Temperature dependence of excess resistance of the normal metal-superconductor interface

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(Submitted 11 March 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 10, 610–613 (20 May 1979)

The temperature dependence of the excess resistance R_e of the normal metal-superconductor interface was obtained by direct measurements. It was found that the temperature dependence varies with decreasing temperature from $R_e \sim (1 - T/T_c)^{-1/4}$ to $R_e \sim (1 - T/T_c)^{-3/4}$, which is attributable to the Andreev reflection of quasiparticles.

PACS numbers: 73.40.Jn, 74.90. + n

The existence of excess radiation R_e at the normal metal (N)-superconductor (S) interface was initially observed by Landau as a result of measuring the resistance of a superconductor in the intermediate state.[1] Subsequently, the resistance R_e was attributed to the penetration of longitudinal electric field into the superconductor to a depth l_E due to the nonequilibrium population of the branches of the quasi-particle spectrum as a result of the flow of current through the S-N interface.[2–4] Artemenko *et al.*[5] and Ovchinnikov[6] calculated this resistance and showed that it is also determined by the Andreev reflection of quasi particles at the S-N interface in the case of a pure superconductor ($l \gg \xi_0$) or by an analogous process in the dirty superconductor ($l \ll \xi_0$) (l is the path length). The Andreev reflection reduces the quasi-particle flux across the interface and hence reduces the electric field in the superconductor. This process occurs at a length $\xi(T)$ and at for large length l_E it is equivalent to a jump of the electric field.

The expression for R_e obtained by Artemenko *et al.*[5] in the case of a thin film ($l \ll \xi_0$) has the following form

$$R_s = \frac{R_N^{\square}}{w} \frac{l_E}{1 + \left(\frac{\pi}{3\sqrt{2}} \frac{l_E}{\xi(T)} \frac{\Delta}{T}\right)^{1/2}},$$

where

$$l_E = l_\epsilon \left(\frac{4T}{\pi\Delta}\right)^{1/2},$$

$l_\epsilon = \sqrt{D\tau_\epsilon}$ is the length, τ_e is the energy relaxation time, D is the diffusion coefficient, $R_N^{\square}$ is the resistance of the film per unit area in the normal state, and w is the width of the film. In the vicinity of $T_c \Delta \ll T$ and the second term in the denominator, which is associated with the Andreev reflection, is small compared to unity. The quantity R_e and its temperature dependence are determined by the penetration of the electric field into the superconductor to a depth $l_E \sim (1 - T/T_c)^{-1/4}$. As T decreases l_E decreases and the role of the Andreev reflection increases. At a certain T the second term in the denominator exceeds 1 and then $R_e \sim (1 - T/T_c)^{-3/4}$. The temperature dependence $l_E \sim (1 - T/T_c)^{-1/4}$ near T_c was observed experimentally for tin films.[7,8] In this paper, using direct measurements we investigated the temperature dependence $R_e(\sim l_E)$ in a wider temperature range in a superconductor (Al) with a larger value $\tau_e \sim 10^{-9}$ sec and observed a transition from the dependence $R_e \sim (1 - T/T_c)^{-1/4}$ to $R_e \sim (1 - T/T_c)^{-3/4}$.

We measured the resistance of the S-N interface by using long ($L \sim 50\ \mu$m), nar-

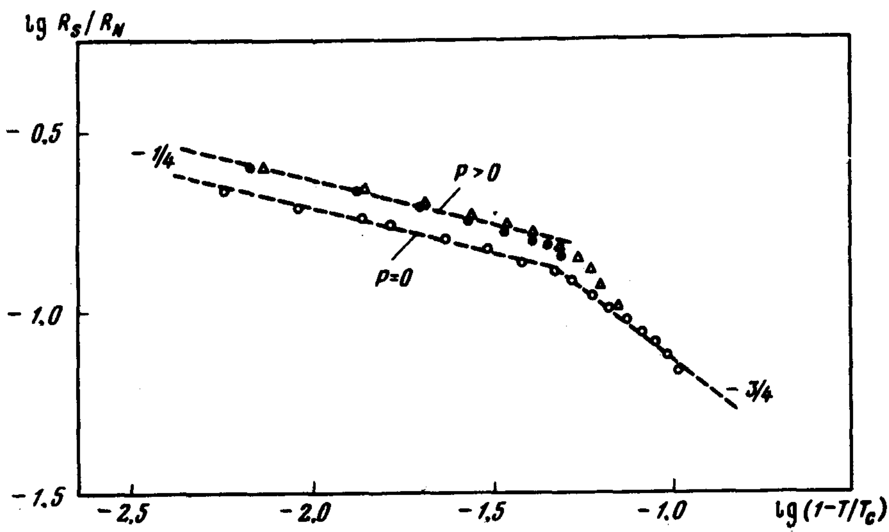

FIG. 1. Temperature dependence of the excess resistance R_e of the S-N interface of the Al bridge: in the absence of radiation (○) and in the presence of radiation (●, 10.4-db damping; △, 12.0-db damping). The radiation frequency is 9 GHz.

row ($w \sim 3$ μm)Al films bridges with banks whose thickness (3000 Å) was greater than that of the characteristic thickness of the bridge (1200 Å). Such bridges were obtained from the original thick bridge by ionic etching of its neck. It is known that the critical temperatures of thin Al films is usually higher than that of the thick films. This made it possible to obtain bridges whose critical temperatures T_c^B are higher than those of their banks T_c^b. The $R(T)$ dependence of the bridges was measured by using a very small (10^{-8} A) acoustic frequency ac current, which was subsequently amplified and detected. The thermoelectric effects do not influence the results of the measurements.

The resistance of the entire bridge initially decreased significantly in a narrow temperature interval as a result of decreasing the temperature, which corresponded to the transition to the superconducting state of the thin-film neck of the bridge ($T_c^B = 1.403$ K). Further, at $T \approx 1.24$ K we observed another smaller jump of the resistance $\Delta R = R_N^b$, which corresponded to the transition of the banks to the superconducting state ($T_c^b = 1.2$ K). In the temperature region $T_c^B > T > T_c^b$ the bridge represented the N-S-N system whose resistance $R(T)$ was higher than R_N^b and the difference $R_e = R(T) - R_N^b$ smoothly decreased with decreasing temperature.[1]

Figure 1 shows the dependence of the normalized value of R_e on $1 - T/T_c$ in the log-log scale (power of the external radiation $P = 0$). The dashed-lines in Fig. 1 correspond to the dependences $R_e \sim (1 - T/T_c)^{-1/4}$ and $R_e \sim (1 - T/T_c)^{-3/4}$. As seen in Fig. 1, near T_c the experimental dependence $R_e(T)$ corresponds to the dependence with the exponent $-1/4$, consistent with the data of Refs. 7 and 8. As a result of further decrease of the temperature R_e begins to decrease more steeply, which corresponds to the change of the exponent to $-3/4$.

The obtained data show that the excess resistance of the S-N interface near T_c is mainly due to the penetration of the electric field into the superconductor and its temperature dependence is in good agreement with the theory.[5,6] At some distance from T_c the Andreev reflection begins to play an important role and according to the theory[5] $R_e \sim (1 - T/T_c)^{-3/4}$. The exchange of mechanism in our case occurs at $T_c - T = 63$ mK. Assuming that this corresponds when the second term in the denominator of the expression for R_e, is equal to unity we can determine the energy relaxation time τ_e in the Al bridges. Using the values $\xi_0 = 1.6$ μm, $v_F = 1.3 \times 10^8$ cm/sec, and $T_c = 1.403$ K, we obtain $\tau_e = 3 \times 10^{-9}$ sec. This value is noticeably smaller than the approximate theoretical estimate $\tau_e \leqslant 10^{-7}$ sec, but is in fair agreement with the latest experimental results, 2×10^{-9} and 5×10^{-9} sec, obtained by other methods.[10,11]

We also investigated the effect of uhf radiation on the Al bridges described above. It was determined that the effect of radiation with frequency of ≈ 9 GHz on the superconducting bridge with normal banks, just as in the usual case of a bridge with superconducting banks,[12] leads to the increase of T_c^B. The maximum increase of T_c^B reached 73 mK, which corresponded to an increase of T_c^B by 5.2%. The curves for the dependence $R_e(T)$ were similar to those for $R_e(T)$ at $P = 0$ when radiation of different power was in effect and the T_c^B shift was taken into account. It can be seen in Fig. 1 that for $P > 0$ initially we have the dependence $R_e \sim (1 - T/T_c)^{-1/4}$ whose exponent subsequently changes to $-3/4$. It follows from this that nonequilibrium of the distribution function caused by radiation, i.e., when the symmetry of population of the branches of the quasi-particle spectrum is conserved, does not materially change the character of the processes at the *S-N* interface, which are due to the nonequilibrium, asymmetric population of these branches. Moreover, the characteristic scale of variation of the distribution function due to radiation is the energy $\sim\Delta$ and in the processes of asymmetric population the characteristic energy scale is $\sim kT \gg \Delta$ (at $T \sim T_c$), which apparently also contributes the lack of "interference" between these two types of nonequilibrium.

We thank A.F. Volkov and S.N. Artemenko for a discussion of the results.

[1)] The excess resistance of the *N-S-N* system due to stimulation of superconductivity in the bridge by external uhf radiation was observed in Ref. 9.

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