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Double-well potential for a Josephson vortex qubit

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Abstract

The prospect of designing a vortex qubit is analyzed theoretically by studying the classical dynamics of a vortex in a double-well potential created in a semiannular Josephson junction. A vortex in a double-well potential behaves like a particle in a two-level system and can be a candidate for a qubit. Tunability of the double-well potential inside a semiannular Josephson junction allows the manipulation of the vortex states. Methods of vortex manipulation and read-out of the classical states of a qubit are also discussed.

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1. Introduction

Quantum-state engineering has emerged as an active research field with potential applications in quantum information processing, quantum computation and communication [1]. Technological refinements are in progress to implement qubits on various systems like trapped ions [2], NMR in molecules [3], quantum optical systems [4], solid-state based systems [5], etc. Among these candidates, solid-state devices offer technical advantage of embedding in electronic circuitry and can be scaled to produce the large number of qubits required for useful computation. All the superconducting solid-state qubits proposed so far are based on Josephson junctions. Ultrashort Josephson junction (JJ) circuits in the charge [6] and flux regime [7] have been tested and realized as qubits. In charge qubits, the charged states of an electron box are used as the basis states of the qubit. Superposition of the basis states and the existence of coherent Rabi-oscillations of charge qubits are already experimentally verified [8]. In flux qubits, the dynamics is governed by the superconducting phase difference across the junction and the flux

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enclosed by oppositely circulating currents in a superconducting loop forms the basis states of a qubit. Various superconducting circuits like rf-SQUIDs, π-junctions and multi-junction loops are under investigation to construct qubits [9].

Apart from these short JJs, long JJs with trapped fluxons (vortices) are also considered for qubit implementation [10–12]. A scheme for the preparation, manipulation and read-out of the vortex states in these qubits in the classical regime is also reported [11]. At millikelvin temperatures, vortices display macroscopic quantum properties and exhibit quantum tunnelling [13]. Vortices in long JJ, which are particle-like (~500 times smaller than the electron mass) collective excitations of the phase difference, do not generate any radiation during their motion and are well decoupled from other electromagnetic excitations.

Earlier theoretical and experimental investigations have predicted and established that a vortex in a double-well potential is a suitable candidate for the realization of a qubit [11]. An annular Josephson junction with a microshort is studied towards this objective and found suitable for the creation of a double-well potential [14]. In this work, we describe a method to create a double-well potential in a semiannular JJ [15]. Compared to an annular geometry, the open boundaries of a semiannular geometry provides the fabrication compatibility with the rapid single flux quantum (RSFQ) logic interface [12]. Using RSFQ circuit, fluxons of required polarity can be inserted into the junction and the initial state preparation of a vortex qubit can be achieved. The RSFQ logic circuit is a natural choice for an interface between vortex qubits and room-temperature electronics.

This letter describes the classical states of a vortex qubit in a double-well potential created in a semiannular JJ. In the following, we formulate the model equations of the vortex dynamics in a semiannular JJ with a microshort and make use of perturbational analysis to calculate an expression for the effective double-well potential. An expression for the vortex pinning current is obtained in terms of the vortex location. Analytical results obtained are verified numerically by solving the model equations. Numerical simulations extended to determine the current–voltage characteristics, critical-current versus magnetic field and the read-out of the classical states of a vortex qubit.

2. Theoretical model

We consider an overlap long semiannular JJ with a microshort at the center placed in an external static magnetic field which is applied parallel to the dielectric barrier and perpendicular to a plane containing the junction boundaries (Fig. 1). A microshort is a thin spot in the dielectric barrier with enhanced Josephson current and can be realized as a narrow bridge (microshunt) connecting the two bulk superconductor electrodes [16,17]. A uniform dc bias is applied across the superconducting electrodes to drive a trapped vortex. The width of the junction is taken much smaller than the length of the junction that reduces the model equations into one dimension.

The influence of an external magnetic field is to induce currents in closed form across the junction which has a net zero value over the length of the junction. Flux quantization in the superconducting junction gives the external flux linked with the junction as $\mathrm{d}\varphi(x) = (2\pi/\Phi_0)(\Delta\overline{B}_\mathrm{e}\cdot\overline{n})\,\mathrm{d}x = (2\pi/\Phi_0)\times \Delta\overline{B}_\mathrm{e}\cos(kx-\frac{\pi}{2})\,\mathrm{d}x$ [18], where $\varphi(x)$ is the superconducting phase difference between the electrodes of the junction, x is the normalized spatial coordinate normalized to λ_J (Josephson penetration depth), $\Phi_0 = h/2\mathrm{e} = 2.064\times 10^{-15}$ Wb is the flux quantum,

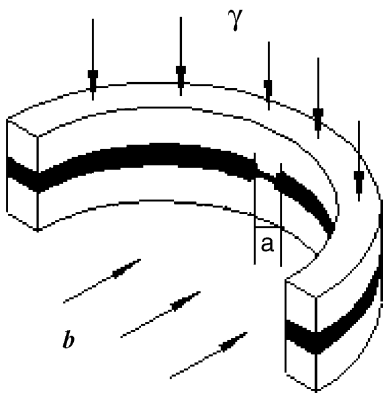

Fig. 1. A sketch of a semiannular JJ with a microshort of width a at the center in an applied magnetic field b (not drawn to scales). The directions of the bias current and the applied field are indicated using arrow marks.