Properties of a metal-dielectric-metal point junction before and after electrical breakdown of a dielectric nanolayer

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The work is a continuation of the research of an original and straightforward method of creating Josephson junctions during electrical breakdown of a dielectric nanolayer [1, 2]. Unlike junctions we have previously studied, the considered one is formed by mechanical point pressing of a U-shaped wire with a diameter of about 50 microns (**Fig.1**). The wire made of an InSn alloy (cathode) is closely positioned to the surface of an oxide nanolayer on the Nb film (anode). The breakdown method is similar to that described in [1, 2]. At 300K, the structure and **electrical properties of the junction were studied before and after electrical breakdown of the oxide with a thickness ranging from 15 to 60 nm**. Before breakdown, the capacitance of the junction with an oxide thickness of 15 nm with a corresponding current-voltage characteristic (CVC) were measured. The CVC shape indicates a **semiconductor type of oxide** (**Fig.2**). During the short breakout time, two simultaneous processes occur. First, the wire cathode melts at the point of contact over an area of about 6 μm^2. Second, an InSn **nanobridge is formed inside of the oxide with a length, equal to the thickness of the oxide (Fig.3).** The resistance obtained (at oxide thicknesses of 30–60 nm) is close to that one of nanobridges during breakdown between film electrodes [1, 2] (**Table1**). For the first time, it was discovered that the CVC of bridges with a length of 15 nm consists of an initial linear and two nonlinear sections (**Fig. 4**). Two phase transitions explain the dynamics observed: the **solid bridge turns into liquid** (starting at 15 mA) **and then evaporates** (at 34 mA) due to overheating of the bridge by the transport current [3].

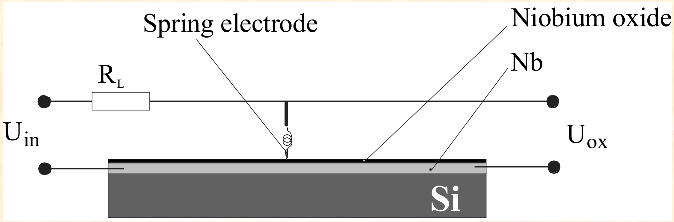

Fig.1 Schematic of the experimental structure.

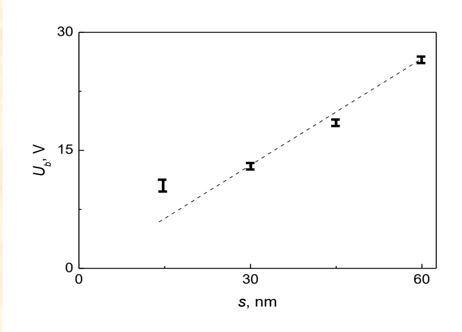

Fig. 3 Dependence of oxide breakdown voltage U_b on its thickness when using method of the combined action of direct voltage and capacitor discharge). The vertical lines correspond to the spread of U_b values at four different points on the oxide surface.

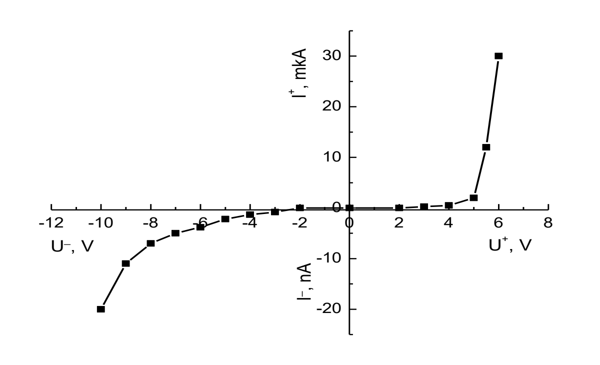

Fig. 2 Current-voltage characteristic of a point section of niobium oxide before breakdown.

Table 1. Breakdown voltage U_b of oxides of different thicknesses *s* at different values of the limiting resistance (R_L=R_2).

s / R_L	U_b, V			
	10^5, Ω	10^6, Ω	$3\cdot10^6$, Ω	10^7, Ω
15	10–12	6.8–8.4	7–10	5 + NB before 30 V
30	13–18	12.5–13.5	14 +Voltage jumps	12 + Voltage jumps
45	17–22	17–20	—	9 + Voltage jumps
60	23–27	24–27	—	NB before 30 V

Notes: NB — no breakdown.

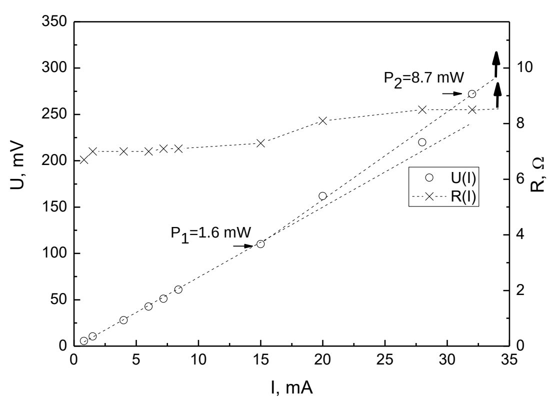

Fig. 4 Current-voltage characteristic $U(I)$ of the bridge formed by electrical breakdown of niobium oxide with a thickness of 15 nm and the dependence of the bridge resistance on the current $R(I)$. The horizontal arrows show the values of the thermal power P_1 and P_2 released in the bridge at currents of 15 and 32 mA, the vertical arrows show the place on the current-voltage characteristic where a sharp increase in voltage occurs at a current of about 33 mA.

Conclusions. The semiconducting properties of an oxide with a thickness of 15 nm and an area of about 6 square microns were established. At negative and positive potentials on a massive electrode made of an indium-tin alloy, electrical breakdown of the oxide occurs at a voltage of 10 and 6 V, respectively. It has been established that the breakdown electric field strength is about $4\cdot10^6$ V/cm for nanooxides with a thickness of 30, 45, and 60 nm, and with a thickness of 15 nm, it increases to $6\cdot10^6$ V/cm. The resistance of bridges arising after the breakdown of an oxide with a thickness of 15 nm is greater than after the breakdown of oxides with a thickness of 30, 45, and 60 nm. A study of the features of a point breakdown depending on the value of the limiting resistance that determines the breakdown current showed that at breakdown currents less than 1–2 μA, breakdown either does not occur or occurs only in some areas of the oxide. A study of the characteristics of breakdown depending on the capacitance value of the capacitor in the breakdown circuit showed that with a capacitance of less than 10^{-3} μF breakdown does not occur. The transport properties of the bridge formed as a result of the breakdown of niobium oxide with a thickness of 15 nm are manifested in its nonlinear current-voltage characteristic and the unusual dependence of the bridge resistance on current. It is shown that their appearance is explained by a change in the phase state of the bridge as the current through it increases. It should be noted that in the solid state, the bridge is capable of passing current with a density of up to $0.4\cdot10^{10}$ A/cm^2. This suggests that such a bridge is very resistant to random electrical interference that exists under real operating conditions.

[1] S. I. Bondarenko, A. V. Krevsun, V. P. Koverya, A. G. Sivakov, R. S. Galushkov, Low Temp. Phys. 48, 741 (2022). https://doi.org/10.1063/10.0013310.
[2] A. V. Krevsun, S. I. Bondarenko, V. P. Koverya, Low Temp. Phys. 49, 83 (2023). https://doi.org/10.1063/10.0016479.
[3] S. I. Bondarenko, A. V. Krevsun, V. P. Koverya, Low Temp. Phys. 50, 350 (2024). https://doi.org/10.1063/10.0025302.