Nonlinear electric effects at superconductor-normal metal contacts

V. N. Gubankov and N. M. Margolin
Institute of Radio Engineering and Electronics, USSR Academy of Sciences

(Submitted 12 March 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 12, 733–737 (20 June 1979)

The gap singularities, excess current and nonmonotonic temperature dependence of the first derivative of the I–V characteristic of the superconductor-normal metal microcontact with direct conductivity, which is associated with the variation of the conductivity mechanism as a result of decreasing the temperature, were observed experimentally.

PACS numbers: 73.40.Jn, 85.20.Sn, 85.25. + k

A number of papers[1,2] reported the existence of a nonlinear current-voltage (I–V) characteristic for a direct current and a nonlinear behavior of the superconductor-constriction-normal metal (S-c-N) system in the microwave field with a constriction (c) of either S or N, which results in a direct contact between the superconductor and the normal metal. However, in-depth studies of nonlinear effects and of the causes of their occurrence in S-c-N contacts have not been conducted. Meanwhile it was interesting to determine whether the energy gap in the spectrum of electronic excitations of the superconductor has an effect on the nonlinear I–V characteristic and, if so, the extent of this effect.

In this paper we examine the results of experimental studies of the temperature evolution of the I–V characteristic of S-c-N submicron-size point contacts. We detected singularities clearly associated with the energy gap: characteristic minima in the dependence of the first derivative of the I–V characteristic dV/dI on V and the effect of the excess current. We found that the properties of the S-c-N contacts differ markedly from those of the tunneling weakly linked S-I-N structures,[3] in which the transfer of the electric charge in the region of the weak link is accomplished via tunneling of quasi particles across the insulation layer (I).

The object of our investigation was the point contacts which were formed by pressing a pointed (radius of curvature $\approx 3\ \mu$m) tantalum wire to a flat surface of the copper electrode. In this paper, we examine contacts with a resistance in the normal state $R_N = 20 - 200\ \Omega$ (contacts with $R_N > 0.5$ kΩ and I–V characteristics typical of the tunneling S-I-N transitions).

Figure 1 shows typical $dV/dI\,(V)$ dependences for a contact with $R_N = 65.80\ \Omega$ in the range $T/T_c \approx 1 - 0.5$. At $T/T_c \geqslant I\ dV/dI\,(V) = \text{const} = R_N$ in the current and voltage range in which the generation of phonons by fast electrons[4] does not affect the I–V characteristic. As T decreases below T_c dV/dI decreases in the region $V = 0$ $dV/dI\,|_{V=0} < R_N$. As is well known, such a temperature evolution near T_c indicates a direct microshorting between the S and N electrodes.[2] With further decrease of T, the characteristic minima, which are shifted with decreasing T to the region of large V and which correspond to $\Delta\,(T)/e$, appear on the $dV/dI\ (V)$ curves. At the same time,

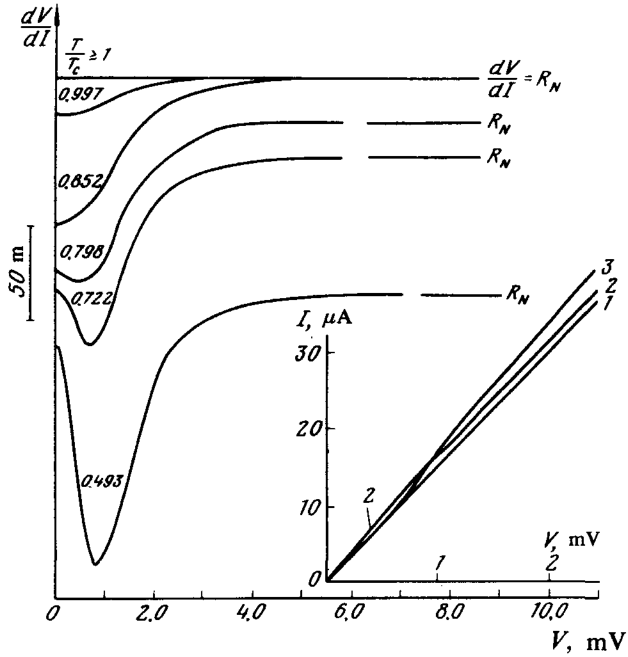

FIG. 1. Dependence of dV/dI on V at different temperatures (the numbers on the curves represent the values of T/T_c). The curves for $T/T_c \leqslant 0.798$ are displaced downward relative to the initial curves. The contact with $R_N = 65.8\ \Omega$. A family of I–V curves is shown in the inset: 1, $T/T_c \geqslant 1$; 2, $T/T_c \leqslant 1$; 3, $T/T_c \ll 1$.

dV/dI, which was measured at $V=0$ ($dV/dI|_{V=0}$), begins to increase and reaches a value of 0.957 R_N at the minimum value of $T/T_c \approx 0.49$ obtained experimentally.

The structure of the I–V characteristics for the three limiting cases ($T \geqslant T_c$, $T \leqslant T_c$, and $T \ll T_c$) is shown in the inset in Fig. 1. The temperature dependence $dV/dI|_{V=0}$ with the characteristic minimum at $T/T_c = 0.817$ is shown for the same point contact in Fig. 2. It can be seen that the minimum $dV/dI|_{V=0}$, which is approximately equal

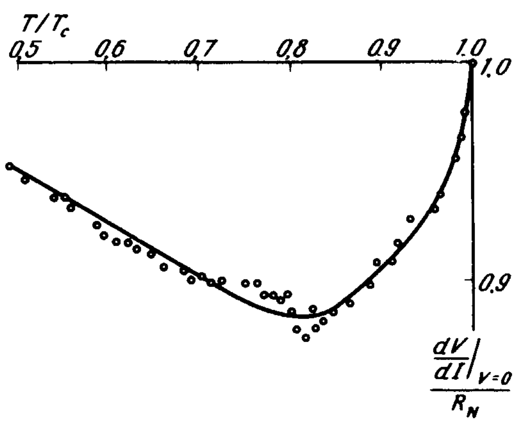

FIG. 2. Temperature dependence of $(dV/dI|_{V=0})/R_N$.

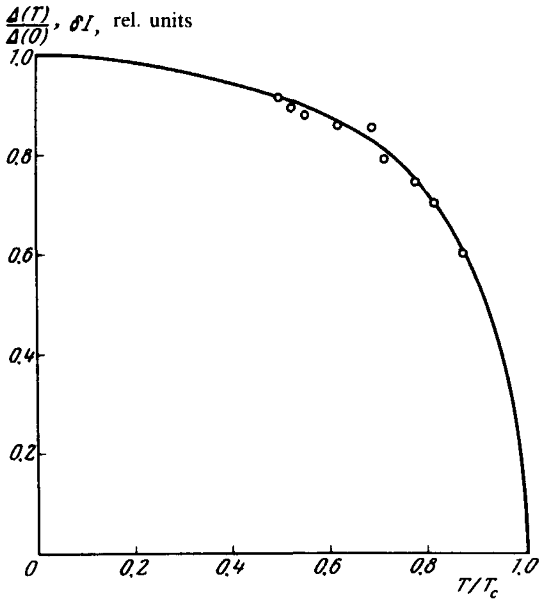

FIG. 3. $\delta I(T)$ dependence (o, results of the measurements); solid line represents the theoretical dependence $\Delta T/\Delta(0)$.

to 0.87, does not exceed R_N in the entire temperature interval.

It can be seen from the analysis of the I–V characteristics and from the $dV/dI(V)$ dependence for the different T that small-size *S-c-N* contacts have an excess current δI, which is known for the *S-c-S* contacts[5] and which is absent in the superconducting tunneling structures with an insulation layer (the excess-current effect at high voltages is represented by the straight section of the I–V curve, which is displaced relative to $V = IR_N$ by the amount $\delta I(T)$ independent of V). Figure 3 shows the dependence of the normalized value of $\delta I(T)$.

The described evolution of the I–V characteristics differs substantially from the I–V (T) dependences which are related in type and in geometry of the weakly linked superconducting structures. As is well known, when T varies from T_c to a value close to zero, $dV/dI|_{V=0}$ in *S-I-N* tunneling[3] goes from R_N to infinity; in the *S-c-S* contacts it remains equal to zero and at voltages $V = 2\Delta/ne$ (n, 1, 2, 3,...) we observed dV/dI peaks which are attributable to destruction of the Cooper pairs due to absorption of the Josephson self-radiation.[1]

The theoretical analysis of *S-c-N* small-size contacts [with a microshorting diameter $a < \zeta(T)(1 - T/T_c)^{1/4}$ this condition is satisfied in our experiments] conducted recently by Artemenko *et al.*[6] showed that a minimum should exist in the temperature dependence $dV/dI|_{V=0}$; moreover, as $T \to 0$ $dV/dI|_{V=0}$ approaches R_N asymptotically, which is consistent with the experimental data. The $dV/dI|_{V=0}$ minimum is attributable to the following causes. According to the theory,[6] two conductivity mechanisms can exist simultaneously in the *S-c-N* contacts: because of the transfer of a charge by quasiparticle 1) with an energy $E < \Delta$ and 2) with an energy $E < \Delta$, which move from the N region to the S region and are converted to Cooper pairs in the S region. The gap in the S region does not hinder the charge transfer across the *S-N* boundary by the quasi particles with $E > \Delta$, as in the case of Andreev reflection. The total conductivity of the contact increases as a result of appearance of the second mechanism below T_c; as T continues to decrease, the conductivity due to the first mechanism decreases because of the decrease of the number of quasi particles with an energy $E > \Delta$, whereas the conductivity due to the second mechanism, which approaches a constant determined by the number of quasi particles in the interval $E \leqslant 2\Delta$ (T), becomes dominant. This slowly increases $dV/dI|_{V=0}$ when T is noticeably smaller than T_c.

The calculations of Artemenko *et al.*[6] indicate that the dV/dI minimum is present at $V = \Delta/e$, which is caused by the increase in the number of quasi particles that pass directly across the *S-N* boundary. They also indicate the presence of the excess-current effect at $V > \Delta/e$, which is attributed to the second conductivity mechanism (i.e., this is an additional indication of the formation of a direct superconductor-normal metal contact). As seen in Fig. 1, the transition of the I–V curve to a straight line, which is parallel to $V = IR_N$ (i.e., when dV/dI reaches a constant level R_N $dV/dI = R_N$), occurs when $V > \Delta/e$. The experimental value $\delta I(T)$ is proportional to $\Delta(T)$ (Fig. 3), consistent with the theory.

We thank A.F. Volkov for useful discussions.

[1)]The control experiments showed that the Josephson effects in the *S-c-N* contacts were missing during the irradiation by uhf radiation; specifically, the I–V characteristics did not have the well-known current steps.

[1]I.Ya. Krasnopolin and S.M. Khaĭkin, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 290 (1966) [JETP Lett. **4**, 196 (1966)]; O. Iwanshyn and H.J. H. Smith, Phys. Rev. **B6**, 120 (1972); U. Kaiser-Dieckhoff, Conf. SQUID-77, C7, 54, Berlin, 1977.
[2]Yu.G. Bevza, V.I. Karamushko, and I.M. Dmitrenko, Zh. Tekh. Fiz. **47**, 646 (1977) [Sov. J. Tech. Phys. **22**, 387 (1977).
[3]Tunnel'nye yavleniya v tverdykh telakh (Tunneling Effects in Solids), Ch. 19, edited by E. Burshnein and S.L. Lundquist, Mir, M., 1973.
[4]N.I. Bogatina and I.K. Yanson, Zh. Eksp. Teor. Fiz. **63**, 1312 (1972) [Sov. Phys. JETP **36**, 692 (1972)].
[5]J.I. Ponkove, Phys. Rev. **21**, 406 (1966).
[6]S.N. Artemenko, A.F. Volkov, and A.V. Zaĭtsev, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 637 (1978) [JETP Lett. **28**, 589 (1978)]; S.N. Artemenko, A.F. Volkov, and A.V. Zaĭtsev, Solid State Comm. **30**, 12 (1979).