Frequency dependence of superconductivity stimulated by a high-frequency field in film bridges

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The existence of lower and upper frequency limits to the growth of the critical current of film bridges under the action of high-frequency radiation is established experimentally.

The phenomenon of stimulation of superconductivity in narrow film bridges by high-frequency fields was observed earlier.[1,2] In these and in subsequent investigations,[3,4] they studied the growth of the critical current and of the transition temperature of the bridge as a function of the powerful radiation at certain fixed frequencies ~10 GHz.

We have investigated in detail the frequency dependence of the growth of the critical current of a bridge in the region from 8 to 78 GHz at different temperatures, and observed the existence, besides of a lower frequency limit of this effect, also of a higher limit. In the interpretation of the results, we have compared our experimental data with the theory developed by Eliashberg and co-workers[5,6] for superconductivity stimulated by a high-frequency field in thin films. The previously advanced explanations of this effect[7,8] are not convincing enough, being based on a purely phenomenological approach and do not make it possible to make a comparison with experiment.

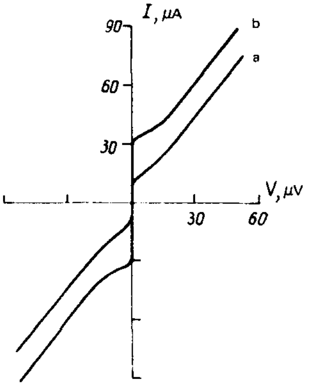

FIG. 1. Current-voltage characteristic of a tin bridge on a sapphire substrate. Length 1 μ, width 2 μ. $T_c = 3.82$°K, $T_c - T = 0.017$°K. a) CVC without radiation, b) CVC under the influence of radiation of frequency 27.2 GHz, incident power ≈ 2 ×10^{-5} W.

The central physical idea on which[5,6] are based is the following. Under the influence of the microwave field, the "center of gravity" of the distribution function of the quasiparticles shifts upward in energy, leading to an increase in the energy gap of the superconductor. In these papers, a number of concrete results concerning the singularities of the investigated effect was obtained, and, in particular, the presence of a lower frequency limit was indicated. This makes it possible to compare (subject to definite stipulations) our experimental data with these results.

The measurements were performed with tin bridges obtained by a previously described method.[9] To improve the heat dissipation, the substrates were made of sapphire. The width and length of the bridge necks ranged from 0.3 to 2 μ, and the thickness was 1000—

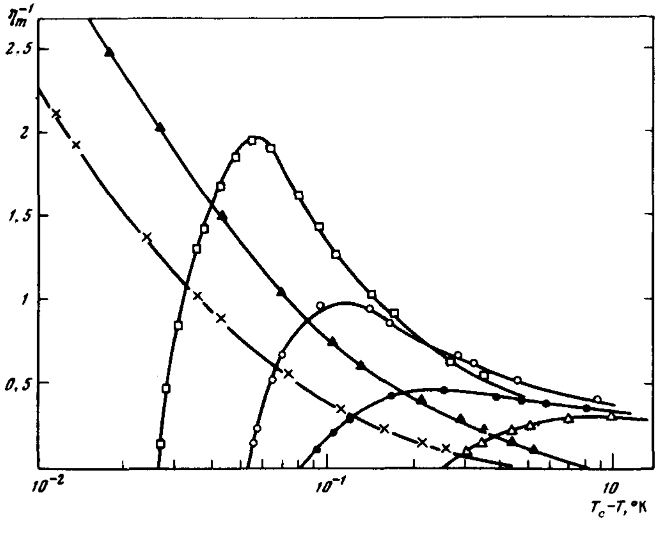

FIG. 2. Dependence of the maximum growth of the critical current of the bridge on the temperature under the influence of microwave fields with different frequencies: + —10.2 GHz; ▲—23.1 GHz; □—48.7 GHz, ○—53.5 GHz; ●—70.6 GHz; △—76.9 GHz.

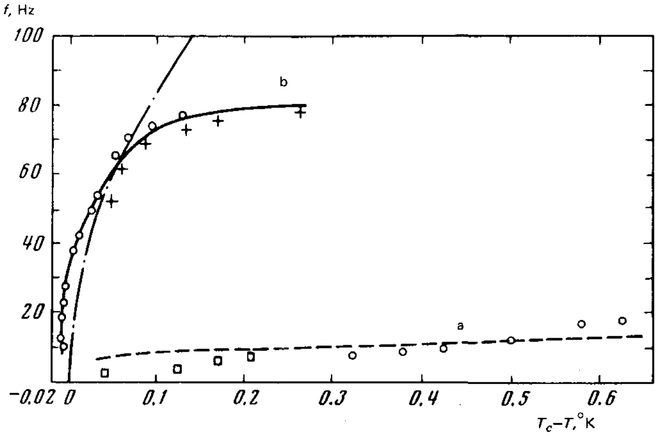

FIG. 3. Temperature dependence of the frequency limits of the growth of the critical current. The points on the curves correspond to the following samples: +—$T_c = 3.82$ °K, neck dimensions 0.8×2 μ^2; ○—$T_c = 3.83$ °K, 1×1.2 μ^2; □—from data of[2].

1200 Å. The bridge was placed in a 3-cm waveguide in the antinode of the field parallel to the transport current in the sample. The accuracy with which the temperature was measured and maintained was 0.003 °K. The critical current I_c was measured oscillographically by means of the current-voltage characteristic (CVC) of the sample (Fig. 1).

The experiment was performed in the following manner: At a fixed generator frequency and a fixed temperature of the helium bath, we measured the dependence of I_c on the incident radiation power. The measurements were then repeated at another temperature, and after passing through the entire temperature interval, a cycle of similar measurement was performed, but at a different frequency. We denote by η the ratio of the value of I_c under the influence of the microwave field to its value in a zero field, $\eta = I_c(W)/I_c(0)$. At a certain power, η reaches its maximum value $\eta_{\max}$. Then the condition under which I_c can grow is $\eta_{\max} > 1$. We measured the temperature dependence of $\eta_{\max}$ in the region $T_c - T \lesssim 0.8$ °K under the influence of radiation with frequencies from 8 to 78 GHz (Fig. 2.)

It is seen from Fig. 2 that near T_c, at frequencies $\omega \lesssim 30$ GHz, the curves move sharply upward because of the very large influence of the radiation on the small I_c of the bridges at these temperatures. The effect of stimulation of the superconductivity (the production of a superconducting state and the corresponding value of I_c) was observed also in a certain region $T \gtrsim T_c$ ($T - T_c \approx 0.01$ °K), where a vertical section appeared on the linear Ohmic CVC under the influence of radiation with frequency $\omega \lesssim 30$ GHz. With decreasing temperature below T_c, the growth of I_c decreases, and at a certain temperature it is no longer observed—the $\eta_{\max}(T)$ curve crosses the abscissa axis. It is this intersection point which determines the limit of the existence of the effect.

When radiation of frequency larger than 30 GHz is applied, as seen from Fig. 2, no growth is observed in the immediate vicinity of T_c. It begins only with a certain temperature that depends on the frequency, and does not vanish down to the lowest temperatures measured by us, $T_c - T < 0.8$ °K. It should be noted that the magnitude of the effect decreases with increasing frequency. If all these limiting points for the onset and disappearance of the growth of I_c are plotted, with the abscissas representing the temperature $T_c - T$ and the ordinates the frequency (Fig. 3), then we obtain two curves that delineate the region of existence of a growth of the critical current in the bridges. The growth of I_c is observed in the band between these curves, and is not observed outside this band. If we take any point inside this band and estimate the amplitude of the field in the neck of the bridge, then it turns out that the value of the field at which the growth begins agrees in order of magnitude with the corresponding theoretical values. [6]

In a previously published experimental paper[4] there were certain indications of the existence of a lower frequency limit, and if we use the data of this paper, then we obtain several points that agree well with out experimental data (Fig. 3, curve a). The existence of the lower limit follows also from theoretical papers[5,6] in which it is shown that the action of the high-frequency radiation leads to an increase in the energy gap Δ only if $\omega < \omega_c$, where ω_c is determined by the following relation:

$$\omega_c^2 \ln \frac{8\Delta}{\omega_c} = 2\pi \tau_0^{-1} \Delta . \tag{1}$$

The time τ_0 is the smaller of the two times of excitation relaxation as the result of the electron-electron or electron-phonon mechanisms, and at $T \approx 4.2$ °K it is of the order of 10^{-9} sec. The dependence of ω_c on $T_c - T$, calculated from (1) for $\tau_0 = 2 \times 10^{-10}$ sec, is shown in Fig. 3 by the dashed curve. Taking into account the difference between our experimental conditions or objects and the theoretical analysis (bridge rather than film; measurement of the growth of I_c and not of T_c; influence of thermal effects), the agreement between the experimental data and the theoretical curve can be regarded as satisfactory.

The situation changes in the case of the upper frequency limit. The existence of the upper frequency limit observed by us (Fig. 3, curve b) does not follow from the theory. [5,6] Comparing our experimental temperature dependence with that of the energy gap, we see that in the frequency region up to 70 GHz they are very close to each other (dash-dot curve in Fig. 3). That is to say, in this temperature region the upper frequency limit is determined in all probability by the energy gap of the superconductor. This may be due to the fact that at $\hbar\omega \gtrsim 2\Delta$ the dominating process is still the pair-breaking process, and an increase in the number of quasiparticles should lead to a decrease of the gap.

The deviation of the experimental curve from the temperature dependence of the gap, which occurs at frequencies higher than 70 GHz, is apparently connected with the fact that at these frequencies $\hbar\omega$ becomes of the order of kT. As shown by estimates carried out by us on the basis of the theoretical paper, [6] in the frequency region $\hbar\omega \approx kT$ the effect of stimulation of superconductivity should vanish. It is possible that the difference between the theoretical and experimental results, concerning the upper frequency limit, is due to the already mentioned difference between the conditions and objects in the experiment and in the theory.

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