

Heating of quasiparticles in a superconducting film in the resistive state

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The effect of electromagnetic radiation on a superconducting film in the resistive state has been observed. The measurements in a broad range of frequencies corresponding to the energy gap indicate that this effect is due to the heating of quasiparticles.

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The effects in a homogeneous superconductor produced as a result of variation of the distribution function of quasiparticles due to the influence of radiation have been investigated theoretically and experimentally.¹ The effect of heating of electrons in a normal metal on its transition to the superconducting state has also been analyzed.² The influence of radiation on the resistive (i.e., inhomogeneous) state of a superconductor, which is realized in the presence of vortices³ and centers of phase slippage⁴ and phase separation induced by excess quasiparticles,⁵ has been studied much less extensively.

We have detected a new effect of electromagnetic radiation on a superconductor in the resistive state.

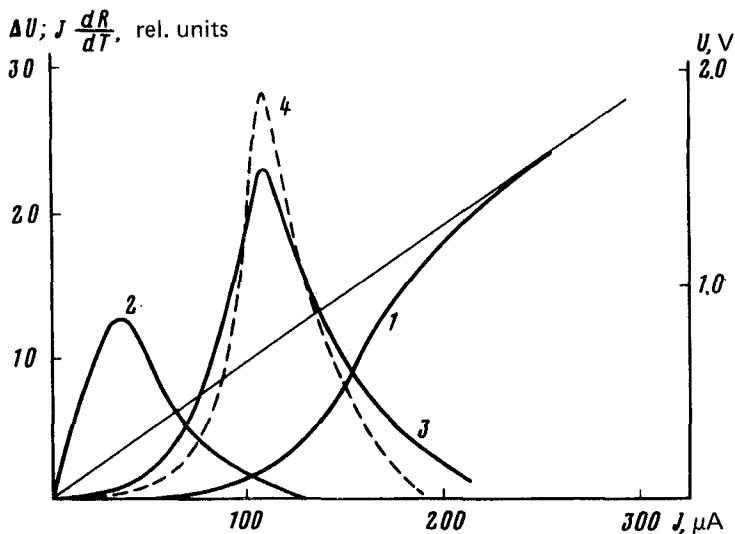


FIG. 1. Volt-ampere characteristic of the sample and $\Delta U(J)$ and $JdR/dT(J)$ dependences at $T = 0.3 T_c$ and $H = 0.8 H_{k2}(T)$. 1—volt-ampere characteristic, 2— ΔU for $\nu = 2 \times 10^8$ Hz, 3— ΔU for $\nu = 3 \times 10^{11}$ Hz, 4— JdR/dT .

In the experiment we used niobium films of thickness $d = 100 \text{ \AA}$, width $W = 1 - 10 \text{ }\mu\text{m}$, and length $L \geq 5 \text{ mm}$, which were deposited on sapphire or silicon substrates by rf sputtering; the geometry of the samples was formed by means of photolithography. The measurements were performed in the millimeter and submillimeter ranges of wavelengths ($\lambda = 0.25 - 8 \text{ mm}$) using rf-amplitude-modulated generators—backward-wave tubes (BWT)—capable of being tuned smoothly in a broad range of frequencies ν . The modulation frequency f of 10^9 Hz was reached by varying the anode resistance of the BWT and by heating the radiation intensity of two BWT, whose generation frequency was shifted.⁶ Specific measurements were also performed at longer wavelengths ($\lambda > 3 \text{ cm}$) using klystrons.

Figure 1 shows the volt ampere characteristic (VAC) of niobium film, as well as the variation in resistance of the sample induced by radiation ΔU for two radiation frequencies of the current J . The films had smooth VAC in the temperature range $0.8 \leq T/T_c \leq 1$ (T_c is the critical temperature), as well as in a sufficiently strong magnetic field H at any temperature; at $T \leq 0.8 T_c$ a vertical section of the VAC and a critical-current hysteresis appeared in the absence of a field. Note that the relation $W < \delta_{\perp}(T)$, where δ_{\perp} is the effective penetration depth of the magnetic field, was satisfied for the films under investigation in the entire temperature range, and the unpairing currents were produced near T_c .⁷ The broad resistive section of the VAC, which will be analyzed below, is apparently connected with the microscopic "phase" separation—the centers of phase slippage (CPS).⁴ It can be seen in Fig. 1 that the maximum ΔU at $\nu \geq 10^{10}$ Hz corresponds to the maximum of the $JdR/dT(J)$ dependence, and that it shifts in the direction of lower values of J with decreasing frequency ($\nu < 10^{10}$ Hz).

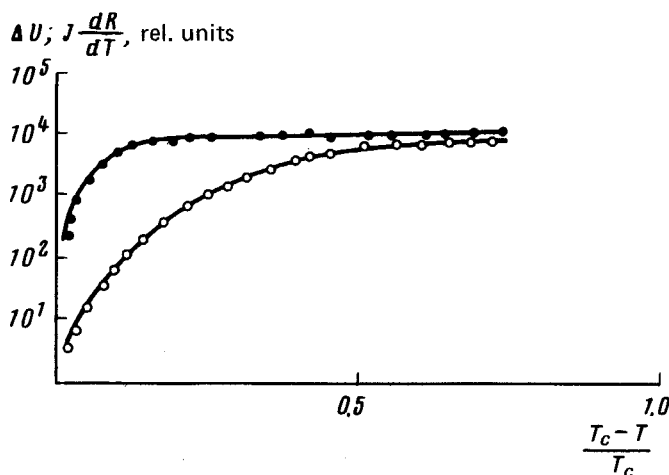


FIG. 2. Temperature dependences of $\Delta U(\circ)$ and $JdR/dT(\bullet)$.

The typical temperature dependence ΔU in Fig. 2 corresponds to the absolute maximum of a double parametric dependence $\Delta U(J, H)$ for a fixed radiation power. This effect is almost independent of ν but varies strongly with T . The $JdR/dT(T)$ dependence in Fig. 2 was determined for the same values of J and H as $\Delta U(T)$.

The measurements of the time constant of the effect of radiation on the film resistance, i.e., the dependence of ΔU on f for any fixed J , H , T , and ν , show that the value of ΔU remains the same to $f \approx 2 \times 10^8$ Hz; the time constant $\tau = 8 \times 10^{-10}$ sec corresponds to a decay at higher frequencies.

The results show that the observed effect of radiation on the superconducting film does not reduce to the effects observed previously. In fact, the bolometric effect (produced as a result of variation of the temperature of the crystal lattice), which was estimated from the measurements of the thermal resistance at the boundaries between the film, the substrate, and liquid helium, gives values of ΔU three to four orders of magnitude smaller than those observed at $T = 1.5\text{--}3$ K. In addition, the temperature dependence ΔU differs dramatically from the $JdR/dT(T)$ dependence (Fig. 2), although these dependences must be in agreement with each other for the bolometric effect. It should be noted that a bolometric effect, whose characteristics completely correspond to the data in the literature,⁸ can be observed in the films with $d = 300\text{--}500$ Å, in addition to the weakened effect under investigation. The appearance of the effect in the temperature region near T_c , where a homogeneous unpairing is realized, shows that the effect is not attributable to the energy dissipation due to the motion of vortices. The nonselectivity of the effect—in particular, the absence of systematic features in the gap—indicates that the effect under investigation cannot be accounted for by the breaking of pairs by radiation and cannot be attributed to the nonlinear I-V characteristics.

The observed effect apparently can be explained by the heating of quasiparticle radiation in the superconducting film in the resistive state. The typical times ob-

tained and the frequency nonselectivity are further evidence of the validity of this explanation. The time constant τ is in good agreement with the estimate of the cooling time of the electron subsystem in the normal regions and with the estimate of the quasi-particle subsystem in the superconducting regions.⁹ In addition, the energy relaxation time τ_e characteristic of a superconductor corresponds to the frequency $\nu \approx 10^{10}$ Hz, at which the maximum of $\Delta U(J)$ corresponds to that of $JdR/dT(J)$ (Fig. 1).¹⁰ However, the complex processes occurring in the resistive state of a superconductor so far have made it impossible to describe the observed effects in detail.

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