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Persistent Currents in Superconducting Nanorings

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Abstract.
Superconductor-insulator-superconductor-insulator-superconductor (SIS'IS) tunnel nanostuctures with the central electrode S' in a shape of a loop have been fabricated. It has been shown that at low temperatures at a fixed voltage bias $V$ the tunnel current oscillates in perpendicular magnetic field $B$ with period $\Delta \Phi$ few times exceeding the superconducting flux quantum. The normalized magnitude of oscillations reaches its maximum close to the quadruple superconducting energy gap $4\Delta$. At higher and lower biases the oscillations are effectively damped. Low energy ion sputtering has been used to progressively reduce the cross-section of the line forming the loop-shaped 'island'. It has been found that at very narrow linewidths the magnitude of oscillations decreases, and their shape starts to deviate from the saw-tooth behavior typical for wider samples. The effect is associated with manifestation of quantum phase slips which remove the energy level crossing at the degeneracy points.

1. Introduction
Zero resistance is known to be a fundamental attribute of superconductivity. It is very tempting to utilize superconducting elements in nanoelectronic systems to minimize heat dissipation and, hence, greatly increase the level of integration. Unfortunately, there are indications (both experimental [1] - [9] and theoretical [10]-[20]) that below a certain level $\sim 10$ nm quantum fluctuations suppress dissipationless current in ultra-narrow quasi-one-dimensional superconducting channels.

Another attribute of superconductivity are persistent (Meissner) currents induced in a superconductor exposed to an external magnetic field. In non-single-connected systems (e.g. loops or hollow cylinders) the effect manifests itself as flux quantization which can be measured using magnetization [21], [22] or electric conductance in the resistive state close to $T_c$ [23]. When the cross-section of the line forming the superconducting loop is small, contribution of quantum fluctuations of the order parameter, also called quantum phase slips (QPS), becomes important. It has been demonstrated theoretically [24] that a gap opens in the energy spectrum at the degenerate points $\Phi/\Phi_0 = L \pm 1/2$, where $L = 0, \pm 1, \pm 2, \ldots$. In this paper we demonstrate the experimental observation of the effect in superconducting aluminium loop-shaped tunnel nanosructures.

2. The model
When a superconducting loop of circumference $S$ is exposed to a perpendicular magnetic field the energy $E_L$ of the $L$-th state is given by:
where \( L = 1/2\pi \oint \nabla \theta ds \) is the quantum winding number (also called vorticity), \( \theta \) is the coordinate-dependent phase of the superconducting order parameter, and the integration is made along the contour of the loop. \( \Phi \) is the magnetic flux through the area of the loop, and \( \Phi_0 = h/2e \) is the superconducting flux quantum. If the system follows its ground state, then sweeping the magnetic field causes variation of the energy with period \( \Delta \Phi = \Phi_0 \) corresponding to transitions \( \Delta L = \pm 1 \) (Fig. 1, solid thick line). Persistent current in the loop is proportional to the derivative of the energy \( I \sim dE/d\Phi \), and shows the characteristic saw-tooth behavior with the same period. It has been demonstrated theoretically [24] that if the contribution of quantum phase slips is important, then a gap opens in the energy spectrum of the loop at the degenerate points \( \Phi/\Phi_0 = L \pm 1/2 \) with \( L = 0, \pm 1, \pm 2, \ldots \). The corresponding saw-tooth persistent current pattern evolves into a sinusoidal one with smaller magnitude (Fig. 1, dotted lines). The effect can be detected experimentally by measuring magnetization of a tiny superconducting nanoring. However, taking into consideration the very narrow linewidth forming the loop (to enable QPS), the signal is expected to be very small. To our knowledge, so far the experimental observation of the effect has not been reported elsewhere.

The above picture of persistent current oscillations in a loop assumes that system always stays in its ground state, giving rise to strictly \( \Delta L = \pm 1 \) periodicity. This might be correct when the superconducting energy gap is small (e.g. at temperatures close to the critical one \( T_c \)). The 'switching' supercurrent density corresponding to transitions from the state with vorticity \( L \) to the nearest state \( L \pm 1 \) is \( j_{\text{switch}}^0 \sim 1/S \) (Fig. 1b, solid line). However, if the system can follow metastable states (Fig. 1, dashed lines) then the corresponding periodicity can exceed the single flux quantum. The ultimate condition of changing the quantum number (vorticity) is the equivalence of the persistent current to the critical value \( j_c \sim 1/\xi \), where \( \xi \) is the superconducting coherence length. Thus, in loops with perimeter \( S \gg \xi \) one may observe vorticity changes \( \Delta L \sim j_c/j_{\text{switch}}^0 \sim S/\xi \gg 1 \). In recent experiments [25], [26] measurements of magnetization of small superconducting rings did show transitions with changes of vorticity \( \Delta L \) few times larger than unit. Another approach is to study the effect at ultra-low temperatures in tunnel normal metal- insulator- superconductor (NIS) structures with the loop-shaped superconducting electrode [27]. 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 [28]. In a full accordance with the theoretical predictions [28] in systems with sufficiently large loops the period of the tunnel current oscillations dramatically exceeded the 'orthodox' value \( \Delta \Phi/\Phi_0 = \pm 1 \) [27].

3. Experiment and discussion

To study the impact of quantum fluctuations on properties of a non-single-connected superconductor we have fabricated superconductor - insulator - superconductor - superconductor tunnel nanostructures (SISTIS) with the central S' electrode in a shape of a loop (Fig. 2). Compared to our earlier results [27], in present paper we have selected not a NIS, but SISTIS configuration eliminating the undesirable finite sub-gap current and the quasiparticle poisoning, which might mask the effect under investigation. Structures were fabricated by all-aluminium two-angle evaporation through an e-beam patterned double layer P(MMA-MAA)/PMMA mask on non-oxidized doped Si. After the deposition of the bottom layer the aluminium electrodes were oxidized without exposure to atmosphere at partial pressure of pure oxygen \( \sim 10 \) mBar followed immediately by deposition of the top central ring-shaped 'island'. Typical thickness of the aluminum loop is \( \sim 100 \) nm, linewidth \( \sim 120 \) nm and the diameter is \( 3 \mu \text{m} \). The nominal overlapping area between the bottom electrodes and the loop
is about 100 nm × 250 nm. Just after the fabrication the tunnel resistance at cryogenic temperatures varied from sample to sample roughly from 100 kΩ to 400 kΩ. The majority of experiments were made in a voltage-biased mode showing good quality $I(V)$ characteristics typical for such systems at ultra-low temperatures ($T \leq 100$ mK). The derivatives $dI/dV(V, B = 0)$ were measured simultaneously with the $I(V)$ dependencies by lock-in technique using $\sim 0.5 \mu V$ AC modulation of the bias voltage $V$. Experiments were made using $^3He/^4He$ dilution refrigerator placed inside an electromagnetically shielded room. Only battery powered front-end amplifiers were kept inside the room. These were connected to the remaining electronics outside through carefully shielded coaxial cables carrying analogue signals. All lines contained both room temperature and cold RLC filters. The Earth’s magnetic field was not screened. The method is not destructive enabling a study of size-dependent phenomena on a same sample.

At zero magnetic field the current-voltage characteristics $I(V, B = 0)$ and the derivatives $dI/dV(V, B = 0)$ show typical behavior for SIS'IS junctions with sharp singularity at energies $|eV| = 4\Delta \approx 760 \mu V$ for aluminium (Fig. 3a). Experimentally the value of the gap can be defined as corresponding to the maximum of the $dI/dV(V)$ dependency. The assumption is quite justified at temperatures well below $T_c$ when the $dI/dV(V)$ characteristic is 'sharp'. The majority of measurements were made at temperatures below 100 mK, while the critical temperature $T_c$ of the co-deposited aluminium layer of the same thickness is about 1.3 K. The ‘bumps’ on $I(V)$ characteristic at $eV \approx \pm 2\Delta$ are reproducible from sample to sample, and eventually originate from the small difference in the energy gap of the electrodes and the central loop-shaped island. Aluminium films and nanowires [6] are known for having different critical temperature (energy gap) depending on the thickness and the level of disorder.

We have applied our proprietary method of a nanostructure shaping by the low energy ion beam sputtering [29] to reduce the cross-section of the line forming the ring electrode. The method is not destructive enabling a study of size-dependent phenomena on a same sample. The $I(V)$ characteristics do evolve after sequential sessions of the ion beam etching (Fig. 3a), but no degradation of the tunnel junctions have been observed down to the loop linewidth $\sim 30$ nm. The increase of the tunnel resistance after each sputtering is apparently due to the reduction of the effective area of the tunnel junction.

The application of perpendicular magnetic field much smaller than the critical one modifies the $I(V)$ dependencies in a non-monotonous way. Sweeping the field at a constant voltage bias demonstrates the nature of the dependency more profoundly. In a narrow region of biases $0.85 \times 4\Delta \leq eV \leq 1.1 \times 4\Delta$ the tunnel current oscillates in magnetic field (Fig. 3b). The oscillations quickly disappear in noise above the gap, and are not measurable at $eV \leq 0.85 \times 4\Delta$. In all studied samples with the loop diameter equal to 3 µm and the (unsputtered) linewidth $\sim 100$ nm the oscillations display the well-defined saw-tooth behavior with the period twice larger than the superconducting flux quantum. The oscillations are hysteretic with the inclination of the ‘teeth’ determined by the direction of the magnetic field sweep. The monotonous envelope behavior is due to the reduction of the superconducting energy gap by magnetic field. These findings are in a agreement with our earlier experiments on NIS systems [27]. The origin of the effects [28] has been briefly explained in the previous section. The new feature is the modification of the shape of oscillations and the period (?) with reduction of the linewidth of the loop for the same structure (Fig. 3b). After several ion beam sputtering sessions the normalized magnitude of oscillations $\Delta I(B)/I(0)$ drops and the saw-tooth shape ‘rounds’ (Fig. 3b). We associate these phenomena as demonstration of the impact of quantum fluctuations of the order parameter [24]: quantum phase slips induce the gap in the energy spectrum of the loop at the degenerate points $\Phi/\Phi_0 = L \pm 1/2$, where $L = 0, \pm 1, \pm 2, ...$ is the quantum winding number (vorticity). Note that the tendency is observed on all studied structures. Apart from the described transformation of the shape of tunnel current oscillations, other tunneling properties of the system are left unchanged. Hence, a trivial explanation related to degradation of the
tunnel junction is rather unlikely. We have not observed a clear degeneration of the saw-tooth oscillations into a sinusoidal dependence down to $\sigma^{1/2} \sim 30$ nm, where $\sigma$ is the cross-section of the line forming the loop-shaped electrode. According to our previous studies [6], [9] the QPSs start to dominate the resistive state of an aluminium nanowire below the effective diameter $\sigma^{1/2} \leq 15$ nm. Eventually, thinner loops are required to undoubtfuly state observation of the QPS phenomena in superconducting rings.

4. Conclusions
In summary, persistent currents in SIS’IS nanostructures with ring-shaped central S’ island have been studied using tunneling experiments. It has been found that for a given diameter of the loop, the shape of tunnel current oscillations depends on the effective diameter of the line forming the ring. The effect can be associated with manifestation of quantum phase slips which remove energy level crossing at the degeneracy points.

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Figure 1. (a) Energy $E$ of a superconducting loop and (b) persistent current $I$ as functions of external magnetic flux $\Phi$ in units of the superconducting flux $\Phi_0 = \hbar/2e$. If the system stays in the ground state — the energy follows the black solid line, if metastable states can exist — red dashed line. The screening current $I \sim dE/d\Phi$ shows the corresponding saw-tooth oscillations. In presence of QPS the energy gap opens in the degeneracy points (blue dotted line), the magnitude of persistent current oscillations drops and their shape becomes sinusoidal.
Figure 2. SEM image of a typical SIS'IS nanostructure with schematic of the $I(V)$ measurements in perpendicular magnetic field $B$. 
Figure 3. (a) $I(V)$ (left axis) and $dI/dV(V)$ (right axis) characteristics in zero magnetic field for a typical SIS’IS structure at $T = 50$ mK. Inset: zoom of the $I(V)$ dependencies close to the quadruple gap singularity measured for the same structure after several sessions of the ion beam sputtering. (b) Tunnel current oscillations $I(\Phi, V = \text{const})$ measured on the same structure demonstrate the effect of reduction of the cross-section of the line forming the loop. Arrows show the directions of the magnetic field sweep. The diameter of the ring-shaped S’ central ’island’ is 3 µm.
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