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Tunneling spectroscopy of giant vorticity states in superconducting micro- and nanorings at ultra-low temperatures

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Abstract

When a superconducting contour is exposed to a magnetic field screening currents are induced. At temperatures well below the critical temperature T_c periodicity of the persistent currents can significantly exceed the superconducting flux quantum $h/2e$ due to formation of metastable energy states with high quantum winding numbers (vorticity). We have studied the effect in normal metal-insulator-superconductor (NIS) and SIS'IS tunnel structures with the superconducting (S or S') electrode in a shape of a loop. The tunnel current oscillates due to the modulation of the superconducting density of states by the persistent currents reaching the sub-critical values. In the limit of loops with extremely narrow linewidth the magnitude of the oscillations drops and their shape deviates from the 'conventional' saw-tooth behavior. The effect can be accounted to the contribution of the quantum phase slips in the ultra-narrow superconducting ring-shaped electrode.

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1. Introduction

Diamagnetic response is a fundamental attribute of superconductivity. When a superconductor is exposed to an external magnetic field the persistent (Meissner) currents are induced. In non-single-connected systems (e.g. loops or hollow cylinders) the effect manifests itself as flux quantization which can be measured using magnetization [1,2] or electric conductance in the resistive state close to T_c [3]. In those classical experiments the periodicity is set by the superconducting flux quantum $\Phi_0 = h/2e$. In magnetization experiments performed on mesoscopic-size superconducting rings at temperatures $\sim T_c/3$ oscillations with period few times higher than Φ_0 were observed [4,5]. More recently normal metal-insulator-superconductor (NIS) tunnel structures with loop-shaped superconducting electrode were studied [6] at temperatures $T \ll T_c$. The period of the tunnel current oscillations in those experiments dramatically exceeded the 'conventional' $h/2e$ bevavior. The effect has been explained by formation of metastable states allowed at ultra-low temperatures [7]. In present paper we extend our earlier results on NIS structures and additionally study SIS'IS systems with the central S' island in a shape of a ring with very narrow linewidth.

2. The model

The allowed energy states of a superconducting ring in external magnetic field differ by the phase change accumulated over the circumference S of the loop. The energy of the n-th state is given by:

$$E_n = \frac{2\pi^2\hbar^2 n_s \sigma}{m^* S}\left(\frac{\Phi}{\Phi_0} + n\right)^2, \qquad (1)$$

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where n_s is the density of superconducting electrons, m^* is the effective electron mass, σ – cross-sectional area of the wire forming the loop, Φ is the magnetic flux through the area of the loop, and $\Phi_0 = h/2e$ is the superconducting flux quantum Fig. 1 (a). The persistent current is proportional to the derivative of the energy, $I \sim dE/d\Phi$, and shows the characteristic saw-tooth behavior (Fig. 1 b). If the system changes its quantum state n (vorticity) by always relaxing to the ground state, then the persistent current at the switching point is $j^0_{sw} \sim 2\pi/S$ and follows the conventional $h/2e$ periodicity (Fig. 1, solid black line).

However, at temperatures well below T_c the system can be 'frozen' in metastable states with higher vorticity (Fig. 1, grey dashed line). The ultimate condition for switching to another quantum state is the equivalence of the persistent current density to the critical value $j_c \sim 2\pi/\xi$ (Fig. 1 (b), horizontal line of diamonds), where ξ is the superconducting coherence length. In systems with sufficiently large loops the corresponding periodicity $\Delta\Phi/\Phi_0 = j_c/j^0_{sw} \sim S/\xi \gg 1$. The exact solution has been obtained for a superconducting loop with diameter R [8]:

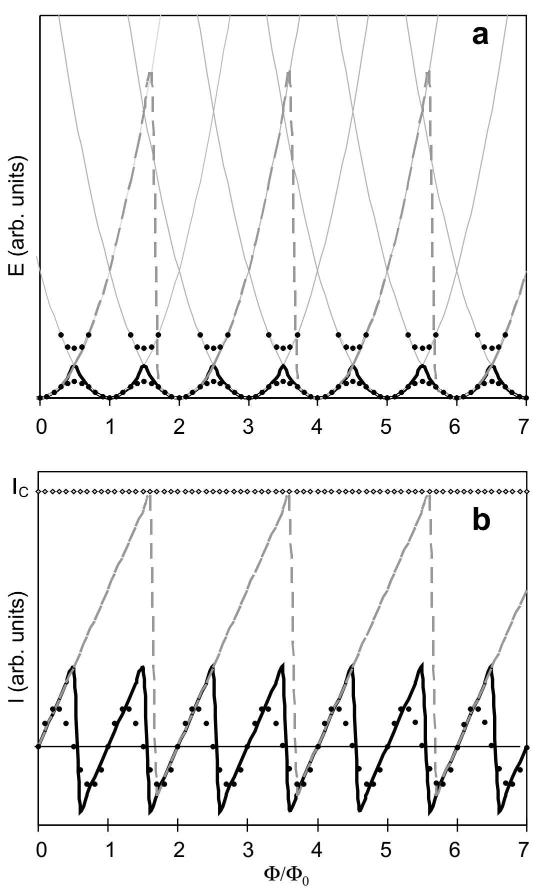

Fig. 1. (a) Energy E of a superconducting loop and (b) persistent current I as functions of external magnetic flux Φ. If the system stays in the ground state the energy follows the black solid line, if metastable states can exist the grey dashed line describes the behaviour. The screening current $I \sim dE/d\Phi$ shows the corresponding saw-tooth oscillations. In presence of QPS the energy gap opens at the degeneracy points (black dotted line), the magnitude of persistent current oscillations drops and their shape becomes sinusoidal.

$$j_c/j^0_{sw} = \frac{1}{\sqrt{3}}\frac{R}{\xi}\sqrt{1 + \frac{1}{2}\left(\frac{\xi}{R}\right)^2} \qquad (2)$$

Experimental study of magnetisation of small superconducting rings [4,5] is in a reasonable agreement with the above model. Another approach has been used to study the effect at ultra-low temperatures in tunnel normal metal-insulator-superconductor (NIS) structures with the loop-shaped superconducting elecrode [6]. The experimentally measured oscillations of the tunnel current are induced by the corresponding periodic variations of the superconducting density of states modulated by the persistent currents reaching sub-critical values [7]. In full accordance with the theoretical predictions [7] in systems with sufficiently large loops the period of the tunnel current oscillations dramatically exceeded the naively expected value $\Delta\Phi/\Phi_0 = \pm 1$ [6].

3. Experiment

In present paper we have studied normal metal (copper)–insulator (aluminum oxide)–superconductor NIS and SIS'IS nanostructures with S (or S') aluminum electrode(s) in a shape of a loop (Fig. 2). Structures were fabricated by two-angle evaporation through an e-beam patterned double layer P(MMA – MAA)/PMMA mask

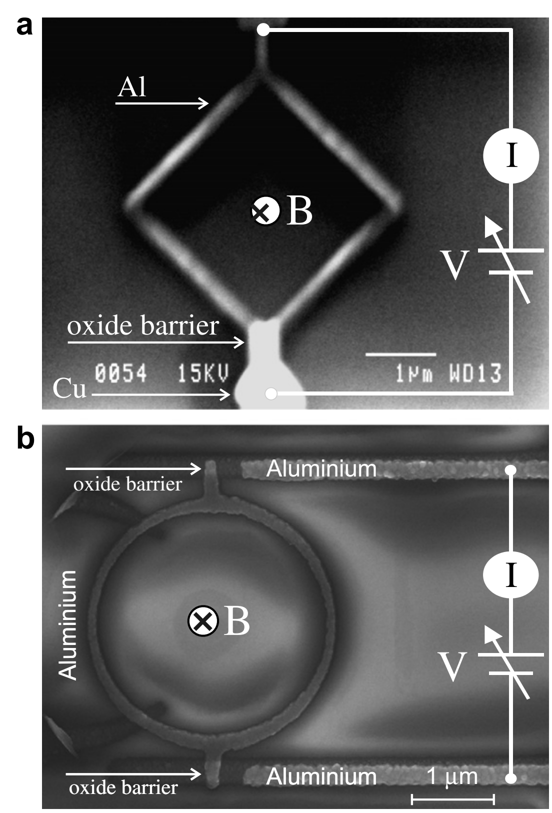

Fig. 2. SEM images of typical (a) NIS and (b) SIS'IS nanostructures with schematics of the $I(V)$ measurements in perpendicular magnetic field B. Normal metal (N) corresponds to copper, insulator forming the tunnel barrier (I) is aluminum oxide, and superconductor (S and S') is aluminum.