Nonequilibrium occupation of quasiparticle states n a superconductor by laser radiation

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It is shown experimentally that the nonequilibrium increment to the quasiparticle distribution function, due to the action of laser radiation on the superconductor, is located in an energy interval on the order of kT above the gap. The effect of "blocking" the states above the gap by the nonequilibrium quasiparticles leads to a decrease of the tunnel current in a narrow voltage interval at $eV \gtrsim 2\Delta$.

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It is known that the absorption of laser radiation in thin superconducting ilms leads to an equilibrium distribution of the quasiiparticles and phonons with respect to energy.[1–3] Usually the characteristics of a nonequilibrium superconductor, measured in experiment (energy gap, dc or microwave resisance[4,5]) depend little on the concrete form of the nonequilibrium distribution function of the quasiparticles and are determined in the main by the total number of excess excitations.[3,6] Parker[6] has shown that almost all the experimental plots are equally well explained by using different model nonequilibrium distribution functions, under the condition that the concentration of the nonequilibrium excitations is low.

It is nontheless obvious that the dependence of the tunnel current on the voltage across a junction illuminated by a radar should reflect the detailed form of the nonequilibrium increment to the quasiparticle distribution function. The present study is an attempt to observe the influence of a nonequilibrium increment to the distribution function on the current-voltage characteristics of superconducting tunnel junctions. In contrast to the preceding studies,[1,7] the measurements were not limited to the voltage interval eV $\lesssim 2\Delta$ (in the case of identical superconductors), but were extended into the region of high voltages eV $> 2\Delta$, where the effect of "blocking" of the states above the gap in the irradiated superconductor, due to the photoexcited equilibrium quasiparticles, was first observed.

Pb—oxide—Pb tunnel junction of area 0.15 mm^2 were irradiated with an He-Ne laser operating at 1.15 μ wavelength. The radiation was fed into the cryostat through a light pipe and focused in the form of a spot of 3.8 mm^2 area sub-

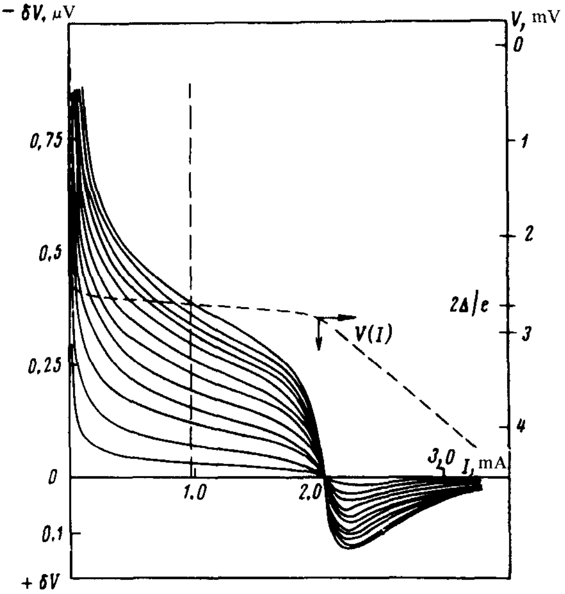

FIG. 1. Dependence of the additional voltage δV produced across the tunnel junction under the influence of laser radiation on the current I, for different radiation power levels (solid curves). The upper curve corresponds to the maximum power $P = 100$ mW/cm^2, and the power for the succeeding curves decreases by equal amounts $P = 8.3$ mW/cm^2. The dashed line shows the current-voltage characteristics of the junction. The junction voltage corresponding to an arbitrary value of the current is determined with the aid of the current-voltage characteristic (thin dashed straight lines). $T = 1.7$ °K.

nding over eight different junctions. The film thickness was 1000 – 2000 Å. he substrate was crystalline quartz or glass. The sample was placed in liquid elium. The laser radiation was chopped at a frequency 420 Hz. The alternatg component δV of the sample voltage was amplified, synchronously detected, nd recorded as a function of the current I through the junction. A family of $V(I)$ curves obtained at different laser radiation powers (maximum specific ower 100 mW/cm^2) is shown in Fig. 1.

The dependence of the increment δI to the tunnel current, due to the laser adiation, on the voltage V is connected with the experimentally-measured $V(I)$ dependence by the relation

$$\delta I\,(V) = -\,\delta V(I\,)\frac{dI}{dV}\ ; \quad I\ = I\,(V)\,, \tag{1}$$

here $I(V)$ is the current voltage characteristic of the tunnel junction, and I/dV, is well known from the literature.[8] The current increment $\delta I(V)$ is ositive at eV $\lesssim 2\Delta$, is equal to zero at a bias barely above threshold, and beomes negative at eV$>2\Delta$.

With increasing radiation power, the gap decreases. The change $\delta\Delta$ of the ap corresponds to δV at the 0.5 level of the current jump (dashed line in Fig. 1). The jump of the current at eV$=2\Delta$ becomes smeared out with respect to voltage. At a per-unit radiation power $P = 65$ mW/cm^2 we have $\delta\Delta(T) = \exp(\Delta/kT)$ at $\Delta/kT \leq 7.5$ and saturation sets in at $\Delta/kV > 7.5$. In the region of low injection velocities, when the number of nonequilibrium excitations δN is much less than the number of quasiparticles in thermal equilibrium ($\Delta/kT < 7.5$), the value of $\delta\Delta(P)$ depends linearly on the power P. At high radiation intensities ($\delta N \gg N_T$) we have $\delta\Delta(P) \sim p^{1/2}$.

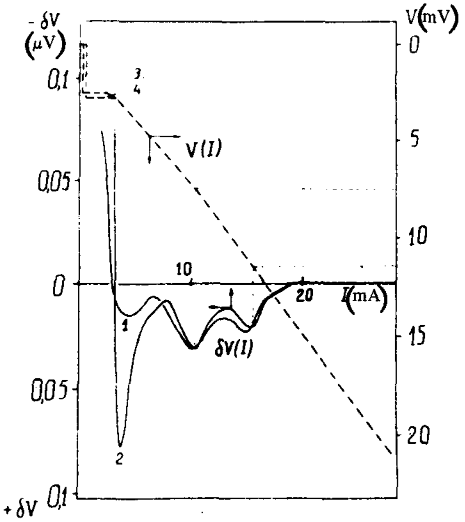

FIG. 2. Plots of $\delta V(I)$ and $V(I)$ at two temperatures: 1, 3—$T = 4.2$ °K, 2, 4—$T = 1.7$ °K. Irradation power 92 mW/cm^2.

Figure 2 shows the changes in the current-voltage characteristic in the region of voltages beyond the gap. In addition to a strongly temperature-depend negative increment of the current, localized directly beyond the threshold, tw smeared-out minima are observed in the region of the phonon singularities of lead, $eV_1=(2\Delta+\hbar\omega_{TA})=7.5$ meV and $eV_2=(2\Delta+\hbar\omega_{LA})=11.6$ meV, corresponding to the maxima of the density of the states of the transverse (TA) and longitudinal (LA) acoustic phonons. As can be seen from Fig. 2, the intensity of these minima does not depend on the temperature.

The changes observed by us in current-voltage characteristic of the tunnel junction exposed to laser radiation can be explained in the following manner. The laser radiation is a source of not only nonequilibrium quasiparticles, but also of nonequilibrium phonons produced in the course of energy relaxation of the quasiparticles and capable in turn of producing quasiparticle excitations ir the superconductor. The phonons, obviously can easily overcome the thin dielectric layer between the superconducting films and produce quasiparticle excitations in both films of the tunnel junction. The increase of the population of the quasiparticle states on both sides of the barrier is apparently equivalen to a certain effective heating[6] of the junction as a whole and should lead to small positive increment to the current at $eV>2\Delta$ in a wide range of voltages, as is the case in contacts between like superconductors as the temperature is increased. In addition, the presence of pure laser injection of quasiparticles adds to the disequilibrium of the distribution function of the quasiparticles in this electrode. According to[2], if $\delta N \ll N_T$ the bulk of this increment is concer trated at the edge of the gap in an interval $\sim kT$, and is given by

$$\delta f \sim \exp[-(E-\Delta)/kT]. \qquad ($$

Figure 2 confirms the localization of the main part of the nonequilibrium increment to the distribution function in an interval of several times kT over the gap in the entire temperature interval from 4.2 °K ($\delta N \ll N_T$) to 1.7 °K ($\delta N \gg N$) At a bias $eV \gtrsim 2\Delta$, a fraction of the states near the edge of the gap turns out to be occupied by nonequilibrium excitations ("blocking of the states") and consequently the tunnel current decreases in a narrow region on the order of kT immediately beyond the threshold. As expected, the half-width of the minimum o the current decreases with decreasing temperature, and its depth increases exponentially, provided that $\delta N \ll N_T$.

The experimentally observed phonon singularities (Fig. 2), which have the same order of magnitude as the first minimum, can apparently not be connected with the nonequilibrium occupation, since the lifetimes of the quasiparticles in the corresponding states are smaller by several orders of magnitude than the recombination time. The cause of the phonon peaks is more readily a cert smoothing of the singularities in the energy dependence of the density of the states of the quasiparticles, which leads to a corresponding smoothing of the current-voltage characteristic. Thus, laser irradiation not only leads to a nonequilibrium population of the quasiparticle states, but acting in analogy with other strong Cooper pair-breaking mechanisms (for example, magnetic impurities), it changes the dependence of the state density on the energy.

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