EXPERIMENTAL OBSERVATION OF COOPER PAIR TUNNELING BETWEEN THIN LAYERS OF SUPERCONDUCTING TIN

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Singularities in the current-voltage curves of Sn—SnO_2—Sn tunnel structures, due to tunneling of superconducting electron pairs and multi-particle tunneling, are investigated experimentally in the 1.5—4.2°K range. The dependence of the superconducting tunnel current on temperature and the magnetic field is investigated.

THE current-voltage characteristics of low-resistance Sn—SnO_2—Sn tunnel structures furnish clear evidence for the existence of effects associated with the tunneling of Cooper pairs and with multi-particle tunneling. In the last two years these effects have been studied intensively both theoretically[1-4] and experimentally.[5-7]

The superconducting tunnel current (STC) predicted theoretically by Josephson[2] was observed to flow between two tin films about 2000 Å thick separated by an oxide layer of about 10 Å. This current flows between the films at zero voltage and is interrupted when its magnitude reaches a certain value I_1 depending on the magnetic field, temperature, and the geometry of the junction. Clear observation of this effect became possible when very thin and very homogeneous oxide layers had been prepared, leading to tunnel junctions having resistivity of the order 4×10^{-3} Ω-mm^2 at 4.2°K. The films were evaporated on glass substrates in a vacuum of 2×10^{-6} Torr. The intersection of the films formed a 0.4×0.4 mm tunnel junction. The tunnel structure was placed within a small single-layer solenoid 10 cm long and 2 cm in diameter enclosed by a soft-steel magnetic shield. One film was parallel to the solenoid axis, while the other film was perpendicular to the axis. Since the area of the junction was small compared with the dimensions of the solenoid, the magnetic field can be considered homogeneous at the junction.

The amplitude of the STC exhibited a periodic dependence on the magnetic field. Current minima are observed whenever the field becomes a multiple of 0.4 Oe. Considering that a minimum must occur when[6]

$$n\Phi_0 = 2\lambda w H_0, \qquad n = 1, 2, 3, \ldots, \qquad (1)$$

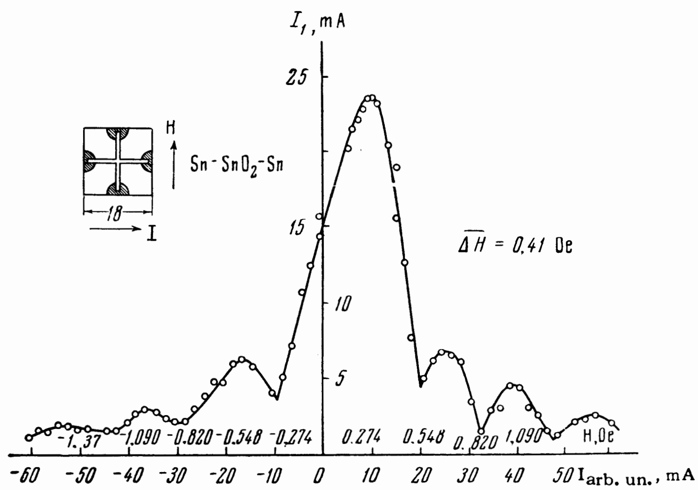

FIG. 1. Dependence of superconducting tunnel current I_1 on extra current I_f in film. Sn—SnO_2—Sn structure; T = 1.61°K.

where $\Phi_0 = 2.1 \times 10^{-7}$ Oe-cm^2 is the quantum of magnetic flux in superconductors, λ is the magnetic field penetration in the superconductor, ω is the width of the film, and H_0 is the field at the current minimum, we obtain $(6.2 \pm 0.6) \times 10^{-6}$ cm as the magnetic penetration in a tin film, in agreement with Zavaritskiĭ's result.[8] In zero field the STC amplitude was 23.9 mA, which is 6/10 of the theoretical value for the given structure and indicates the very high quality of the structure. With increase of the field the STC current maximum decreases monotonically, just as in the case of Pb—oxide—Pb tunnel junctions.[6]

The dependence of the superconducting tunnel current I_1 on an extra current flowing in one of the films is shown in Fig. 1. As expected, the dependence of I_1 on the film current resembles its dependence on the external magnetic field. The shift of the curve to the right by 0.25 Oe appears to result from the small residual magnetization of the

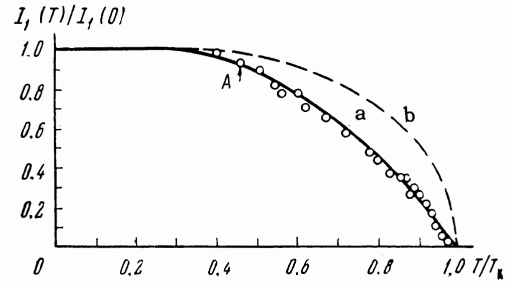

FIG. 2. Temperature dependence of the superconducting tunnel current. a – theoretical dependence,[10] with experimental values indicated by circles; b – temperature dependence of the energy gap.

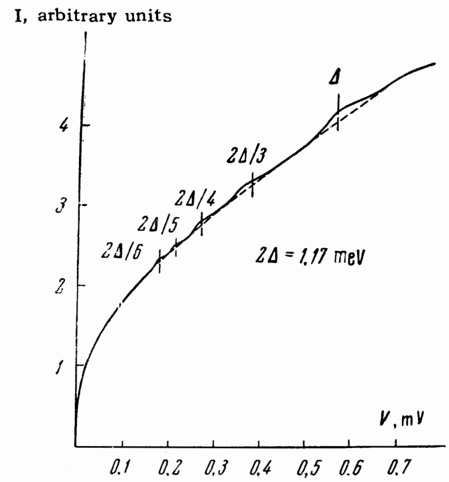

FIG. 3. Singularities in the first segment of the current-voltage characteristic of the $Sn-SnO_2-Sn$ structure. These appear to result from the simultaneous tunneling of several particles. T = 1.61°K; H = 33 Oe.

shield. The magnetic field of the current flowing in the film can be calculated from the formula $H = 0.4\pi I/w$, considering that the second film plays the part of a superconducting screen.[9] The period with respect to the field again corresponds to the magnetic flux quantum Φ_0 in superconductors if the depth of penetration is taken to be $(6.9 \pm 0.7) \times 10^{-6}$ cm, which agrees, within experimental error limits, with the value obtained from the dependence of I_1 on the applied field.

The temperature dependence of the STC is shown in Fig. 2. Since the observed maximum of I_1 is below the theoretical value, the experimental and theoretical curves were placed in coincidence at a single point A for the purpose of comparing their temperature dependences. Since the curve amplitude at a given temperature depends on the current fluctuations, which have different causes, the results were treated as in the case of random variables. The agreement of the rms errors calculated from the simple mean error and from the dispersion indicates a normal error distribution in the present case. The theoretical curve of $I_1(T)$ in Fig. 2 was plotted from the results in[3] together with the latest corrections in[10]. For a symmetric junction we have the formula[10]

$$I_1 = 0.5\pi R_N^{-1}\Delta(T) \tanh \Delta(T) / 2kT. \tag{2}$$

In Fig. 2 the experimental points fit the curve very well, and the formula for a symmetric junction given in[10] is confirmed. The good agreement between experiment and theory for the curves $I_1(H)$ and $I_1(T)$ also indicates that the observed superconducting current is actually a tunnel current, and does not owe its origin to superconducting metal bridges across the junction.

When the magnetic field reaches a few tens of oersteds, the Josephson effect disappears, and processes associated with the ordinary tunneling of quasiparticles are observed. In addition to the main current jump at $V = 2\Delta$, additional singularities were observed on the current-voltage curve at Δ, $2\Delta/3$, $2\Delta/4$, $2\Delta/5$, and $2\Delta/6$ (Fig. 3). These current peaks are possibly associated with simultaneous tunneling of several particles through the barrier,[1,11] although the amplitudes of the peaks diminish considerably more slowly than the theory predicts.[1] The amplitudes of multi-particle tunneling peaks depend largely on irregularities in the thickness of the oxide layer. The model used for the calculation in[1] appears to be too ideal.

In conclusion, we note some anomalies of the current-voltage curves associated with the Josephson effect whose causes are not entirely clear.

1. The amplitude $I_{1,d}$ of the STC attained with gradual increase of the current through the junction can considerably exceed the amplitude $I_{1,r}$ attained in a gradual reduction of the current through the junction (Fig. 4, a and b). In other words, the currents inducing interruption and restoration of superconductivity at a junction are not identical. Also, $I_{1,r}$ is considerably less sensitive to the magnetic field than $I_{1,d}$.

2. Following the application of a sufficiently high magnetic field (of the order of tens of oersteds), which is then turned off, the STC amplitude is not restored to its previous value, but remains lower than before application of the field (Fig. 4c).

3. When the magnetic field or temperature is such that $I_1 \ll I_{1,max}$, the transition from V = 0 to the ordinary tunnel characteristic does not go through only a single voltage jump. Instead, several voltage jumps are observed, which are separated by segments of the current-voltage curve where the current rises while the voltage remains constant (Fig. 4). The number of voltage jumps is not

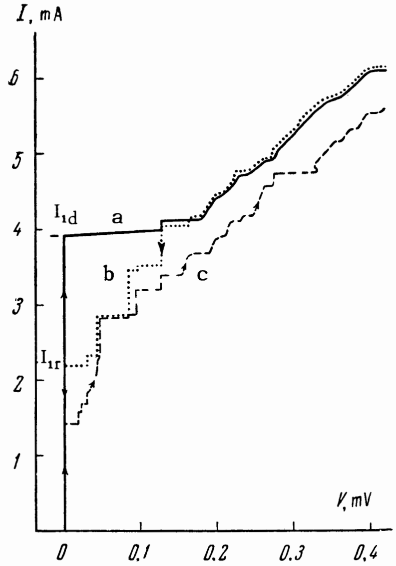

FIG. 4. Singularities in the current-voltage characteristic associated with the Josephson effect. $Sn-SnO_2-Sn$ structure. a – direct run, H = 0, T = 2°K; b – reverse run, H = 0, T = 2°K; c – direct run, H = 0, T = 1.6°K, after applying a 33-Oe field to the structure.

identical for different values of T and H. However, the values for which V is constant coincide and do not depend on T and H for a given junction.

It is possible to account for the first two effects by assuming that the magnetic flux can be partially trapped by inhomogeneities at the edges of the superconducting films. The third singularity can probably be associated with the excitation of an alternating supercurrent, which was also predicted by Josephson,[12] who studied the excitation of electromagnetic oscillations between the films in the region of the junction, and showed that these oscillations have a threshold frequency of the order of thousands of megacycles, in agreement with the voltage spacing of current jumps observed in the present work.

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