Instability of a nonequilibrium state of superconducting niobium films during tunneling injection of quasiparticles

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Experiments show that intense tunneling injection of quasiparticles may be accompanied by an instability of a nonequilibrium state in a niobium film. The threshold current for the instability, I_i, has been found as a function of the bath temperature T_b and of the local temperature near the tunneling contact, T_l.

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There is much interest in superconductors under nonequilibrium conditions, which can be arranged by using various sources to pump quasiparticles into the superconductors.

In this letter we are reporting the first study of superconducting niobium films during intense tunneling injection of quasiparticles. The results show that the homogeneous spatial distribution of the order parameter $\Delta_{\mathrm{Nb}} \neq 0$ becomes unstable when the injection current reaches a certain threshold value I_i if the temperature near the contact, T_l, is lower than T_c, the temperature of the superconducting transition. When the instability occurs, the superconductor converts to a normal or inhomogeneous state.

In order to arrange intense tunneling injection of quasiparticles into the superconducting niobium films, we fabricated Nb–I–Pb tunneling structures with a low tunneling resistivity r_T, $(7\text{–}9) \times 10^{-6}\ \Omega \cdot \mathrm{cm}^2$. The thicknesses of the niobium and lead films were 200 and 500 nm, respectively. The area of the contacts was 1×10^{-4} cm^2. We measured the I-V characteristics of the tunneling contacts and the voltage across the niobium film near the contact.

Figure 1 shows a typical I-V characteristic for these tunneling structures. When the threshold current I_i is reached, a voltage appears abruptly in the niobium film, and the tunneling I-V characteristic of the structure exhibits a sharp voltage decrease. To make sure that the appearance of a voltage across the niobium film was not a consequence of a thermal transition of the film to the normal state, we measured the local temperature T_l near the tunneling contact. For this measurement we developed a pulsed method which enabled us to monitor the thermal relaxation times τ_r of the tunneling structure. These times range from tens to hundreds of microseconds, depending on the temperature difference $\Delta T = T_l - T_b$, where T_b is the bath temperature. The temperature T_l was determined from the voltage $V_\Delta(T)$, where $V_\Delta = (\Delta_{\mathrm{Nb}} + \Delta_{\mathrm{Pb}})/e$, and $2\Delta_{\mathrm{Nb}}$ and $2\Delta_{\mathrm{Pb}}$ are the energy gaps of the niobium and lead films, respectively. The voltage V_Δ was measured 2 μs after the beginning of thermal relaxation. Since $\tau_r \gg 2\ \mu$s, it can be assumed that T_l corresponds quite accurately

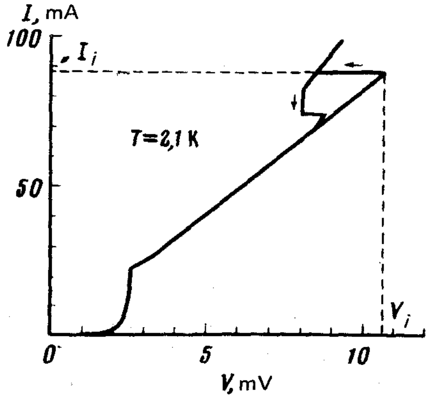

FIG. 1. A typical I-V characteristic of the Nb–I–Pb tunneling contact.

to the actual temperature near the contact as a constant injection current flows across it. As the threshold current for the instability, T_l^i, we used the value of T_l at the injection current $I_0 = I_i - 0.1$ mA. The experiments show that for a film temperature increase satisfying $\Delta T \geqslant 0.5$ K the assumption $T_l \sim I_0$ is quite accurate. We may conclude that T_l^i corresponds within 0.1 K to the temperature of the tunneling structure at the time at which the superconducting film is put in the new state by the instability. The measurements of T_l^i showed that this temperature always remains significantly lower than the critical temperature of the niobium films, $T_c = 9.12$–9.21 K.

We observed a heating of the films, with $T_l = T_b$, only at temperatures above the λ point. At $T_b < T_\lambda$, we observed no changes in the voltage V_Δ. It should be noted, however, that the sensitivity of the pulsed method falls off significantly with decreasing temperature.

The results show that we are not observing a thermal transition of the superconducting films. The appearance of a new state is determined by an instability of a nonequilibrium state of the superconducting films during the intense quasiparticle injection.

The observed effects, which result from an instability of the superconducting state of the niobium film, remain qualitatively the same when the lead film is converted to the normal state by a magnetic field.

We measured the threshold current for the instability, I_i, as a function of the bath temperature T_b and the local temperature T_l. The results are plotted in Fig. 2 in terms of the relative coordinates $i_i = I_i/I_{i\,\max}$ and $t = T/T_c$. The dependence $i_i(t_b)$ is similar to the experimental dependence found by Iguchi[1] for the threshold current (see the inset in Fig. 2). The anomalous temperature dependence in this region has been explained in terms of a diffusion instability of the nonequilibrium superconductor. On the other hand, Elesin[2] has offered a theoretical argument that the diffusion instability does not occur in the case of a broad source. It can be seen that the dependence $i_i(t_l)$ does not exhibit such features, and it can thus be concluded that the anomalous behavior $i_i(t_b)$ is probably a consequence of a warming of the tunneling contact.

Figure 2 also shows the temperature dependence of the critical power in terms of the relative units $\beta_c/\beta_{cT=0}$ from Ref. 3, for the case of laser irradiation of a super-

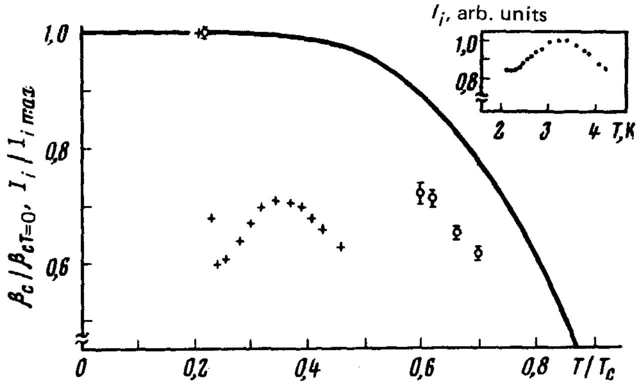

FIG. 2. +–Dependence of the threshold current for the instability on the bath temperature; o–on the local temperature (in relative units); solid curve–temperature dependence of the critical power $\beta_c/\beta_{cT=0}$ from Ref. 3.

conductor. It can be seen that our experimental dependence $i_i(t_l)$ is qualitatively analogous. At temperatures $T > T_\lambda$ the experimental points lie slightly below the theoretical curve of $\beta_c/\beta_{cT=0}$. The discrepancy can be explained on the basis that for our films the reabsorption parameter $\gamma = \tau_{es}/\tau_b$ (Ref. 3) is important; here τ_{es} is the phonon escape time, and τ_b is the phonon reabsorption time. This parameter may have different values at temperatures $T > T_\lambda$ and $T < T_\lambda$, since the escape time is given by[4] $\tau_{es} = 4d/\eta s$, where d is the film thickness and s is the sound velocity; this time depends on the geometric factor η, which incorporates the reflection of recombination phonons from the superconductor–helium interface.

For our experimental conditions we estimate the reabsorption parameter to be $\gamma = 0.94/\eta$. Knowing the threshold current for the instability, I_i, and noting that $d < L$ (L is the quasiparticle diffusion length), we can estimate the concentration of nonequilibrium quasiparticles from the experimental results, using the formula $n_c^u = I_i\tau_R/ev$, where τ_R is the quasiparticle recombination time, and v is the volume of the nonequilibrium superconductor near the contact. Assuming[4] that $\tau_R \approx 10^{-10} s$, we find $n_c^u \approx 10^{17}$ cm^{-3} for $T = 1.9$ K. The reabsorption parameter γ should be taken into account in a determination of the concentration of nonequilibrium quasiparticles (n_c) responsible for the instability of the superconductor. If the expression determining the critical power, which was found in Ref. 3 in the case of laser irradiation, remains valid for finding γ, and noting the possible limits on η, we may suggest that in our case n_c is 10^{18}–10^{19} cm^{-3}, in agreement with theoretical estimates of the critical quasiparticle concentration required for the transition of the superconductor to a new state (a normal state or an inhomogeneous state).

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