Nonselective effect of electromagnetic radiation on a superconducting film in the resistive state

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The quasiparticle-heating effect of electromagnetic radiation on a niobium superconducting film in the resistive state is nonselective over a broad frequency range, from 10^{10} to 10^{15} Hz. The role played by electron-electron collisions in shaping the nonequilibrium quasiparticle distribution function is discussed.

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Of the known mechanisms by which electromagnetic radiation affects a superconductor in the resistive state, only the bolometric effect is independent of the frequency. We have previously[1] reported a new effect of radiation on a niobium superconducting film with a small cross section (with a width $W = 1$–$10\ \mu$m and a thickness $d = 100$ Å) which has been put in the resistive state by an external magnetic field H and a transport current I. A study of the effect, seen as an increase in the resistance caused by the electromagnetic radiation, shows that it is independent of the frequency near the equilibrium energy gap and has a short rise time (the time constant is $\tau = 1$ ns). The effect was said to result from a heating of quasiparticles by the radiation.

In this letter we report a study of the effect over a much broader frequency range. We show that the effect is nonselective and that its rise time remains constant from the rf range to the ultraviolet. We report several aspects of the effect which prove that it is not a bolometric effect. The results show that electron-electron collisions play a significant role in shaping the quasiparticle distribution under these experimental conditions.

Measurements over a broad spectral range require a combination of optical and rf methods. We used centimeter- and millimeter-range klystrons; millimeter- and submillimeter-range backward-wave tubes; infrared, visible-range, and ultraviolet monochromators and lasers; and a blackbody with a set of filters. The radiation power was measured with radiometers; an independent calibration was carried out with the blackbody. The rise time of the effect was determined in both the microwave and optical ranges. In the former case we used a modulation of the power supply of the backward-wave tube or intensity beats of the output from two backward-wave tubes with a frequency difference[2] $f = 10^5$–10^9 Hz; in the latter case we used a pulsed nanosecond nitrogen laser ($\lambda = 0.337\ \mu$m).

Figure 1 shows data on the change in the voltage across the sample, ΔU, caused by electromagnetic radiation of frequency ν in the current-source regime for a niobium film on a sapphire substrate at $T = 2$ K, $H = 20$ kOe, and $I = 30\ \mu$A (the critical temperature for the sample is $T_c = 6.2$ K, $d = 120$ Å, $W = 2.5\ \mu$m). The power level (P) of the radiation incident on the film is held constant. Interestingly, ΔU remains

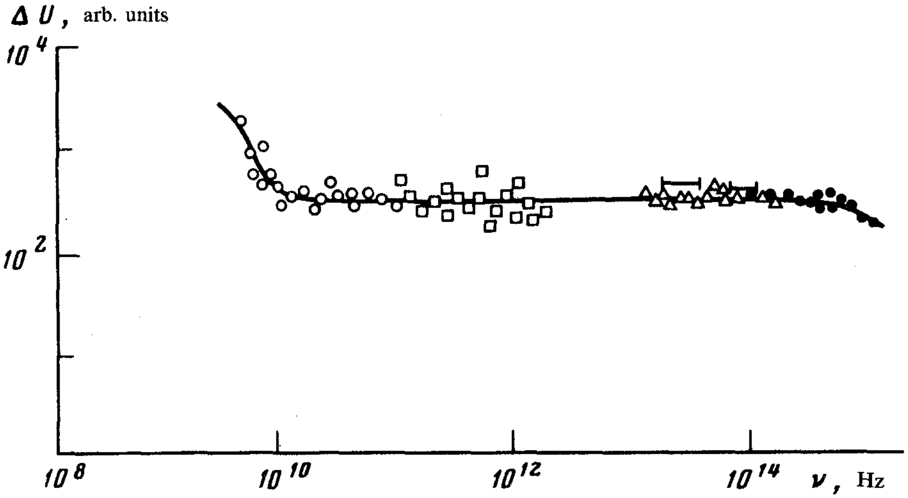

FIG. 1. The dependence $\Delta U(\nu)$ with $P=$ const. ○—Klystron oscillators; □—backward-wave tubes; △—blackbody with filters; ⊢⊣—blackbody (integrated); ●—monochromators with a globar and a mercury vapor lamp.

constant over a very broad frequency range, $\nu = 10^{10}$–10^{15} Hz. Curve 1 in Fig. 2 shows the dependence of ΔU on the modulation frequency f of radiation at the wavelength $\lambda = 1$ mm at $T=5$ K. We see that ΔU remains constant up to $f=2\times 10^8$ Hz; the decay at the higher frequencies corresponds to $\tau = 8\times 10^{-10}$ s. This value remains the

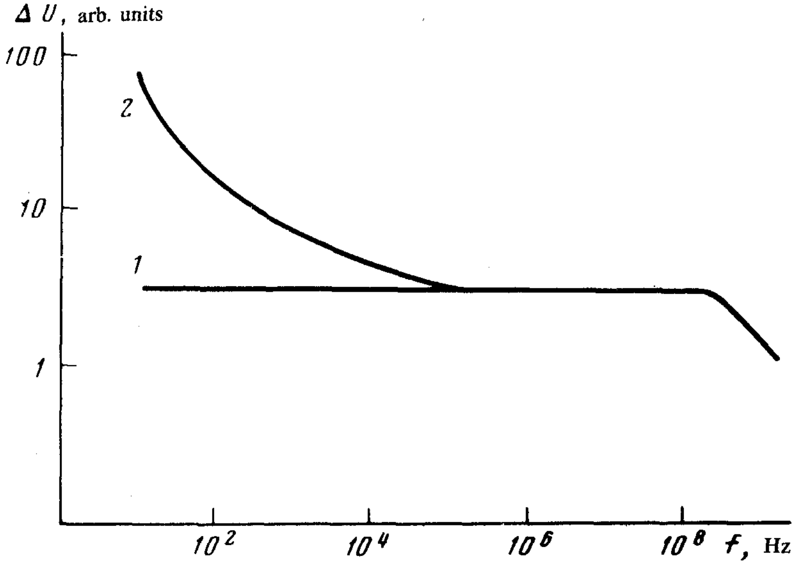

FIG. 2. The dependence $\Delta U(f)$ for niobium films 120 Å thick on various substrates: 1—sapphire; 2—glass.

same at any fixed values of I, H, T, and λ. Similar results were found on the decay of ΔU during pulsed excitation with a nitrogen laser.

To determine whether the effect is a nonbolometric effect, we carried out several independent measurements to supplement the observation that the temperature dependence of ΔU was sharply different from that of[1] $\partial H/\partial T$. The results of these other measurements can be summarized as follows: First, the values of ΔU found experimentally are higher, by as much as three orders of magnitude, than the bolometric effect calculated from measurements of $\partial U/\partial T$, the absorption coefficient for the radiation, and the thermal conductivity of the boundary of the film with the substrate and with the superfluid helium. Next, the magnitude of the effect, ΔU (for $f \geqslant 10^5$ Hz), and the time constant τ are the same for identical films deposited on different substrates (sapphire and glass), with thermal conductivities differing by more than an order of magnitude (Fig. 2). We might note that the bolometric effect exceeds the effect under study only at low modulation frequencies, $f < 10^5$ Hz and with poor heat removal from the films (curve 2).

The observed effect results from a spatially inhomogeneous resistive state. The increase in the resistance caused by the electromagnetic radiation may result from an expansion of the normal regions, an increase in the depth to which the electric field penetrates into the superconducting regions (l_E), and an effect of the radiation on the motion of vortices. This resistance increase is seen both near T_C, where the resistive state is associated with a phase slippage center, and at low temperatures in a strong magnetic field, where the viscous motion of vortices may be important in producing the resistive state. The experiments show that in the latter case all the characteristics of the effect remain the same as the orientation of the magnetic field with respect to the surface of the film is varied from perpendicular to parallel, provided that the magnitude of H, divided by the critical field, is held constant. The magnetic flux penetrating the film changes by more than two orders of magnitude in this experiment. The effect is thus independent of the method used to produce the resistive state, and it cannot be a consequence of a change in the motion of vortices under the influence of the radiation. The two remaining possibilities—a change in the dimensions of the normal regions and a change in l_E—are not mutually exclusive.

A qualitative explanation for the nonselectivity of the effect may be summarized as follows: The radiation absorption coefficient α_s of the superconducting film under experimental conditions such that the superconductivity is strongly suppressed differs only slightly from that of a film of the normal metal, α_n. Calculations for these films in the free-electron model show that the functions $\alpha_n(\nu)$ and $\Delta U(\nu)$ (Fig. 1) essentially coincide at frequencies $\nu > 10^{10}$ Hz. The absorbed electromagnetic radiation heats the electron gas as it interacts with existing quasiparticles and as it destroys Cooper pairs. The hot quasiparticles relax through electron-electron and electron-phonon collisions. The frequency range in which the effect is nonselective includes photon energies $\hbar\omega$ both much larger than kT_D (T_D is the Debye temperature) and smaller than kT. The high-energy phonons emitted by the quasiparticles at $\hbar\omega > kT_D$ are strongly absorbed and do not escape from the film, while for the thermal phonons the film is transparent. When a substantial part of the energy of the quasiparticles, ϵ, is radiated as thermal phonons, however, the distribution function is formed as a result of electron-electron collisions. The reason is that for films with a short mean free path l the scattering of electrons by static defects strongly affects the relaxation of the quasiparticles through the electron-electron interaction, according to Ref. 3. As estimate of the energy relaxation time for the electron-electron collision mechanism from the expression[4]

$$\tau_e^{ee} = \frac{2}{3\pi}\frac{\hbar}{kT}\frac{(K_F l)(K_F d)}{\ln(K_F l)(K_F d)},$$

where K_F is the Fermi wave vector, shows that the scale time for the inelastic electron-phonon interaction, $\tau_\epsilon^{\mathrm{ph}}$, for these films ($l \simeq 10$–$20$ Å) is larger than τ_ϵ^{ee} at $T \leqslant 10$ K. The photon energy is thus effectively distributed over the electron subsystem over a broad range of radiation frequencies, and the magnitude of the effect is determined exclusively by the absorbed power.

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