Current–voltage characteristics of multilayer tunnel structures with high transmission level of tunnel barrier

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The current–voltage characteristics of a double tunnel superconducting structure Sn–I–Sn–I–Pb with a high transmission level of the tunnel barriers have revealed the presence of structural features at the voltages $(\Delta_{\rm Pb} - \Delta_{\rm Sn})/e$, $2\Delta_{\rm Sn}/e$, and $(\Delta_{\rm Sn} + \Delta_{\rm Pb})/e$. These features show that single-particle tunneling through individual junctions has a nonadditive effect on the resultant *I–V* characteristic.

Multilayer structures and superlattices evoke ever wider interest of investigators because these systems have many new physical properties.[1] Multilayer tin-based superconducting tunnel structures with five tunnel barriers were obtained in Ref. 2 and it has recently been reported[3,4] that such structures based on refractory materials have been synthesized. The quasiparticle characteristics of multilayer superconductor–insulator structures so far have not been studied extensively.

In studying the Pb–I–Pb–I–Sn–I–Sn–I–Pb structures with a high transmission level of the tunnel barriers we found that the chain of sequentially arranged thin-film *SIS* junctions may manifest some properties which cannot be described by a simple addition of the characteristics of single tunnel junctions.

The tunnel junctions were synthesized by the standard technology of vapor deposition in a vacuum and oxidation of the films of appropriate materials deposited on a sapphire substrate. The configuration of the tunnel structure and the measurement arrangement are shown in Fig. 1. Films 1 and 2 form a Pb–I–Pb tunnel junction, which was the source of external perturbation or a phonon "injector" to create tin with a higher quasiparticle concentration in the films. Films 3–5 constitute respective-

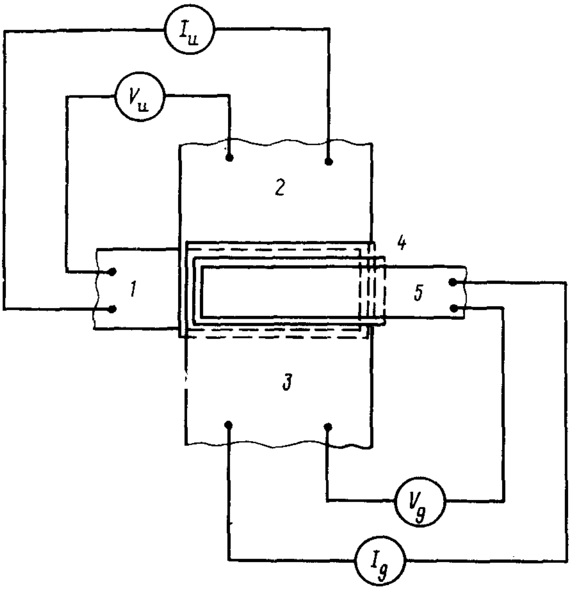

FIG. 1. Schematic diagram of the tunnel structure and its circuit diagram. Films 1, 2, and 5—Lead; films 3 and 4—tin; films 1 and 2—injector; films 3–5—detector.

ly an Sn–I–Sn–I–Pb double tunnel junction (a detector). The thickness of tin films 3 and 4 was 30–50 nm and that of lead films 1, 2, and 5 was 100–150 nm. The thickness of films 1–4 was 0.2, 0.3, 0.3, and 0.2 mm, respectively. To avoid a parallel dc-current connection of the junctions, we displaced the appropriate film edges relative to each other by about 10 μm. The Sn–I–Sn and Sn–I–Pb junctions which comprise the detector had similar tunneling resistivities of about $10^{-5}\,\Omega\cdot\text{cm}^2$. The tunneling resistivities of the Pb–I–Pb junction and the injector–detector junction were of the same order of magnitude.

We measured the current–voltage characteristics of a Sn–I–Sn–I–Pb double tunnel junction. In measuring the *I–V* characteristics we applied an external parallel magnetic field of 60–80 Oe in order to suppress the Josephson steady-state current and the constant component of the Josephson alternating current. The measurements were carried out at a temperature $T = 1.8$K in the current mode. As can be seen in Fig. 1, since the junctions which make up the detector are connected in series, the resultant *I–V* characteristic should be equal to the sum of the individual *I–V* plots of each junction. This turned out to be the case only for the junctions whose tunneling resistivities were higher than those of the samples tested by us. In the case under consideration the situation turned out to be more complex.

Two distinct types of the *I–V* characteristics of a double tunnel structure, shown in Figs. 2 and 3, are clearly identifiable. In the absence of a displacement current in the injector and in the absence of phonon generation the first type corresponds to a series connection of both junctions (curve 1 in Fig. 2). The introduction of a current

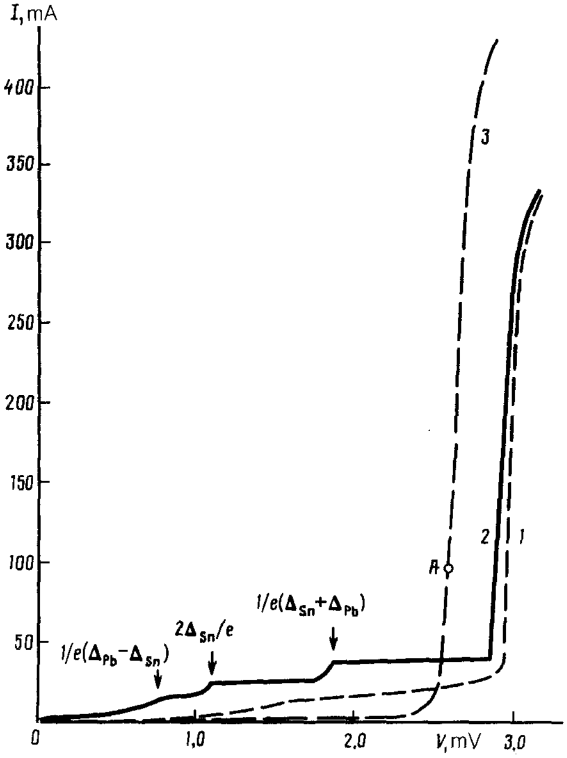

FIG. 2. The *I–V* characteristic of an Sn–I–Sn–I–Pb tunnel structure, which is equivalent to the sum of the *I–V* plots of individual junctions in the absence of phonon bombardment (1) and the modification of these plots (2) upon phonon bombardment, corresponding to point *A* on the *I–V* plot of the injector (3).

through a Pb–I–Pb injector (point *A* on the *I–V* plot, curve 3 in Fig. 2), which has the effect of the bombardment of a detector junction with phonons with an energy higher than $2\Delta_{Sn}$ and the effect of increasing the quasiparticle concentration in tin films as a result of decreasing the energy gap, led to the appearance of structural features on the *I–V* plots (curve 2 in Fig. 2) at voltages $V = 2\Delta_{Sn}/e(\Delta_{Sn} + \Delta_{Pb})/e$ and also to a vaguely expressed feature at $V = (\Delta_{Pb} - \Delta_{Sn})/e(\Delta_{Sn}$ and Δ_{Pb} are the energy gaps of Sn and Pb, respectively).

The other type of the *I–V* curve is characterized by the presence of pronounced features at voltages of $2\Delta_{Sn}/e$ and $(\Delta_{Sn} + \Delta_{Pb})/e$ in the absence of an external perturbation (curve 1 in Fig. 3). Phonon bombardment leads to the appearance of a structural feature on the *I–V* plot at voltages $(\Delta_{Pb} - \Delta_{Sn})/e$ (curve 2), which is very sensitive to the quasiparticle concentration. It is interesting to note that the initial, nearly linear section increases on this type of *I–V* characteristic.

The appearance of structural features at the voltages $(\Delta_{Pb} - \Delta_{Sn})/e$, $2\Delta_{Sn}/e$, and $(\Delta_{Sn} + \Delta_{Pb})e$ on the *I–V* plots of an Sn–I–S–I–Pb double tunnel junction shows that a multilayer tunnel structure with a high transmission level of the tunnel barriers behaves in a qualitatively different manner compared to an ordinary system of series-

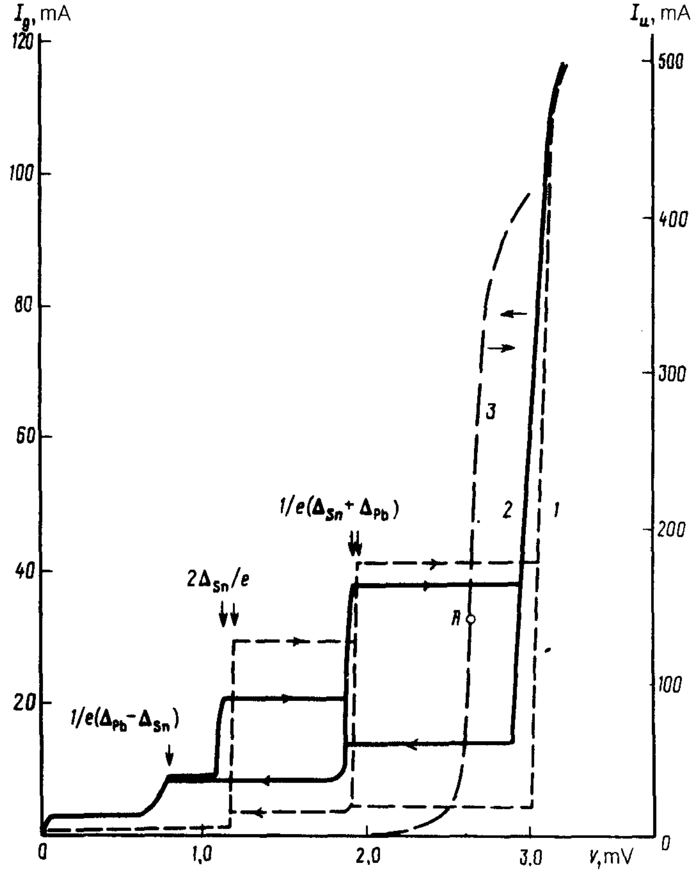

FIG. 3. The I–V characteristic of a tunnel structure Sn–I–Sn–I–Pb, whose structural features are manifested at $V = 2\Delta_{\rm Sn}/e(\Delta_{\rm Sn} + \Delta_{\rm Pb})/e$ in the absence of phonon bombardment (1); 2—the I–V plot of the same structure upon phonon bombardment, showing the appearance of a structural feature at $V = (/\Delta_{\rm Pb} - \Delta_{\rm Sn})/e$. The displacement of the injector in this case corresponds to point A on the I–V plot (curve 3).

connected junctions. In the latter system these characteristic features do not manifest themselves at the given voltages under our experimental conditions (the tunneling resistivities of the individual junctions were approximately equal; the tunneling currents were small, as can be seen from the I–V plots; the Josephson current was suppressed by applying a magnetic field).

Since in the case of the tin films used by us the mean free path of the quasiparticles ($l \sim 50$ nm) is on the order of the thickness of these films, we can assume that the behavior of the multilayer structure under study is similar to that of a single quantum-mechanical system in which the single-particle tunneling through single junctions occurs coherently. A more detailed determination of the nature of this behavior requires further studies.

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