Absolute negative resistance of a tunnel contact between superconductors with a nonequilibrium quasiparticle distribution function

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(Submitted 29 October 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 11, 529–532 (10 December 1986)

Experiments reveal that the resistance of a tunnel junction between superconductors goes negative when excess quasiparticles are excited in the electrode having the larger energy gap Δ_1. This effect occurs at bias voltages $|V| \lesssim (\Delta_1 - \Delta_2)/e$, where Δ_1 and Δ_2 are the values of the energy gap in the superconducting electrodes.

The distribution function of quasiparticles in superconducting electrodes, which form a tunnel junction, is not an equilibrium function. This circumstance appreciably affects the current-voltage characteristic of such a junction.[1] Aronov and Spivak[2] have predicted that the production of an excess population of quasiparticles in the electrode with the larger energy gap Δ_1 might cause the resistance of such a tunnel junction to go negative at low bias voltages $|V| \lesssim (\Delta_1 - \Delta_2)/e$. In the present letter we report an experimental observation of this effect.

The test samples are tunnel junctions between aluminum films synthesized by vacuum deposition and oxidized in air for ~ 1 min. A nonequilibrium population of quasiparticles is produced in the electrode with the larger value of Δ by current injection from an auxiliary tunnel junction. This formulation of an experiment for observing an instability in a tunnel junction was proposed by Larkin and Ovchinnikov.[3] The 1-min^2 area of the rectifying junction is determined by the size of the "window" in the SiO layer, 30 Å thick, between the first and second electrodes (Fig. 1). The area of the injection junction is 1 mm^2. Since the critical temperature T_c of aluminum films depends on the extent of their disorder, we obtained the appropriate values of T_c and Δ by choosing the appropriate thickness of the electrodes of the tunnel junction. In the present letter we are reporting data for a system of tunnel junctions formed by films with thicknesses $a_1 = 60$ Å ($T_c = 2.15$ K) and $a_2 = a_3 = 100$ Å ($T_c = 2.0$ K). Above the critical temperature, the resistances of the rectifying and injection junctions are 245 and 1 Ω, respectively. In the experiments we study the change in the shape of the I–V characteristics of the rectifying junction caused by a current flowing through the injection contact. To measure the I–V characteristics, we use the voltage-setting circuit shown in Fig. 1.

In the absence of an injection current, the I–V characteristic of the rectifying junction can be described satisfactorily over the entire temperature range $T \gtrsim 0.4$ by the expression found from the BCS theory (Ref. 4, for example). Figures 1 and 2 show the I–V characteristics of the rectifying junction for several values of the injection current I_i in different scales ($T = 0.47$ K). As I_i is increased, the shape of the I–V

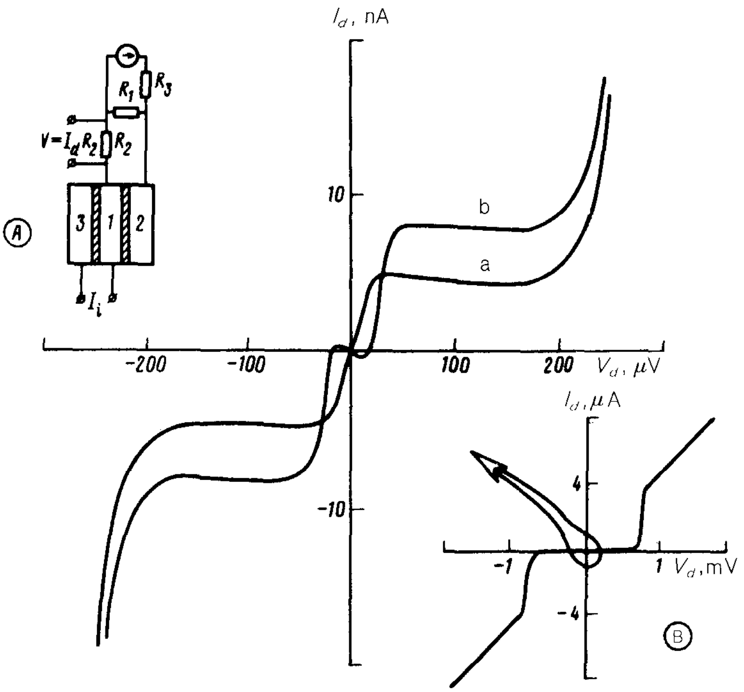

FIG. 1. Current-voltage characteristics of a rectifying junction measured at $T = 0.47$ K. a—In the absence of an injection current; b—at $I_i = 0.136$ mA. Inset A shows the measurement circuit. Inset B shows the I–V characteristic of the rectifying junction at high values of the voltage V_d.

characteristic changes at low bias voltages; at sufficiently high values of I_i, the I–V characteristic acquires a region in which the current through the junction flows in the direction opposite to the applied voltage. This region corresponds to an absolute negative resistance of the junction. The size (Δv_d) of the interval in which the absolute negative resistance is observed depends on the injection current at a fixed temperature, reaching a maximum at a certain I_i (Fig. 2). At the same value of I_i, we find a maximum of $|dI_d/dV_d|_{V_d=0}$, i.e., a maximum of the absolute value of the differential conductivity at $V_d = 0$. The shape of the I–V characteristic does not change when the injection current is reversed.

What conditions are required for observation of this absolute negative resistance? Gray[1] studied the generation of excess quasiparticles by light, i.e., a "wide" source of quasiparticles[5] ($\delta\epsilon \gg \Delta$, where $\delta\epsilon$ is the energy interval in which the distribution function is substantially away from equilibrium). If, as a result of relaxation of the nonequilibrium quasiparticles in the superconductor with the larger gap, a quasiequilibrium distribution is established with the reservoir temperature T and the chemical potential ν, then the condition for the appearance of an absolute negative resistance can be written[1]

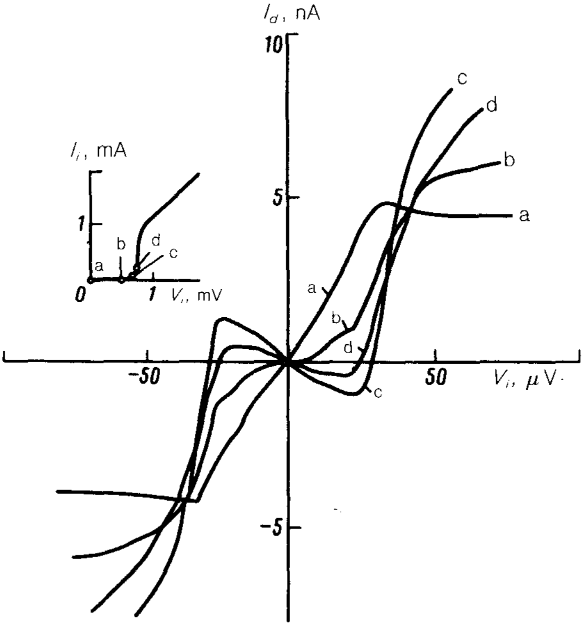

FIG. 2. Current-voltage characteristics of a rectifying junction measured at $T = 0.47$ K. a—$I_i = 0$; b—$I_i = 0.03$ mA; c—$I_i = 0.136$ mA; d—$I_i = 0.227$ mA. The inset shows the I–V characteristic of the injection contact.

$$\exp\left(\frac{\nu}{k_B T}\right) - 1 > \frac{\Delta_1}{k_B T}\left[\frac{\Delta_1^2}{\Delta_2^2} - 1\right] , \tag{1}$$

where $\nu = k_B T \ln[1 + (\delta N_1/N_1)]$, N_1 is the density of equilibrium quasiparticles in the electrode with the large value of Δ, and δN_1 is the excess density of quasiparticles injected into it. If the relation $\Delta_1 - \Delta_2 \ll \Delta_1$ holds, condition (1) can be written

$$\delta N_1 > 2N_1 \ln\frac{N_2}{N_1} . \tag{2}$$

This effect of an absolute negative resistance seems to be insensitive to the particular form of the nonequilibrium distribution function. (In the experimental situation which we are considering here, there is a "narrow" source, and quasiparticles are injected in an energy interval $\delta\epsilon \ll \Delta$; see the inset in Fig. 2.) In discussing the experiment below, we will accordingly focus on the concentration of excess quasiparticles:

$$\delta N_1 = I_i \tau_R / eSa_1 . \tag{3}$$

Here S is the area of the injecting contact, and τ_R is the lifetime of the nonequilibrium quasiparticles in the first electrode. At low temperatures ($T/T_c \ll 1$), the lifetime τ_R is an exponential function of the temperature in the quasiequilibrium case ($\delta N_1 \ll N_1$).

For the "dirty" case in these experiments ($q_T l \ll 1$, where l is the electron mean free path, and q_T is the wave vector of a thermal phonon), the lifetime τ_R can be described by the expression[1] (Ref. 6)

$$\tau_R^{-1}(\Delta, T) = 4\left(\frac{2\Delta}{\pi k_B T_c}\right)^{7/2}\left(\frac{T}{T_c}\right)^{1/2}\exp\left(-\frac{\Delta}{k_B T}\right)\tau_\epsilon^{-1}(T_c), \tag{4}$$

where τ_ϵ (T_c) is the energy relaxation time of the quasiparticles as they interact with phonons in the normal state at[6] $T = T_c$, given by

$$\tau_\epsilon^{-1}(T) = \frac{\pi^4\beta}{5}\,\frac{k_F l}{(k_F u_l)^3}\left(\frac{k_B T}{\hbar}\right)^4\left[1+\frac{3}{2}\left(\frac{u_l}{u_t}\right)^5\right]. \tag{5}$$

The parameter β is ~ 0.7 for aluminum[6], k_F is the Fermi wave vector, and u_l and u_t are propagation velocities of longitudinal and transverse phonons, respectively. [For the first electrode we have $T_c = 2.15$ K, $l = 17$ Å, τ_ϵ (2.15 K)$\approx 5\times 10^{-9}$ s.] In calculating the recombination time we can ignore the "trapping" of the nonequilibrium phonons with energy $\hbar\omega \simeq 2\Delta_1$ which are generated, since the thickness of the films is small in comparison with the mean free path of such phonons. It follows from expressions (2)–(4) that observation of the absolute negative resistance would be facilitated by lowering the temperature and also by reducing the thickness of the common electrode and fabricating it from a metal with larger values of τ_ϵ. The latter requirements are satisfied well by the ultrathin aluminum films used in the present experiments. We must stress that the concentration of nonequilibrium quasiparticles required to achieve the absolute negative resistance is proportional to the quantity[2,3] $(\Delta_1/\Delta_2)^2 - 1$. It was for this reason that we made the difference $(\Delta_1 - \Delta_2)/e$ quite small ($\sim 25\,\mu V$) in the experiments. Experimentally, the absolute negative resistance is observed at temperatures $T \lesssim 0.6$ K. According to calculation from (2)–(5), the region in which the absolute negative resistance is observed at these values of I_i should be broader: up to $T \simeq 0.75$ K. The reason for this discrepancy apparently lies in slight variations of Δ_1 and Δ_2 in the plane of the rectifying contact, which are manifested as a blurring of the structural features on the I–V characteristics at $|V| = (\Delta_1 - \Delta_2)/e$.

An increase in the concentration of nonequilibrium quasiparticles, δN_1, should lead to (first) a decrease in the energy gap Δ_1 and (second) a decrease in the recombination time τ_R. Estimates show that when (only) these two factors are taken into account simultaneously, no limitation on I_i arises. The apparent reason for the experimentally observed disappearance of the absolute negative resistance when the injection current exceeds $I_i \simeq 0.3$ mA is a heating of the sample as a whole by the Joule heat which is evolved in the injecting electrode. [At $T \simeq 0.5$ K the thermal resistance of the interface between the aluminum film and the glass substrate (or liquid ^{3}He) is $\sim 10^3$ cm^2·K/W, and the temperature drop between the sample and the heat sink at $I_i = 1$ mA may exceed ~ 0.1 K.]

Systems of two tunnel junctions of superconductors having one common electrode are widely used to study the nonequilibrium state which is produced in the common electrode by current injection (e.g., Ref. 1). A factor which distinguishes the present experiments from the overwhelming majority of earlier experiments is that in those earlier experiments the common electrode in the structures studied was a superconductor with a smaller value of Δ. In that case, the nonequilibrium phonons with energy $\hbar\omega \simeq 2\Delta$, which are produced in the recombination of the nonequilibrium quasiparticles, cannot break up the Cooper pairs in the second electrode, with the larger value of Δ. In that formulation of the experiment, it is a far more complicated matter to achieve a substantial change in the shape of the I–V characteristic which is unrelated to a heating of the sample. In this connection, the appearance of an absolute negative resistance is one of the clearest manifestations of a deviation from equilibrium in tunnel junctions of superconductors.

We wish to thank A. G. Aronov and B. Z. Spivak for useful discussions, V. N. Bubankov for interest in this study, and N. M. Margolin for assistance in the experiments.

(1) We wish to thank M. Yu Reĭzer and A. V. Sergeev for pointing out that a factor of π^{-6} was erroneously omitted from the expression for $\gamma_R^{-1}(\Delta,T)$ given in Ref. 6.

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Translated by Dave Parsons