Observation of thermoelectric effect in an *SNS* junction

M. V. Kartsovnik, V. V. Ryazanov, and V. V. Shmidt
Institute of Solid State Physics, USSR Academy of Sciences

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The appearance of a finite voltage across a Ta-Cu-Ta Josephson junction due to a heat flux through the junction has been observed; this is attributable to the non-steady-state Josephson effect, which is caused by the flow of a thermoelectric current. The initiation of thermoelectric currents comparable to I_C is caused by the low V_C value ($\sim 10^{-13}$ V) of the junctions.

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Among the possible methods of observing thermoelectric effects in superconducting systems, attention has been focused on the method of Clarke and Freake,[1] who observed an asymmetry in the critical values of the superconducting transport currents in different directions in Josephson point contacts when a temperature gradient is present. Independently, Aronov and Gal' perin[2] showed theoretically the possibility of observing an analog of the non-steady-state Josephson effect, which is caused by the flow of a thermoelectric current. Shmidt[3] examined theoretically the effects that occur in a distributed Josephson *SNS* (superconductor-normal metal-superconductor) junction when its electrodes are at different temperatures.

The behavior of a Josephson junction in the presence of a temperature gradient is easy to understand on the basis of its resistive model. The presence of a temperature difference $T_1 > T_2$ across the junction leads to the appearance of a normal component, the thermoelectric current I_T. However, no buildup of charges occurs at the electrodes of an isolated junction since a compensating superconducting current travels through the "weak link"[1]

$$I_S = -I_T = -\alpha\,(T_1 - T_2)/R_N\ . \tag{1}$$

Here α and R_N are, respectively, the absolute differential thermoelectromotive force and the resistance of the junction metal in the normal state. When the temperature difference across the junction exceeds the value

$$(T_1 - T_2)_C = I_C R_N/\alpha = V_C/\alpha \tag{2}$$

the thermoelectric current I_T exceeds the critical value I_C and an electrochemical potential difference V appears across the junction, which leads to Josephson oscillation with a frequency $\omega_0 \approx (2e/\hbar)\,\alpha(T_1 - T_2)$ for values $(T_1 - T_2) > V_C/\alpha$.[2]

In the cited experiment[1] it was impossible to achieve values of the thermoelectric current I_T close to I_C because of the high value of V_C of the point contacts ($\sim 10^{-5}$ V). The purpose of our work was to observe thermoelectric effects in Josephson *SNS* sandwiches, whose V_C values are only $\sim 10^{-13}$ V; this made it possible to expect considerably higher thermoelectric currents in the new system at relatively small temperature gradients.

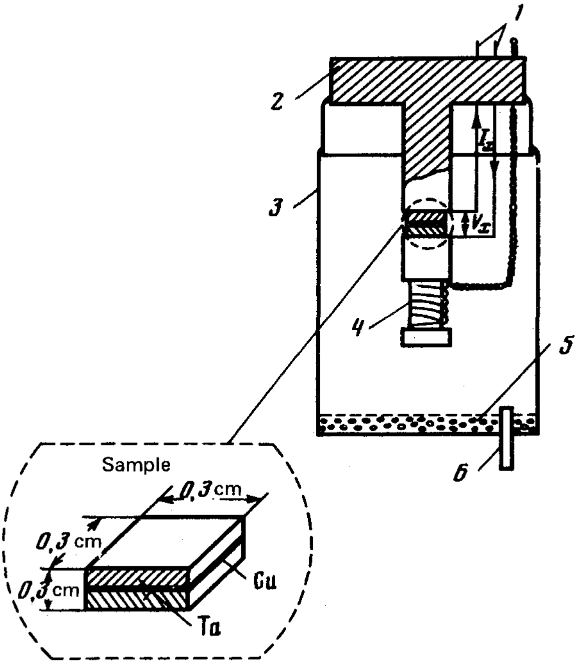

FIG. 1. Evacuable glass with the sample.

The *Ta-Cu-Ta SNS* sandwiches were fabricated by the method of combined hot rolling in a vacuum. The obtained thick plates were subsequently rolled some more, so that the initially diffusion-fused *NS* interface was stretched out several fold; this ensured the purity of the *NS* boundary. The absence of oxides on most of the *NS* surfaces of the junction was confirmed by the results of measurements of the excess resistance and by the Josephson properties of such sandwiches.[4] The thickness of the copper layer was 7 μm and 10 μm in different samples. The samples were cut by an electric-spark method and then etched in an acid mixture to remove the tantalum bridges formed during the cutting; this was checked by means of a scanning electron microscope.

Figure 1 shows the glass (3) in which the sample was placed during the experiment and held securely by BF-2 cement between two copper heat conductors. One of the heat conductors (2) was in contact with a helium bath, while the other was wound with a noninductive heater (4). The superconducting leads (1), which were attached to the sample by spot welding, were used to carry the current I_X from the external source and to measure the voltage V across the junction. The glass was evacuated at room temperature via the lead tube (6) and was sealed. Activated charcoal (5) was placed inside the glass. The voltage across the sample ($\sim 10^{-13} - 10^{-12}$ V) was measured by a compensation circuit, in which a hf-SQUID[5] was used as the null detector. The error did not exceed ±5%.

Figure 2 shows two characteristic voltage dependences for one of the samples: the dependence on the current I_X through the sample and on the heater power P, which were measured at a temperature of 4.2 K ($T/T_C = 0.97$). The I_X and P scales

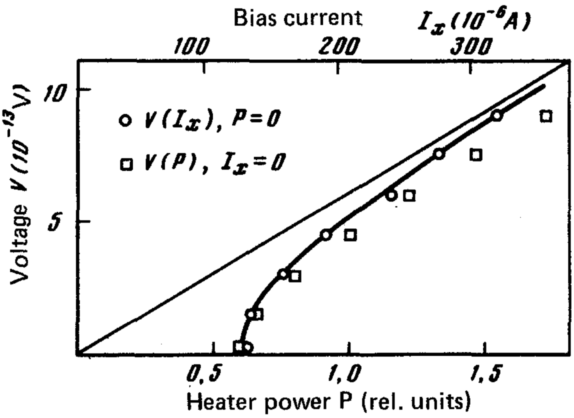

FIG. 2. Dependences of the voltage across sample on the external current and on the heater power.

are normalized by superimposing the points at which a detectable voltage (~3 × 10^{-14} V) appears. The IV characteristic $(I_X)V\,(P=0)$ matches well the dependence[6] $V=R_N\sqrt{I_X^2-I_C^2}$ for $R_N\approx 3\times 10^{-9}$ ohm. The measured temperature dependence of the critical current matches satisfactorily the dependence[7] $I_C\sim(1-T/T_C)^2$ for an *SNS* junction near T_C. All of this indicates that the sample is an *SNS* junction with a uniform distribution of the external current over the junction area (the Josephson penetration depth is $\lambda_J\approx 0.16$ cm); this makes it possible to compare the dependences[3]

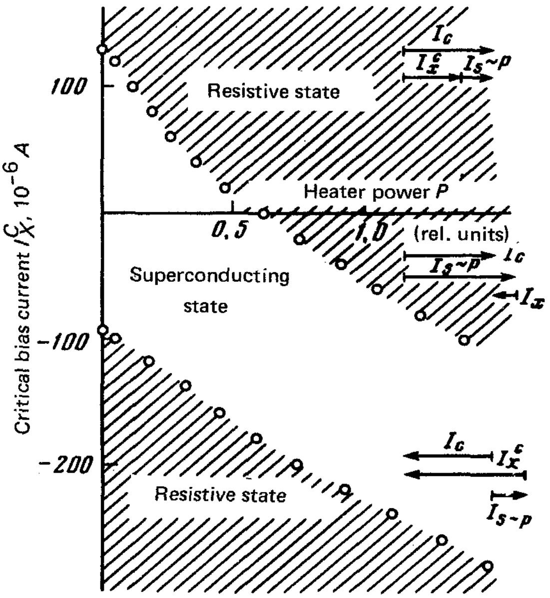

FIG. 3. Influence of heat flux through the junction on the critical transport current.

shown in Fig. 2. The $V(P)$ ($P \sim 10^{-4}$ W) and $(I_X)V$ curves are in good agreement; their signs of V are opposite for the same direction of the currents I_X and I_T (a positive sign is obtained for the α of the Josephson layer). This is in complete agreement with a treatment used within the framework of the resistive model, which gives the dependence $V \approx R_N \sqrt{I_T^2 - I_C^2}$ in the "warm" case.

The "asymmetry"[1] of the critical values of the transport current I_X^C for this sample, produced as a result of switching the current I_X, is shown in Fig. 3 for different values of heat flux in one direction. The upper branch in the upper half of the graph corresponds to parallel flow of the superconducting thermoelectric current $I_S = I_T$ and of the external-source current I_X^C. The part of the upper branch in the negative half of the graph corresponds to the case $|I_S| \geqslant I_C$, but the oppositely directed current I_X^C reduces it to the critical value. The lower branch corresponds to the case $|I_X| \geqslant I_C$, but I_S flows opposite to I_X, so that $I_X - I_S = I_C$. Such an interpretation of the results in Fig. 3 is valid for $\alpha > 0$ of the Josephson layer.

Assuming that $\alpha \approx 10^{-8}$ V/K (which is a typical value for pure copper), we can obtain for $V_C \approx 4 \times 10^{-13}$ V the following estimate for the "critical" temperature difference across the Josephson layer (2): $(T_1 - T_2)_C \approx 4 \times 10^{-5}$ K. It must be noted, however, that both a copper layer (an upper estimate of its resistance gives $\sim 5 \times 10^{-10}$ ohm) and the nearest nonequilibrium layers of the superconducting tantalum, which contribute to the excess resistance of the NS boundary, can participate in the thermoelectric processes that occur in the region of the Josephson weak link.[8]

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