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Local and Integral Properties of a Quasi-One-Dimensional Superconductor Governed by Quantum Fluctuations of the Order Parameter

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Abstract—Utilization of of superconducting materials for new-generation nanoelectronic devices seems extremely tempting because of the absence of energy dissipation during the electric current flow. However, in small systems, the role of fluctuations can be highly important. In this study, the transport properties of thin superconducting titanium nanoribbons have been experimentally and theoretically investigated. It has been shown that quantum fluctuations of the order parameter differently affect the integral and local characteristics of a quasi-one-dimensional superconductor. In sufficiently thin nanowires, a finite electrical resistance can be observed at lowest temperatures, while the tunneling I–V characteristics only exhibit slightly diffuse gap features and a finite Josephson current. The phenomenon is of fundamental importance for mesoscopic superconductivity and should be taken into account when designing cryoelectronic nanodevices.

Keywords: superconductivity, quantum fluctuations, tunnel contacts

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1. INTRODUCTION

In recent years, the growth of the degree of integration of commercial micro- and nanoelectronic devices has slowed down, formally signifying a violation of Moore's law [1]. The two reasons for this are the great heat dissipation per unit volume (area) and various quantum-size effects. The first problem can be presumably solved via the transition from normal metals or semiconductors to superconducting materials in critical components of nanoelectronic circuits. In mesoscopic-size superconductors, several effects are observed that can lead to qualitatively new applications, for example, to quantum-logic elements (qubits) [2] and to a quantum standard of electric current [3, 4].

It is well known that superconductivity is a macroscopic quantum phenomenon described by complex order parameter $\Delta = |\Delta| e^{i\phi}$. The ground state of a non-current-carrying bulk superconductor has the same phase ϕ and absolute value $|\Delta|$ over the entire volume. However, as the dimension of a system is reduced, the fluctuations start playing an important role. In a quasi-one-dimensional channel, the fluctuations of the order parameter can significantly affect its physical properties [5, 6]. At temperatures close to the critical temperature ($T \to T_c$), the thermal fluctuations make the main contribution, while the quantum fluctuations [7] even at $T \ll T_c$ lead to a finite resistance of nanowires [8–10] and suppression of the Meissner currents in a closed superconducting loop [11, 12].

The above-mentioned phenomenological attributes of superconductivity, zero resistance and diamagnetism, reflect the integral properties of a system. The appearance of the microscopic Bardeen–Cooper–Schrieffer (BCS) model made it clear that the superconducting state in classical superconducting materials is inextricably linked with the presence of a gap in the quasiparticle excitation spectrum. The energy gap is a local parameter of a superconductor, which can be measured at a point by tunneling spectroscopy, in contrast, for example, to the electronic conductivity, which requires sufficiently long samples to be measured. The objective of this study is to compare the effect of quantum fluctuations of the order parameter on the local and integral properties of quasi-one-dimensional superconducting channels.

2. EXPERIMENTAL

Using lift-off electron lithography and directed vacuum deposition, we fabricated hybrid nanostructures in the form of long aluminum strips with a line width of about 150 nm and a thickness of 30 nm oxidized in pure oxygen atmosphere with the subsequent deposition of transverse titanium nanowires (Fig. 1a). The aluminum electrode cross section was chosen to be significantly larger than the scale at which the fluctuation phenomena in this material should be taken into account [9, 13]. In turn, the cross section of titanium nanowires (the length is $X = 20$ μm) was chosen to overlap the region from the strong to weak contribution of the quantum fluctuations of the order parameter. Taking into account the exponential dependence of the quantum phase slip (QPS) rate on the cross section of a superconducting channel [5, 7], in our previous studies [10, 11, 14, 15] we showed that, for a titanium strip with thickness of about $d = 30$ nm, the width w change from 30 to 60 nm corresponds precisely to the specified range. In addition, it should be noted that, in the investigated titanium nanowires, the superconducting coherence length is $\xi(T \to 0) \sim 140$ nm, which indicates the fulfillment of the quasi-one-dimensional condition $d, w \ll \xi \ll X$ in a wide temperature range not too close to T_c.

The same multi-terminal structure (Fig. 1b) made it possible to measure both the current–voltage $V(I, T = \text{const})$ and temperature–voltage $V(T, I = \text{const})$ characteristics of individual titanium nanowires, as well as the tunneling I–V characteristics at the points of overlap of aluminum and titanium nanostrips (the Al–AlO_x–Ti junction). All the measurements were performed in a 3He4He dilution refrigerator using analog voltage and current preamplifiers connecting the cryogenic circuit with room digital electronics. Particular attention was paid to filtering the input and output lines from the external electromagnetic interference [16]. The derivatives $dI/dV(V)$ of the I–V characteristics were measured by the modulation method using lock-in technique. The data were collected and processed by an automated setup based on a PC.

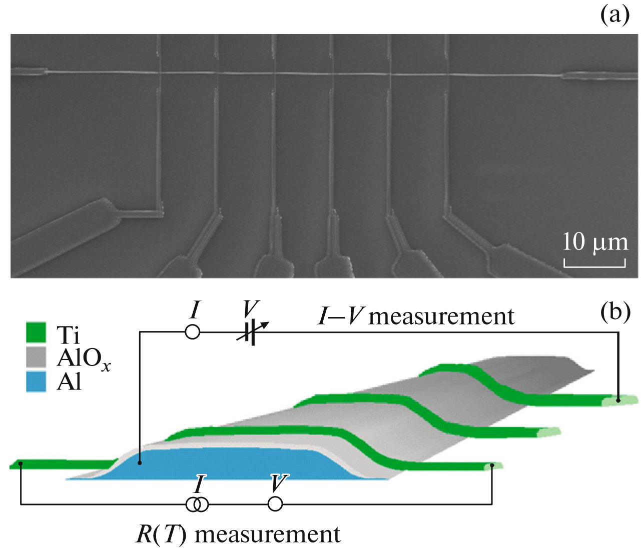

Fig. 1. (a) Microphotograph of a typical nanostructure. The horizontal line stands for aluminum (Al) strip. Vertical lines are the titanium (Ti) electrodes of different widths, which overlap aluminum through a thin aluminum oxide (AlO_x) layer forming tunnel contacts. (b) Schematic of the nanostructure and measurements.

3. RESULTS AND DISCUSSION

Typical temperature dependences of resistance $R(T)$ for two titanium nanowires with different line widths w are shown in Fig. 2. Due to technical limitations of nanostructure fabrication (minimization of contact pads on a chip), the $R(T)$ measurements were only possible in a pseudo-4-contact configuration (inset in Fig. 2). It can be clearly seen that the superconducting transition of the thinner nanostrip ($w = 40$ nm) is significantly broadened as compared with the wider sample ($w = 53$ nm) and the corresponding $R(T)$ dependence is not extrapolated to the zero resistance at $T \to 0$. The observed trend is typical of ultranarrow superconducting channels, explained by the QPS effect [5] and, as applied to titanium [10, 11, 15], reasonably agrees with the model [7]. It should be noted, however, that the model from [7] considers the QPS as a weak perturbation; i.e., the system is in the superconducting state and the quantum fluctuations are a rare phenomenon, which, according to the Josephson relation, leads to the occurrence of nonzero time-averaged voltage $\langle V \rangle = (h/2e)d\phi/dt$, which in current biased mode experimentally manifests itself as the finite resistance $R \cong \langle V \rangle / I$. Strictly speaking, the model from [7] can explain the weak temperature dependence $R(T)$, as, for example, for the sample with $w = 40$ nm in Fig. 2, only qualitatively: the QPSs occur so frequently that completely suppress the superconducting state. Physics in the regime of strong fluctuations was deeper understood relatively recently [17].

The quantum fluctuations of the order parameter in quasi-one-dimensional superconducting channels are characterized by the two dimensionless parameters [17]

$$g_\xi = R_q/R_\xi \sim \sigma, \quad g_Z = R_q/Z \sim \sqrt{\sigma}, \qquad (1)$$

where $R_q = h/e^2 = 25.8$ kΩ is the quantum resistance, R_ξ is the resistance of a sample section with a length equal to the superconducting coherence length ξ, $Z = (LC)^{1/2}$ is the impedance, L and C are the kinetic

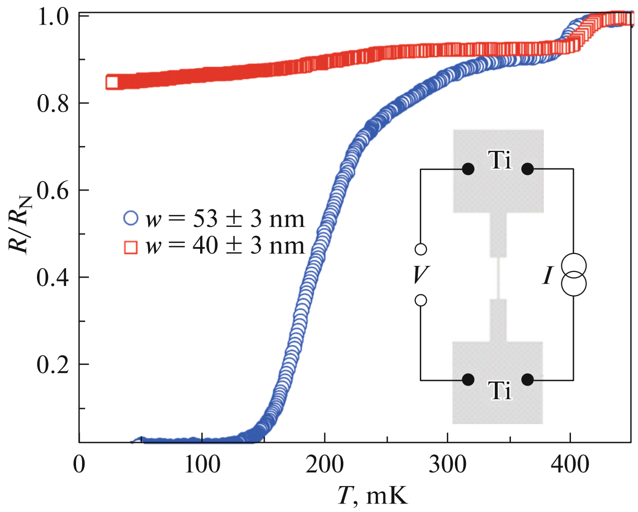

Fig. 2. Typical temperature dependence of the resistance normalized to resistance R_N in the normal state for two titanium nanowires of the same length $X = 20$ μm and a thickness $d = 35$ nm, but with different widths w indicated in the figure. For clarity, in this experiment the non-current-carrying aluminum electrode is not shown in the inset.

inductance and specific capacity of the sample per unit length, respectively, and $\sigma \approx dw$ is the effective cross section of the nanowire. Parameter g_ξ determines the amplitude of fluctuations of the absolute value of the order parameter $\delta\Delta/\Delta \sim 1/g_\xi$ and the quantum amplitude of the QPS per unit length $\Gamma_{QPS} = b(g_\xi\Delta/\xi)\exp -ag_\xi$, where $a \approx 1$ and $b \approx 1$ are the numerical dimensionless constants of the model [18]. Parameter g_Z describes long-scale fluctuations in the phase of the superconducting order parameter due to the interaction between individual QPS acts via plasmon oscillations of the charge density (the Mooij–Schoen waves) [19] propagating along a superconductor with velocity $v \sim 1/(LC)^{1/2}$. In other words, parameter g_ξ is responsible for the excitation of isolated QPSs, while parameter g_Z is responsible for the interaction of the QPSs. It was shown in [7] that, at a sufficiently low temperature ($T \to 0$), the situation $g_Z = 16$ corresponds to superconductor–insulator transition, separating the "superconducting" state with $g_Z > 16$ from the "dielectric" state with $g_Z < 16$. The estimates for the narrowest and widest titanium nanostrips investigated in this study are $3 < g_\xi < 40$ and $1 < g_Z < 3$, respectively. For all our samples in the dielectric limit, i.e., with $g_Z < 16$, a certain correlation length can be determined as [20, 21]

$$X_c \sim \xi \exp\left\{\frac{ag_\xi - \ln b}{2 - g_Z/8}\right\}, \qquad (2)$$

which, physically, is a characteristic scale of localization of Cooper pairs [12] due to tunneling of magnetic flux quanta (fluxons). The systems with the length $X \le X_c$ can exhibit the superconducting properties in the presence of QPSs, while in the limit $X \gg X_c$, the supercurrent is completely suppressed by the quantum fluctuations and a quasi-one-dimensional superconductor exhibits a finite resistance even at $T \to 0$. This is exactly what is observed in our $R(T)$ experiments on nanowires of different cross sections (Fig. 2). The estimation for a sample with $w = 53$ nm yields a correlation length of $X_c \approx 12$ μm comparable with a geometric length of $X = 20$ μm; correspondingly, the system remains in the superconducting state (with zero resistance) at a sufficiently low temperature ($T < T_c$), while the narrower sample with $w = 40$ nm, taking into account strong exponential dependence (2), corresponds to the limit $X \gg X_c$ and, consequently, even at the lowest temperatures, has a finite resistance (Fig. 2). The identical dependences were found for a great number of titanium nanoribbons and are not shown in Fig. 2 solely for clarity of the graphical data presentation. All the aforesaid concerning the manifestation of the "superconducting" properties refers to the electrical resistance as an integral characteristic of the system.

It is reasonable to ask a question whether the discussed fluctuation suppression of superconductivity is valid for the local characteristics, including the energy gap and/or the density of states. In order to test this hypothesis, the I–V characteristics of the Al–AlO_x–Ti tunnel contacts formed at the crossing points of titanium and aluminum nanostrips were measured through a thin oxide layer on the same multiterminal nanostructures (Fig. 1). The corresponding I–V characteristics of the same titanium nanowires as in Fig. 2 are shown in Fig. 3a. Surprisingly, the two I–V characteristics are quite similar, despite the drastically different $R(T)$ behavior of titanium electrodes. As was previously reported, the quantum fluctuations lead to weak suppression of the gap and smearing of the I–V features in the region of the gap singularity $|eV| \sim \Delta(\mathrm{Ti}) + \Delta(\mathrm{Al})$ [22–24]. In particular, it was shown that the penetration of states into the subgap region originates from the Gaussian fluctuations in the order parameter phase, causing the excitation of charge density waves [19] interacting with conduction electrons, which leads to the renormalization of the electron density of states [22–25]. All the investigated Al–AlO_x–Ti contacts exhibit, along with the tunneling BCS characteristics very similar to standard ones (in our case, however, with a slight diffusion of the density of states), the Josephson effect (Fig. 3b). Due to presence of quantum fluctuations in the titanium electrode, the critical current is strongly suppressed as compared with the value following from the Ambegaokar–Baratov relation and vanishes above the critical temperature. In view of the aforesaid, we can conclude that the local superconductivity attributes determining the shape of the tunneling dependences are weakly

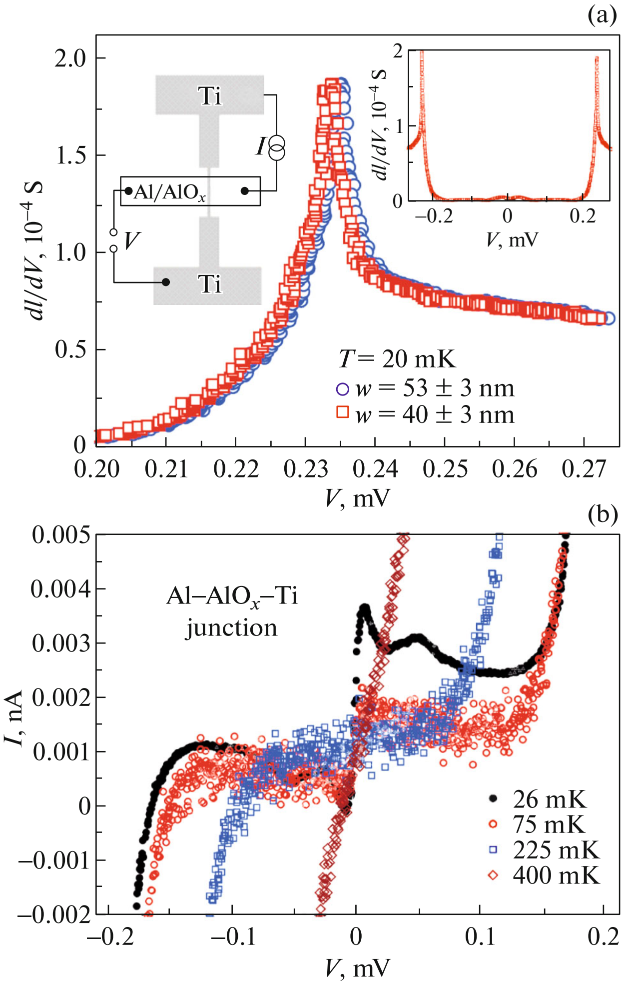

Fig. 3. (a) Zoom of the differential $dI/dV(V)$ characteristics for two Al–A1O$_x$–Ti tunnel contacts close to the gap singularity eV ~ Δ(Ti) + Δ(Al) formed by the same titanium nanowires as in Fig. 2. The left-hand inset shows the measurement scheme. The right-hand inset shows the same dependences on a wider scale: there is almost no difference between the two dI/dV curves. (b) I–V characteristics at small bias $|eV| \ll \Delta(Ti) + \Delta(Al)$. One can clearly see the Josephson current, which is strongly suppressed by temperature and completely vanishes above the critical temperature of superconducting titanium. A minor shift of the experimental points along the current axis is related to the zero drift of an analog amplifier.

suppressed by quantum fluctuations of the order parameter.

4. CONCLUSIONS

It was shown experimentally and theoretically that, in the titanium quasi-one-dimensional superconducting channels, the integral (effective resistance) and local (energy gap) characteristics are differently suppressed by quantum fluctuations of the order parameter. In sufficiently thin nanowires, at the lowest temperatures, a finite electrical resistance can be observed, while the tunneling I–V characteristics exhibit only slightly diffuse gap features and a finite Josephson current. This state of a substance can be considered as a superconducting insulator, which is caused by a weak Coulomb blockade of Cooper pairs. This phenomenon is universal and, as shown in this study, observed also in fairly homogeneous superconducting channels without tunnel barriers, which reflects the fundamental duality of the properties of a quasi-one-dimensional superconductor in the quantum fluctuation mode and a small Josephson junction.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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