Nonlinear electrical and microwave properties of superconductor–normal metal microcontacts

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The nonlinear electrical phenomena (gap singularities in the current-voltage characteristics (CVC), the excess-current effect, the nonmonotonic temperature dependence of the differential conductivity measured in the absence of a constant bias field) occurring in superconductor–constriction–normal metal microcontacts with direct conductivity have been investigated. The experimental data are found to be in accord with the results of the microscopic theory, and are explained by the existence of two mechanisms of electric-charge transfer across the *S–N* interface. Investigations of the temperature evolution of the singularities of the CVC allow the estimation of the relative contribution made to the microcontacts total conductivity by the conductivity due to the tunneling of quasiparticles through the oxide layer and by the direct conductivity of the metallic short circuit. The action of weak microwave radiation leads to an increase in the differential conductivity in the region of weak currents, and possible causes of this phenomenon are discussed.

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INTRODUCTION

Investigations of the nonlinear phenomena occurring in superconductor-constriction-normal metal (*S-c-N*) contacts during the passage of a transport current through, or the action of microwave radiation on, them indicate that these phenomena may be due to several different causes. Iwanshyn and Smith[1] have computed the CVC of *S-c-N* contacts, and assert that the nonlinearity of the CVC (the increase of the resistance with increasing current) is due to the warming up of the contact and its gradual transition into the normal state as a result of the growth of the normal-phase region. Dmitrenko *et al.*[2] relate the shape of the initial segment of the nonlinear CVC to the superconductivity existing in a section of the *S-c-N* contact, and further attribute the nonlinear microwave properties of such contacts to the spreading under the action of the microwave field of the superconducting phase into the normal region, i.e., to a change in the proximity effect. In Ref. 3 Khaĭkin and Krasnopolin report the observation of nonlinear CVC of *S-c-N* point contacts at a temperature T higher than the critical temperature T_c of the superconducting electrode. The nonlinearity of the CVC is explained by Khaĭkin and Krasnopolin as being due to the stimulation in the normal electrode of coherent emission of phonons, which retard the electron flux at the location of the constriction; the retardation effect should lead to an increase in the contact resistance. Finally, Kaiser-Dieckhoff[4] has quite thoroughly investigated the nonlinear properties of *S-c-N* contacts within broad ranges of their electrical and geometric parameters; but in his paper[4] the experimental data obtained are not discussed in detail, and virtually no physical interpretation is given.

Artemenko, Volkov, and Zaĭtsev[5] (AVZ) have recently developed a microscopic theory of *S-c-N* contacts with direct conductivity in the "dirty"-limit approximation under the condition that

$$a, L<\xi(T)(1-T/T_c)^{1/4} \tag{1}$$

[here a and L are respectively the transverse dimension and length of the microshort and $\xi(T)$ is the coherence length in the weak-link region]. They show that these contacts' properties (the presence of excess current, the appearance of gap singularities in the CVC as the temperature is lowered, the nonmonotonic temperature dependence of the first derivative of the CVC) discussed in Ref. 6 are accounted for by a change in the mechanism underlying the conductivity in the weak-coupling region when the temperature is lowered. This theory also predicts interesting anomalies in the behavior of *S-c-N* contacts in a microwave field.

The aim of the present work was to investigate in greater detail than was done in our previous experiments[6] the properties of S-c-N contacts with direct conductivity, whose geometry and parameters are close to those stipulated in the condition (1), and to carry out a detailed investigation of the conditions for the occurrence of the nonlinear phenomena during the action on the contact of a constant electric or a microwave field.

EXPERIMENTAL PROCEDURE

In the experiments we used clamped niobium-copper point contacts, with the copper electrode normally serving as the optically polished plane target and the tapered end of a wire fabricated from the superconducting material as the point. The diameter of the wire was ~70–100 μm. The tapering was carried out mechanically by obliquely cutting with a scalpel; the radius of the point normally did not exceed 3–5 μm. The contacting and the formation of the contact were carried out at a liquid-helium temperature. The contact was placed in a rectangular 8-millimeter waveguide parallel to its narrow side. We measured the temperature dependences of the CVC, the temperature and field dependences of the differential conductivity $dI/dV = G_d(V, T)$ of the contacts, and the changes in the CVC and G_d under the action of 8-millimeter radiation.

The parameters of a contact varied during its formation owing, as a rule, to the variation of the pressure between the S and N electrodes (the wire and the tar-

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get); the resistance of the contact in the normal state ($R_N = I/G_N$) could vary within fairly broad limits—from several kΩ down to hundredths of an ohm. The structure of the CVC and the $G_N(V, T)$ dependence also changed appreciably in the process; typical CVC of several contacts with significantly different R_N values because of the different conditions under which the wires are pressed to the targets are shown in Fig. 1. As the pressure is increased, there usually occurs a transition from contacts with CVC of the type (1) to contacts with CVC of the type 3 (the curves *1*–*3*, respectively, in Fig. 1). It can be seen that the high-resistance contacts have the CVC (1), with a shape typical of normal *S-I-N* tunnel junctions (*I* is an insulator),[1)] while the relatively low-resistance contacts with the CVC (3) possess "quasi-Josephson" properties: in particular, when irradiated by a microwave signal, their CVC exhibit the well-known current steps, which, however, have a constant slope equal to the magnitude of dV/dI in the low-voltage region, and most probably determined by the resistance of the series-connected *N* region.

Of definite interest is the study of contacts with CVC of the type (2), usually obtained after the formation of high-resistance *S-I-N* tunnel junctions as a result of some increase in the pressure between the *S* and *N* electrodes. In such contacts, the Josephson effect does not occur, the temperature dependence of the quantity $G_d(V \to 0) = G_d^0$ (for greater details, see Figs. 2–4 below) differs significantly from the analogous G_d^0 dependence of *S-I-N* junctions, and, moreover, the presence of an excess current (Fig. 1) allows us to suppose that in this case a direct metallic microshort between the *S* and *N* electrodes obtains in the pressure region.[2)]

Knowing the quantity R_N, we can estimate for the contacts with direct conductivity the dimensions of the microshort. Contacts with CVC of the type (2) form probably as a result of the "cracking" of the oxide layers on the surfaces of the electrodes as the pressure increases in the constriction region of *S-I-N* junctions and the formation, as a result, of a metallic microshort (i.e., of a conducting channel[9]). The length of the microshort is then determined by the thickness of the oxide layer, and is, under the conditions of our experiment, ~100 Å (see Ref. 7).

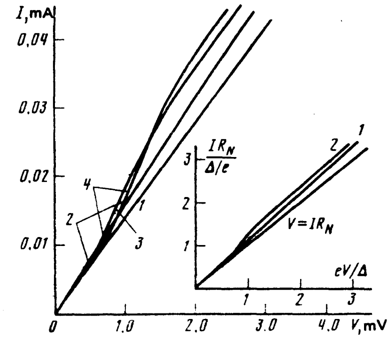

FIG. 2. Current-voltage characteristics of a Nb-Cu contact with $R_N = 72\ \Omega$ for different T/T_c values: *1*) 1.05; *2*) 0.783; *3*) 0.456; *4*) 0.256. The inset shows the CVC computed in Ref. 5 for $T \lesssim T_c$ (*1*) and $T \ll T_c$ (*2*).

In the case of the high-resistance contacts with a conducting channel, the transverse dimension of the microshort can be significantly smaller than the electron mean free path in the bulk electrodes[10]; the electron mean free path in the weak-coupling region then turns out to be of the order of *a* if $a \lesssim L$ [the latter condition holds for niobium contacts with $R_N \approx 50$–$100\ \Omega$ (Ref. 13)]. Under these conditions the formula[10,11]

$$R_N \approx \frac{\rho l}{a^2}\left(1 + \frac{a}{l}\right), \tag{2}$$

where ρ is the resistivity and l is the mean free path, can be used to estimate the order of magnitude of *a*. Normally, for niobium, $\rho l \approx 10^{-11}\ \Omega\text{-cm}^2$ (Ref. 12), and $a \approx 40$ Å for $R_N \approx 100\ \Omega$. This R_N value is characteristic of the contacts investigated in our experiment.

Thus, the condition (1) is fulfilled for such contacts, at least in the region of temperatures not too different from T_c. Below we present and discuss the experimental data obtained precisely for contacts with CVC of the type depicted by the curve *2* in Fig. 1, the fulfillment of the condition (1) allowing us to carry out a suf-

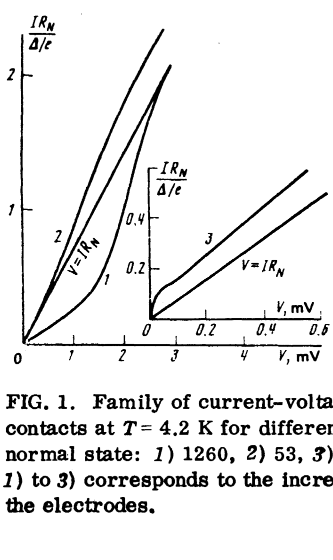

FIG. 1. Family of current-voltage characteristics of Nb-Cu contacts at $T = 4.2$ K for different contact resistances in the normal state: *1*) 1260, *2*) 53, *3*) 5.0 Ω. The transition from *1*) to *3*) corresponds to the increase of the pressure between the electrodes.

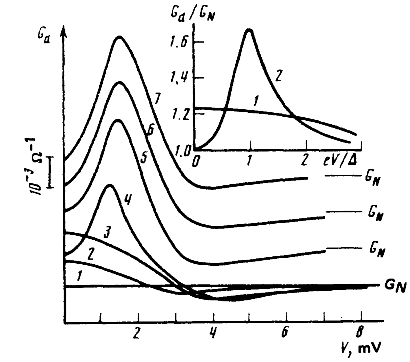

FIG. 3. The $G_d(V)$ dependence for a Nb-Cu contact with $R_N = 72\ \Omega$ for different T/T_c values: *1*) 1.06; *2*) 0.94; *3*) 0.81; *4*) 0.61; *5*) 0.456; *6*) 0.39; *7*) 0.347. The curves *5*)–*7*) have been shifted upward relative to the first curves. The inset shows the conductivity functions of the S-N microshort, computed in Ref. 5 for $T \gtrsim T_c$ (*1*) and $T \ll T_c$ (*2*).

ficiently correct quantitative comparison of the experimental data with theory.[5]

THE EXPERIMENTAL DATA AND THEIR DISCUSSION

1. In Figs. 2 and 3 we show typical CVC and characteristic $G_d(V)$ dependences for one of the considered Nb–Cu contacts with $R_N \approx 72\ \Omega$ at different temperatures. At a temperature higher than T_c the CVC of the contact is, at least for not too high bias current and bias field values, linear [i.e., $G_d(V) = \text{const} = G_N$]. When the temperature is lowered ($T \lesssim T_c$), there arises in the region of small I and V a characteristic CVC region with differential conductivity $G_d > G_N$, with the quantity G_d monotonically decreasing and approaching G_N as V increases; at a voltage $V > \Delta/e$ the CVC exhibits a strongly pronounced section with excess current δI. When the temperature is lowered further (usually at $T \lesssim 0.7\ T_c$), the character of the CVC and the dependence $G_d(V)$ changes: the quantity G_d^0 begins to decrease; as the voltage is increased, G_d at first increase, attains a maximum, and then decreases to a value $\approx G_N$. The position of this maximum corresponds to the value $V_{\text{opt}} = \Delta/e$, and shifts toward the region of high voltages, as the temperature is lowered, according to a law close to $\Delta(T)$; the height of the G_d peak itself increases with decreasing temperature. Figure 4 shows a typical temperature dependence of the G_d^0 of Nb-Cu contacts. It can be seen that the lowering of the temperature first leads to an increase and then to a decrease of G_d^0. The maximum value $(G_d^0)_{\max}$ normally corresponds to the temperature $T \approx (0.7-0.8)\Delta/k$.

Figure 5 shows the V dependence of the excess current measured at two different temperatures. As follows from these graphs, the maximum value $(\delta I)_{\max}$ of the excess current is attained in the region of $V \approx (3-4)\Delta/e$; as the voltage is further increased, the quantity δI decreases slowly.

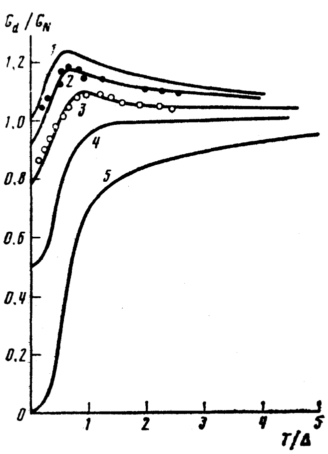

FIG. 4. The temperature dependence of the G_d^0/G_N of Nb-Cu contacts (the measurement data are indicated by the circles) with $R_N = 127\Omega$ (•); 201Ω (○). The continuous curves are plots of the theoretical G_d^0/G_N functions computed for different relations between G_{NT} and G_{NM}: 1) $G_{NT} = 0$; 2) $G_{NT} = 0.1G_{NM}$; 3) $G_{NT} = 0.3G_{NM}$; 4) $G_{NT} = G_{NM}$; 5) $G_{NM} = 0$.

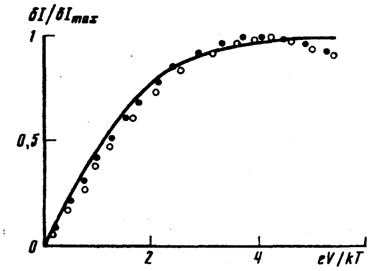

FIG. 5. The bias-voltage dependence of the excess current of a Nb-Cu contact with $R_N = 127\Omega$. The continuous curve is a plot of the theoretical $\delta I/\delta I_{\max}$ function, (4), for $T/T_c = 0.83$ (•) and 0.76 (○).

2. The above-described temperature evolution of the CVC and the quantity $G_d(V, T)$ has features that distinguish these dependences from the corresponding dependences for the related—by kind and geometry—weakly coupled S-I-N and S-c-S structures. For example, in the S-I-N tunnel junctions, as the temperature is lowered from T_c to the lowest possible value, the quantity G_d^0 monotonically decreases; in S-c-S contacts, in the entire range $T < T_c$, $(G_d)^{-1} = 0$ for $V \to 0$, and there occur in the regions $V = 2\Delta/ne$ ($n = 1, 2, 3, \ldots$) maxima[17] that are probably due to the breakup of the Cooper pairs as a result of the absorption of the Josephson self-radiation.

The nature of the variation of the CVC and $G_d(V, T)$ with temperature corresponds with the results of the microscopic theory of S-c-N contacts. The insets in Figs. 2 and 3 and Fig. 4 show the CVC and the field and temperature dependences of the conductivity computed in Ref. 5 for an S-N microshort. Evidently, the results of the theory are in good agreement with the experiment; the theory predicts the experimentally observed excess-current effect and the peak in the temperature dependence of G_d^0; the gap singularity in the $G_d(V)$ dependence does not manifest itself clearly if the temperature is close to T_c.

The existence of the temperature peak in G_d^0 is explained by the presence in the S-N microshort, besides the well-known mechanism of charge transfer by quasiparticles with energy $|E| > \Delta$, of a second conductivity mechanism resulting from charge transfer by quasiparticles with energy $|E| < \Delta$, which are transformed into Cooper pairs in the S region. The presence of a gap in the S region does not impede the transfer of charge by quasiparticles with energy $|E| < \Delta$, just as in Andreev scattering. The appearance below T_c of a second mechanism leads to growth of the total conductivity of the contact; as the temperature is lowered further the conductivity due to the first mechanism decreases as a result of the decrease of the number of quasiparticles with energy $|E| > \Delta$, whereas the conductivity due to the second mechanism tends to a constant value, determined by the number of quasiparticles in the interval $|E| < 2\Delta(T)$, and becomes dominant. This circumstance causes a decrease in conductivity at temperatures appreciably lower than T_c; the difference in the properties of S-c-N contacts and S-I-N tunnel junctions is accounted for precisely by the existence of the second mechanism. The theoretical temperature dependence of the conductivity of a S-N microshort obtained under the condition (1) in Ref. 5 is shown in Fig. 4 by the continuous curve *1*.

A more detailed quantitative comparison of the experimental data with the theory has revealed that, as a rule, the experimental value for $(G_d^0)_{max}$ is somewhat smaller than the theoretical value given in Ref. 5, and that the maximum itself is realized at a higher temperature (this can be seen from Fig. 4); the quantity G_d^0 $(T \ll T_c)$ is not equal to G_N (as follows from the theory), but is slightly less. This discrepancy can be explained by assuming that, besides the conductivity G_{dM} of the metallic S-N microshort, the conductivity G_{dT} due to the tunneling of quasiparticles through the part of the oxide layer remaining in the weak-coupling region (after the formation of the microshort) makes a definite contribution to the total conductivity G_d of the S-c-N contact,[2] i.e., that

$$G_d = G_{dM} + G_{dT}; \qquad (3)$$

$G_N = G_{NM} + G_{NT}$, where G_{NM} and G_{NT} are respectively the conductivity of the microshort and the conductivity due to the tunneling of carriers through the oxide layer at $T > T_c$. The theoretical temperature dependence of $G_{dT}^0 = G_{dT}(V \to 0)$ is quite well known (see for example, Ref. 8), and is depicted in Fig. 4 by the continuous curve *5*.

It is not difficult to see that the addition of G_{dT}^0 should make the quantity $(G_d^0)_{max}/G_N$ smaller than the value obtained by Artemenko, Volkov, and Zaĭtsev for the S-N microshort,[5] and shift $(G_d^0)_{max}$ toward the high-temperature region. Naturally, this shift will be greater the more ponderable the contribution made by the quasiparticle tunneling to the total conductivity and the more feebly the peak in the dependence $G_d^0(T)$ manifests itself [this is illustrated by the $G_d^0(T)/G_N$ dependences computed according to (2) for different ratios of G_{NT} and G_{NM} and shown in Fig. 4]. It can be seen that the experimental $G_d^0(T)/G_N$ dependence shown in Fig. 4 agrees better with the computed dependence for $G_{NT} \approx 0.1\ G_{NM}$ for the contact with $R_N = 127\ \Omega$ and $G_{NT} \approx 0.3\ G_{NM}$ for the contact with $R_N = 201\ \Omega$. Thus, a comparison of the theoretical and experimental $G_d^0(T)$ dependences allows us to determine at least approximately the contributions of the conductivities G_{dT} and G_{dM}. This result is especially interesting, since these estimates can be made for clamped point contacts, i.e., for microstructures whose electrical and geometric parameters cannot be sufficiently accurately determined and controlled. It should, however, be emphasized that the expression (3) can be used to make approximate estimates for a contact with parameters that can vary only in a fairly narrow interval and arise only upon formation of a narrow conducting channel in the insulating layer. The simple subdivision of G_d into a "tunnel" component and a "metallic" component is not justified at a higher pressure on the electrodes, because of significant changes produced in the electrical properties of the material of the electrode itself in the pressure region by the presence of surface inhomogeneities, strains, and impurities (especially of oxygen in the case of niobium or tantalum).

In the presence of a constant electric field with a characteristic scale $V = \Delta/e$, the most interesting qualitative difference between S-c-N and S-I-N contacts manifests itself in the region $V > \Delta/e$. Indeed, both the AVZ model and the well-known theoretical model of S-I-N contacts[8] predict (in accord with experiment) the occurrence in $G_d(V)$ at $V \simeq \Delta/2$ of a peak whose height in both cases increases with decreasing temperature and shifts toward higher voltages like $\Delta(T)$. Another situation arises in the contacts investigated by us at $V > \Delta/e$, where the excess current effect is observed: as has already been noted above, this effect can exist only in the presence of direct microshort between the S and N electrodes. It is of interest to carry out in this region of V a quantitative comparison of the experimental data with the AVZ theory.

Figure 5 shows along with the experimental data the V dependence of the excess current computed in accordance with the AVZ theory[5]:

$$\frac{\delta I}{\delta I_{max}} = \operatorname{th}\frac{eV}{2kT}; \quad \delta I_{max} = G_{NM}\left(\frac{\Delta}{2e}\right)\left(\frac{\pi^2}{4} - 1\right). \qquad (4)$$

The expression (4) is strictly valid at $V > \Delta/e$. As can be seen from the figure, the character of this dependence agrees fairly well with experiment, at least in the region $V \lesssim 4\Delta/e$. For a quantitative comparison with the theory, G_{NM} was estimated from the temperature dependence of G_d^0 [see Fig. 4 and the expression (3)]. Normally, the computed δI_{max} exceeded the measured value some what (by ~20%). For example, for the already discussed contact with $R_N \approx 201\ \Omega$, the measured (at $T/T_c \approx 0.76$) $\delta I_{max} \approx 2.8\ \mu A$, while the computed value is $3.45\ \mu A$. The discrepancy between the measured and computed values of δI_{max} is probably explained by the heating, neglected in the AVZ theory,[5] of the contact by the constant electric field. The increase observed in this discrepancy for a number of contacts as the temperature is lowered is probably due to the fact that the condition (1) for L may not be fulfilled at $T \ll T_c$ (Ref. 13). The violation of this condition may also explain a certain difference between the experimental values of $G_d^0(T)$ and the theoretical values computed with allowance for G_{NT} at $T \lesssim 0.6\ T_c$ (Fig. 4). In the region $T \gtrsim 0.6\ T_c$ the temperature dependence of δI_{max} turns out, as noted in Ref. 6, to be close to $\Delta(T)$.

The slow decrease of the excess current observed at $V \gtrsim 4\Delta/e$ may also be explained by the heating in the weak-coupling region. According to estimates obtained from a comparison of the field and temperature dependences of the excess current, the increase in the temperature of the Nb-Cu microshort at $T \approx 8$ K and $V \gtrsim 5$ mV attains a value $\gtrsim 0.5$ K. This value agrees with the estimates obtained by the method of Tinkham *et al.*[14] for the overheating of the contact by the electric field.

The excess-current effect observed in S-c-S point contacts and thin-film bridges[15] have been related by a number of authors, directly to the existence of a nonstationary Josephson effect (see, for example, Ref. 16).

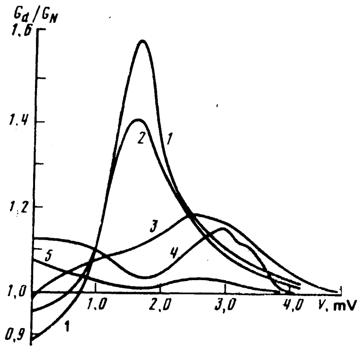

FIG. 6. The dependence $G_d/G_N(V)$ for a Nb—Cu contact with $R_N = 65\ \Omega$ at $T = 2.44$ K for different ($\lambda = 8$ mm) microwave radiation power levels. The transition from 1) to 5) corresponds to the increase of the radiation power (in dB): 1) ∞; 2) 34; 3) 24); 4) 20; 5) 6.

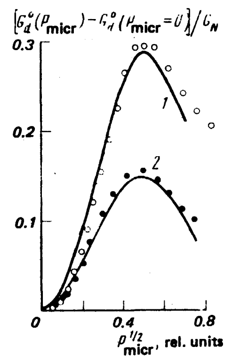

FIG. 7. Dependence of $[G_d^0(P_{micr}) - G_d^0(P_{micr} = 0)]/G_N$ for a Nb-Cu contact with $R_N = 65\Omega$ on the ($\lambda = 8$ mm) microwave radiation power level at $T = 2.44$ K (1, ○) and $T = 4.2$ K (2, •). The continuous curves are plots of the theoretical functions computed by the AVZ method[5]; the circles indicate the experimental data.

But the Josephson effect does not occur in the S-c-S contacts investigated by us, so that at least in this case the excess current is due to the transfer of electric charge by quasiparticles with $|E|<\Delta$ across the S-N interface (Ref. 5).

3. The presence of microwave radiation alters the character of the dependence $G_d(V)$ for S-c-N contacts, this change being especially significant at temperatures appreciably lower than the critical temperature. Figure 6 shows a typical family of $G_d(V)$ dependences measured for different 8-mm radiation power levels at $T = 2.44$ K. Besides the general tendency of G_d to approach the quantity G_N, the increase of the microwave-radiation power leads to the appearance of specific anomalies in the $G_d(V)$ curves. First, the action of relatively weak radiation leads to the increase of G_d^0 (Fig. 7 shows plots of G_d^0 for the same contact as a function of the radiation power P_{micr}). Secondly, the maximum of G_d in the region $V = \Delta/e$ is replaced by a minimum.

The effect whereby the G_d^0 of S-c-N contacts increases at low temperatures in weak microwave fields has been observed before.[2]

The increase of G_d^0 in a microwave field at $T \ll T_c$ (i.e., in the temperature region where the second conductivity mechanism predominates) can be explained as follows. The action of weak radiation with frequency $\omega \ll \Delta/\hbar$ (this condition is fulfilled for $\lambda = 8$ mm at $T/T_c < 0.9$) leads to the "spreading" in the N region of the quasiparticles with energy E_F over the energy interval $E_F - \hbar\omega \lesssim E \lesssim E_F + \hbar\omega$, and the increase of the number of quasiparticles with energies $E_F \pm \hbar\omega$ (E_F is the Fermi energy). Since the density of states in the S region increases rapidly with distance from E_F toward the limits $E_F \pm \hbar\omega$, the growth of the number of quasiparticles with energies $E_F \pm \hbar\omega$ in the N region leads to the increase of the probability for charge transfer across the S-N interface and, consequently, of the conductivity of the contact. This effect is, to some extent, similar to the increase of the temperature (at least for the quasiparticles in the N region); therefore, the $G_d^0(P_{micr})$ and $G_d^0(T)$ dependences are similar for small values of P_{micr}. As the radiation power is increased, the many-photon absorption processes begin to play a greater and greater role, and the number of quasiparticles with energies $E^* \gg E_F + \Delta$ and $E^{**} \ll E_F - \Delta$ increases; but owing to the smallness of the corresponding value of the density of states in the S region, these quasiparticles make a smaller contribution to the conductivity of the contact. This circumstance is the cause of the peak in the dependence $G_d^0(P_{micr})$ and, upon further increase of the radiation power, the decrease of the quantity G_d^0. Figure 7 shows the results of the computation of the dependence $G_d^0(P_{micr})$ with the aid of the AVZ method.[5] The decrease of $G_d^0(P_{micr})$ to the value G_N with increasing P_{micr} is also facilitated by the normal warming up of the contact in the microwave field.

The appearance at $T \ll T_c$ of a minimum in G_d in the region $V \approx \Delta/e$ under the action of a microwave field can be explained in similar fashion. In the absence of radiation, the conductivity of the contact due to the second mechanism of charge transfer has its maximum value at $V = \Delta/e$, since the energy distribution of the quasiparticles is such that to the largest number of quasiparticles in the N region (with energy $E_F + \Delta$) corresponds the maximum density of states in the S region. The action of the microwave field causes the "spreading" of these quasiparticles in the energy range $E_F + \Delta \pm \hbar\omega$ and, consequently, the decrease of the quantity G_d ($V = \Delta/e$) relative to the conductivity measured at $V \lesssim \Delta/e$. Further increase of the power leads to the suppression of the second conductivity mechanism (as a result of the many-photon absorption processes) and the heating of the contact and its transformation into the normal state.

Thus, there are observed in the case of S-c-N contacts singularities in the CVC and the temperature dependence of the conductivity measured for $V \to 0$; the existence of these singularities agrees with the results of the microscopic theory,[5] and is due to the existence of two conductivity mechanisms in the metallic microshort. The excess-current effect observed in S-c-N contacts and its dependence on the temperature and the electric field are explained by the possibility of the transfer of electric charge across the S-N interface by quasiparticles with energy $|E| < \Delta$ (with transformation in the S region into Cooper pairs). The results of the $G_d^0(T)$ measurements can be used to roughly estimate the contribution made to the contact's total conductivity by the conductivity due to the tunneling of quasiparticles through the oxide layer and the direct conductivity of the microshort. The anomalies in the behavior of S-c-N contacts in a microwave field (the increase of G_d^0, the appearance of a minimum in G_d in the region of $V \sim \Delta/e$) have been investigated, and possible causes of their appearance are discussed.

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1) Under experimental conditions the oxide film, which is always present on an electrode surface, serves as the insulator.[7]

2) The excess-current effect, which consists in the fact that in some interval of fairly high bias voltages ($V \gtrsim \Delta/e$) the CVC is close in shape to a straight line parallel to the CVC of the contact in the normal state, but shifted relative to this CVC by the amount $\delta I = V/R_N - I$, is well known, and has been thoroughly investigated for S–c–S Josephson contacts with direct conductivity. The presence of an excess current in a S–c–S contact is considered to be a clear indication of the existence of direct microshorting between the superconducting electrodes (as has been shown in a number of theoretical and experimental investigations,[8] this effect does not occur in tunnel structures).

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