Dependence of the excess current in superconducting point contacts on temperature and voltage

Yu. Ya. Divin and F. Ya. Nad'
Institute of Radio Engineering and Electronics, USSR Academy of Sciences

(Submitted 11 March 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 9, 567–570 (5 May 1979)

We have experimentally established that, in accordance with the existing microscopic theory for short superconducting contacts, the excess current in the voltage region $V > \Delta/e$ increases as th $(eV/2kT)$ and its maximum value at high voltages $(eV \geq 5kT)$ depends on the temperature, as also does the magnitude of the energy gap $\Delta(T)$. Results indicate that the excess current mechanism considered here theoretically is also applicable to longer contacts.

PACS numbers: 74.50. + r

One of the significant differences between experimentally observed volt-ampere characteristics (VAC) of weakly-bound superconductors (bridges and contacts) and the VACs resulting from the resistive model is the presence of excess current δI which is a voltage-independent (at large V) increment to the current $I(V) = V/R$. Although the excess current was first observed more than a decade ago,[1] its physical nature was not clear until recently. Different mechanisms for the excess current—based on either purely phenomenological concepts[2] or applicable only in the case of gapless superconductors[3]—fail to explain all the experimentally-observed features of this effect. In particular, it is evident from Refs. 2 and 3 the value of excess current δI is proportional to the critical current of weak coupling I_c. However, we observed in practice that the characteristic scale of the excess current is not I_c but the size of the superconductor energy gap Δ.[4] Quite recently, an expression for current in a point contact (or a short bridge) with length $L < \xi(T)(1 - T/T_c)^{1/4} = \eta(T)$ was obtained on the basis of microscopic theory:[5]

$$I = V/R + (\Delta/R)(\pi^2/4 - 1)\,\mathrm{th}(eV/2kT),$$

which holds for $eV > \Delta$ and any temperature T. In this work, dependence of δI on V and T is studied experimentally results are compared with the theory,[5] and an assumption is made concerning the applicability of the mechanism for longer contacts with $L \gtrsim \eta(T)$.

Measurements were carried out using stable superconducting point contacts (SPC) Nb-Nb whose basic Josephson properties are determined by intrinsic micro-short-circuits.[4] We measured the VACs of contacts with resistances $R = 10^{-1}$–10^{-3} ohm in the temperature range 4.2–10 K and at voltages of tens of mV. All the subject contacts were characterized by expressed excess and critical currents within the indicated range of temperatures and resistances. The relationship between experimental values of excess δI and critical I_c currents was such that at $T \ll T_c$ $\delta I \sim I_c$ and, at $T \lesssim T_c$, $\delta I \gg I_c$. Therefore, for $T \lesssim T_c$, the measured current $I(V)$ over almost the entire range of voltages represents a sum of the ohmic current V/R and excess current $\delta I(V)$. For $T \ll T_c$, other components, for example, the Josephson current, contribute to the total current at $eV \gtrsim \Delta$. In view of this, we determined the dependence of excess current on voltage from differences in the experimental VACs of contacts at $T \lesssim T_c (I = V/R + \delta I)$ at $T > T_c$ $(I = V/R)$.

Figure 1 shows the $\delta I(V)$ function for a contact with $R = 5.9$ ohm at two fixed temperatures 9.57 and 9.66 K ($T_c = 9.87$ K), starting with voltages $eV \gtrsim \Delta$ and going to higher voltages $eV \gtrsim 5kT$ where δI remained practically unchanged. All values of δI were normalized to excess current values at $eV \gtrsim 5\,kT$. The solid curve corresponds to

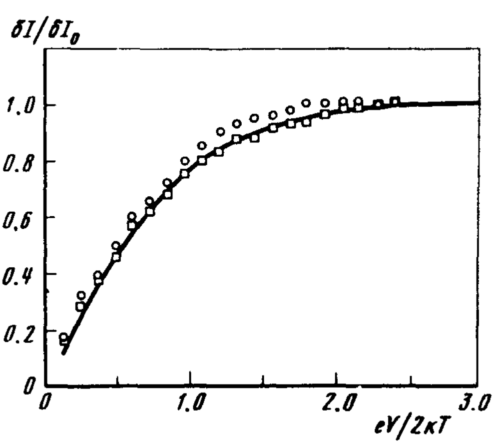

FIG. 1. Dependence of excess current δI in SPC on voltage V for two temperatures T,K ○—9.57 and □—9.66. Excess current is normalized by its value δI_0 at $eV \gtrsim 5\,kT$. STC resistance R in normal state is 5.9 ohm. Solid curve—th $(eV/2kT)$.

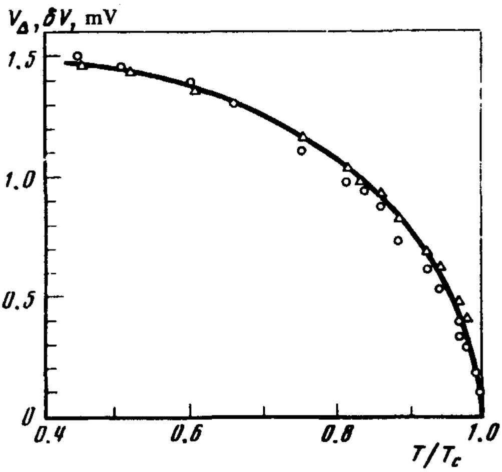

FIG. 2. Temperature dependence of voltage $\delta V(0)$ equal to a product of excess current δI and resistance R, and the gap property $V_\Delta(\Delta)$ for a contact with $R = 5.9$ ohm. Solid curve—function $\Delta(T)$ given by the BCS theory.

the function th($eV/2kT$) which follows from the microscopic theory.[5] Clearly, a good agreement exists between the experimental and theoretical $\delta I(V)$ functions.

The temperature dependence of excess current—multiplied by the contact resistance, $\delta V = \delta IR$—is shown in Fig. 2 for the same contact with $R = 5.9$ ohm. The value of δV was measured at voltage $V \approx 4$ mV. During the measurement two conditions hold over the entire temperature interval: first $eV/2kT \approx 2.5$ and the values th($eV/2kT$) differ from unity by not more than 2% and, second, the condition $eV > \Delta$ is also satisfied. Also appearing in Fig. 2 are the experimental data points for the temperature-dependent voltage V_Δ which corresponds to the gap properties of contact VAC, i.e., the actual temperature dependence of the size of the energy gap. As is evident from Fig. 2, the experimental functions $\delta V(T)$ and $V_\Delta(T)$ coincide well and both quantitatively agree with the function $\Delta(T)$ with respect to the BCS theory. Thus, while experimental and theoretical[5] (see aforementioned expression for the current) functions $\delta V(T)$ are identical by nature, with respect to magnitude the theoretical value of δV is 1.5-fold higher. The reasons for this divergence may be the peculiarities of the conduction mechanism of real SPCs[4] and thermal effects occurring in them (especially at small R).

We noted above that the microscopic theory[5] is strictly applicable only to the case of contacts with length $L < \eta(T)$. The dimensions of micro-short-circuits in the subject contacts with $R \sim 10$ ohm are—according to calculations (order of magnitude): length $L \sim 100$ Å, diameter ~ 10 Å. In such contacts, taking into account the fact that the electron free mean path length is determined by micro-short-circuit diameter, the condition $L < \eta(T)$ is satisfied at $T \sim T_c$ and upset only when the temperature falls below T_c, $T \sim 1$K. This is also evidenced by the change in the nature of contact VAC as a function of T.[4] At the $T \sim T_c$, VAC is hyperbolic for small V which is in agreement with the theory for short contacts $L < \eta(T)$.[6] As the temperature decreases, $T_c - T \gtrsim 1$K, the SPC VAC undergoes bending which, in accordance with theory, is characteristic for contacts with length $\eta(T) < L < \xi(T)$ and depends on stimulation of I due to wall oscillations of the potential well in the contact neck at currents $I \gtrsim I_c$.[7]

Similar deflection occurs in film bridge VACs, where the condition $\eta < L < \xi$ begins to be satisfied at some distance from T_c.[8] Regardless of transition from the case $L < \eta$ to $L > \eta$, the excess current—as our measurements show (Fig. 2)—is preserved and its dependence on T follows the function $\Delta(T)$. This, evidently, indicates that the proposed mechanism of excess current[5] is also applicable in the case $\eta(T) \lesssim L \lesssim \xi(T)$.

The authors thank S. N. Artemenko and A. F. Volkov for useful discussions of results.

[1]J.I. Pankove, Phys. Lett. **21**, 406 (1966).
[2]B.S. Deaver and J.M. Pierce, Phys. Lett. **38A**, 81, (1972).
[3]K.K. Likharev and L.A. Yakobson, Zh. Eksp. Teor. Fiz. **68**, 1150 (1975) [Sov. Phys. JETP **41**, 570 (1975)].
[4]Yu. Ya. Divin and F. Ya. Nad., Fiz. Nizk. Temp. **4**, 1105 (1978); [Sov. J. Low Temp. Phys. **4**, 520 (1978).
[5]S.N. Artemenko, A.F. Volkov and A.V. Zaĭtsev, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 637 (1978); [JETP Lett. **29**, 172 (1979)] [**29**, 152 (1979)].
[6]S.N. Artemenko, A.F. Volkov and A.V. Zaĭtsev, Materialy 20-go Vsesoyuznogo soveshchaniya po fizike nizkikh temperatur (Proceedings of the 20th All-Union Conference on Physics of Low Temperatures) part III, 261 (1979).
[7]L.G. Aslamazov and A.I. Larkin, Zh. Eksp. Teor. Fiz. **70**, 1340 (1976). [Sov. Phys. JETP **43**, 698 (1976)].
[8]V.N. Gubankov, V.P. Koshelets and G.A. Ovsyannikov, Zh. Eksp. Teor. Fiz. **73**, 1435 (1977). [Sov. Phys. JETP **46**, 755 (1977)].