency

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Within the framework of the quasiclassical Usadel equations we study the Josephson effect in superconductor-insulator-ferromagnet-superconductor (SIFS) and SIFNS (N is a normal metal) structures with a steplike transparency of the FS or NS interface. At certain parameters the steplike transparency leads to the formation of a region, where the critical current-density distribution $J_C(y)$ along the junction exhibits a damped oscillation with a sign change. This results in the formation of a 0-π nanojunction with the characteristic length of 0 and π regions of the order of the coherence length ξ_F for SIFS and ξ_N for SIFNS junctions, respectively. Using several transparency steps one can create an array of nanojunctions. Such structures exhibit an unusual behavior in an external magnetic field H. The total critical current grows with increasing H up to a certain value, which depends on the size of a single nanojunction, and has multiperiodic oscillations in the case of an array.

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I. INTRODUCTION

Recently, unconventional properties of Josephson junctions (JJs) have attracted a lot of attention.[1–3] Contrary to the already well-known 0 JJs with a Josephson phase $\varphi=0$ in the ground state, junctions with ferromagnetic barriers may have a ground state with $\varphi=\pi$ (π-JJs). These junctions may be used in electronic circuits, e.g., in JJ flux qubits with low decoherence,[4] self-biased rapid single flux quantum digital circuits,[5] or complementary logic.[6] If the current-phase relation of a JJ has the usual form $J(\varphi)=J_C \sin(\varphi)$ the ground state $\varphi=0$ is realized for $J_C>0$ and the ground state $\varphi=\pi$ for $J_C<0$. The last condition may be satisfied in the case of a ferromagnetic barrier. Such a junction consists of two superconducting electrodes (S) separated by the ferromagnetic layer (F). It could include also a thin insulating tunnel barrier (I), i.e., SFS or SIFS multilayers may be considered.

Modern technology allows to manufacture not only 0 or π-JJs but also the so-called 0-π Josephson junctions, i.e., junctions some parts of which behave as 0 junctions and other parts behave as π junctions.[7] In these structures, intensively studied experimentally, the different sign of J_C can be achieved by introducing a steplike change in the thickness of the F layer.[8–12]

The interest in these structures has been stimulated by the existence of unusual topological vortex solutions in these 0-π junctions. A spontaneous Josephson vortex carrying a fraction of the magnetic-flux quantum $\Phi_0 \approx 2.07 \times 10^{-15}$ Wb may appear at a 0-π boundary.[7,13,14] In the region, where the phase φ changes from 0 to π, there is a nonzero gradient $\partial\varphi/\partial y$ of the Josephson phase along the junction that is proportional to the local magnetic field. In essence this field is created by supercurrents $\sim\sin(\varphi)$ circulating in this region. These currents are localized in a λ_J vicinity of the 0-π boundary (λ_J is the Josephson penetration depth) and create a vortex of supercurrent with total magnetic flux equal to $\pm\Phi_0/2$, whereas a usual Josephson vortex carries $\pm\Phi_0$, provided that the junction length $L \gg \lambda_J$. In the case of $L \lesssim \lambda_J$ the spontaneous flux[7,13,15–17] $|\Phi|<\Phi_0/2$. It was shown theoretically[17,18] and indicated in experiments[9–11] that for certain conditions the existence of a fractional Josephson vortex at the 0-π boundary is energetically favorable in the ground state. The fractional vortex is pinned at the 0-π boundary and has two polarities that may be used for information storage and processing in the classical and quantum domains, e.g., to build JJ-based qubits.[19] We note that the fractional vortex described above is always pinned and is different from fractional Josephson vortices that are the solutions of a double sine-Gordon equation.[20–22]

Not only single Josephson junctions but also superconducting loops intersected by two JJs [dc superconducting quantum interference devices (SQUIDs)] and their arrays may be used in applications. Such arrays consist of N Josephson junctions connected as a one-dimensional parallel chain in such a way that $N-1$ individual superconducting loops are formed. Such an array exhibits an unusual dependence of its mean voltage on the magnetic field H for overcritical applied bias current. If the loops are identical the voltage response $V(H)$ is Φ_0 periodic. For JJ arrays with incommensurate loop areas the voltage response $V(H)$ is nonperiodic, and can have a rather sharp dip at $H=0$. This property may be used to create a sensitive absolute field magnetometer that is called superconducting quantum interference filter (SQIF).[23–27] So far, these SQIFs are based on usual JJs. However, recently it was also suggested to realize 0-π SQIFs, using constriction junctions in d-wave superconductors.[28] In the present paper we suggest SQIF-like

