Chapter 6
Ferromagnetic Josephson Junctions with Critical Current Density Artificially Modulated on a "Short" Scale

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Abstract We study the Josephson effect in junctions with a ferromagnetic (F) barrier having its properties (interface transparency or the F-layer thickness) artificially modulated on a scale less than the Josephson penetration length. Within the framework of the quasiclassical Usadel equations, we describe SIFS and SIFNS (S is a superconductor, I is an insulator, N is a normal metal) structures with a step-like transparency of the FS or NS interface. The step-like change in parameters may lead to oscillations (including sign change) of the critical current density $J_C(y)$ along the junction in the vicinity of the step, resulting in the formation of a 0–π nano-junction near the step. Such structures exhibit an unusual behaviour in an external magnetic field H. The properties of arrays of nano-junctions with

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several transparency steps are also investigated. We propose a method to realize a φ Josephson junction by combining alternating 0 and π parts made of "clean" SFS sub junctions with different F-layer thickness and an intrinsically non-sinusoidal current–phase relation (CPR). The latter can significantly enlarge the parameter range of the φ ground state and make the practical realization of φ Josephson junctions feasible. Such junctions may also have two different stable solutions, such as 0 and π, 0 and φ, or φ and π.

6.1 Introduction

The interest in Josephson junction (JJ) devices with a ferromagnetic barrier has been continuously increasing during the last years [1, 2]. Such a junction consists of two superconducting electrodes (S) separated by a ferromagnetic layer (F). It may include also a thin insulating tunnel barrier (I) and/or a normal metal layer (N), i.e. SFS, SIFS, or SIFNS multilayers may be considered. The critical current density J_c of an SFS junction exhibits damped oscillations as a function of the F-layer thickness d_F so that the Josephson phase ϕ can be 0 or π in the ground state [1,2]. π junctions can be used as (non-dischargeable) on-chip π-phase batteries for self-biasing various electronic circuits in the classical and quantum domains, for example self-biased RSFQ logic [3] or flux qubits [4, 5]. In addition, for quantum circuits self-biasing also decouples the circuit from the environment and improves decoherence figures, for example in the quiet qubit. [4, 6, 7] In classical circuits, a phase battery may also substitute the conventional inductance and substantially reduce the size of an elementary cell [8]. Some of these proposals were already realized practically [3,9].

Modern technology allows to manufacture not only 0 or π JJs, but also so-called 0–π Josephson junctions (see Fig. 6.1), i.e. junctions some parts of which behave as 0 junctions and other parts as π junctions [10]. In these structures, intensively studied experimentally, the different sign of J_C can be achieved by introducing a step-like change of the thickness of the F layer [11–15].

The interest in these 0–π junctions has been stimulated by the existence of unusual topological vortex solutions. A spontaneous Josephson vortex carrying a fraction of the magnetic flux quantum $\Phi_0 \approx 2.07 \times 10^{-15}$ Wb may appear at the 0–π boundary [10, 16, 17]. In the region where the phase ϕ changes from 0 to π there is a non-zero gradient $\partial\phi/\partial y$ of the Josephson phase along the junction that is proportional to the local magnetic field. In essence, this field is created by supercurrents $\sim \sin(\phi)$ 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 [10, 16, 18–20] $|\Phi| < \Phi_0/2$. It was shown theoretically [20,21] and indicated in experiments [11,14,22] that for certain conditions the existence of a fractional Josephson vortex at the 0–π boundary is