On the dependence of UHF radiation-stimulated superconductivity in film bridges on their length

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Experimental measurement shows that decrease in the length of the bridge below $\sim(D/\omega)^{1/2}$ results in a change of the mechanism for stimulating superconductivity in the bridge by UHF radiation.

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For some time much attention has been given to theoretical and experimental investigation of nonequilibrium phenomena in homogeneous and inhomogeneous superconductors and, specifically, the very interesting effect of stimulated superconductivity from UHF radiation (see for example, the review in Ref. 1).

The fundamental cause of stimulated critical current in superconducting bridges by the radiation effect appears to be the resulting nonequilibrium distribution function for quasiparticles. For long homogeneous bridges, nonequilibrium originates directly from influence of the electromagnetic field on quasiparticles,[2,3] and for short, that is, inhomogeneous bridges (with characteristic dimension $\sim\xi$), from the oscillating gap in bridge neck.[4] The differences in the character of stimulation for long and short bridges are a consequence of this. Stimulation in long ($L>\xi$) bridges and its mecha-

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TABLE I.

Sample	L, μm	w, μm	R_n	T_c, K
T-1	0.6	1,0	0,24	3.80
T-2	0,7	1,0	0.22	3.75
T-3	3,3	1.5	0,10	3.75
D-1	0,6	0,5	0,66	3,78
D-2	0,7	0,9	0.28	3,77
D-3	1,0	1,2	0,55	3.83
D-4	1.7	1.4	0,49	3,82
0-1	1360	0,9	135	3,79

nism are relatively well understood experimentally.[1,5] For short bridges, there are qualitative preliminary results.[1,6] It follows from theory[4] that the nature of the stimulation depends essentially on bridge length and on geometry. In this connection the

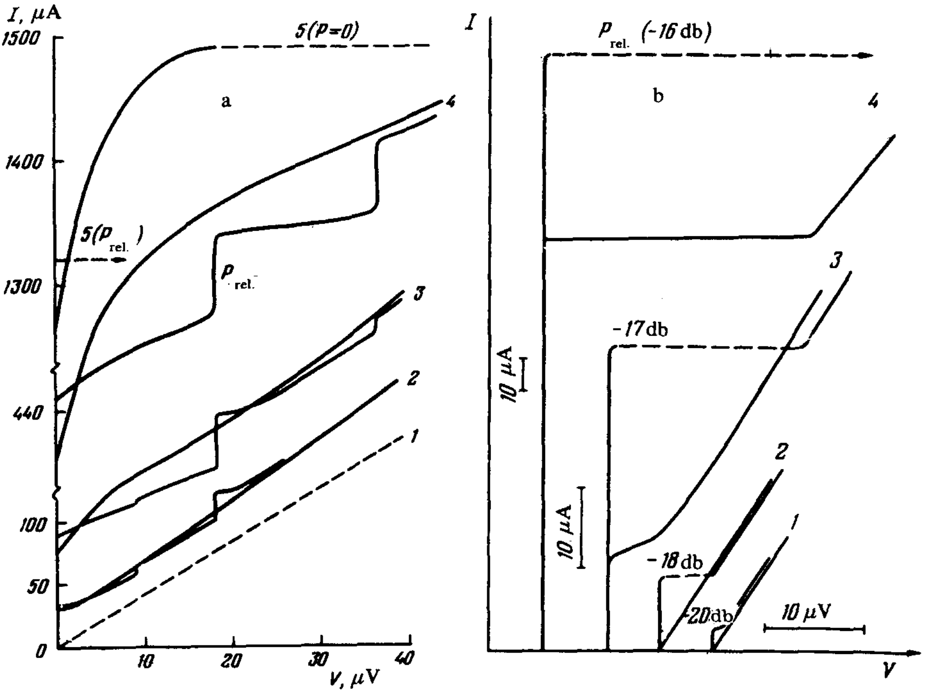

FIG. 1. Change in volt-ampere characteristic of superconducting bridges as a function of temperature T and power P of the UHF radiation: a) VAC of bridge T-2 at T,K:1—3.752, 2—3.726, 3—3.706, 4—3.585, 5—3.320, each at two values P:$P=0$ and $P=P_{\mathrm{opt}}$, which corresponds to damping of 20–30 db; b) VAC of bridge D-4 at T, K: 1—3.828, 2—3.825, 3—3.809, 4—3.760, each at $P=0$ and at $P=P_{\mathrm{opt}}$ (shown in db above respective curves).

study of the change in the nature of the stimulation of I_c with a change in bridge length and the clarification of the relative contributions of the foregoing mechanisms, as well as "accompanying" Josephson and thermal effects, was of great interest.

We investigated long $L \gg \xi$ bridges of thin tin films (practically one-dimensional superconducting channels), two-dimensional plane, and three-dimensional bridges of varying thicknesses as well as lengths, and also short bridges (see Table I). Parameters L and w in the table are correct to 0.2 μm. The thickness of the neck of all bridges was approximately the same, ~ 1000 Å, and the thickness of the edge of three-dimensional bridges $\sim 1 \mu$m. The method of preparation was previously reported.[5] The value of the critical current and its dependence on temperature and on radiation power ($f = 9$ GHz) were determined by the volt-ampere characteristic (VAC) recorded with a two-coordinate recorder. The accuracy of the measurement of I_c is 1%, and the accuracy of the temperature maintained is 1 mK.

Figure 1 shows typical VAC for a short bridge (Fig. 1a) and for a long one (Fig. 1b). The VACs of a plane bridge and that of a bridge with varying thickness with similar neck dimensions are qualitatively similar, although there is some quantitative difference (see below). A basic feature of stimulated super conductivity in short bridges should be noted. When $T \lesssim T_c$, VAC has a nearly hyperbolic form, and a transient Josephson effect is observed without stimulated current I_c. At reduced temperatures stimulated I_c appears clearly (curve 2, Fig. 1a), and later the characteristic VAC curvature in the unexcited bridge (curve 3) also appears. The latter is due to a nonequilibrium function distribution of quasiparticles because of Josephson oscillations in the gap with flow of constant current $I > I_c$.[6-8] The differential resistance of the linear initial portion of VAC decreases without irradiation with decreasing temperature and, finally, at a considerable distance from T_c (for sample T-2 more than 0.4 K) voltage and hysteresis jumps (curve 5) appear in VAC, resulting from the thermal effects.[9] The effect of radiation in the entire temperature region causes an increase in I_c. However, as is evident from Fig. 1a, $I_c(P)$ never exceeds typically the magnitude of current corresponding to the curvature of VAC without radiation I_s^0.

The dependence of parameter $\eta = I_c(P)/I_c(0)$ on the power P is as follows. First, at low power η remains practically constant or decreases slightly by $\sim 2\%$. For increasing P, η increases reaching a maximum $\eta_{\max}$ (the case shown in Fig. 1a) and then decreases approximately proportionally to $I_0\,(P)^{1/2}$, i.e., in the same way the oscillation decreases the critical current of the Josephson junction. Moreover, a change in amplitude of the n-th step approximately follows the corresponding function $I_n(P)^{1/2}$. In other words, for a certain radiation power, when I_c ceases to grow, the nonstationary Josephson effect suppresses the stimulation effect. Obviously because of this $I_c(P)$ does not attain its maximum value I_s^0 predicted by theory.[4]

Analogous changes in the VAC occur in short planar bridges of approximately the same neck size (for instance, D-1), except that thermal hysteresis begins closer to T_c (for D-1 when $T_c - T \approx 0.2$ K), and the Josephson effects exhibited in them are weaker.

Qualitatively, a different picture of the variation in VAC is observed in bridges with $L \gtrsim 1$ μm. Figure 1b shows, for example, bridge D-4. Here, when $T > T_c$ radi-

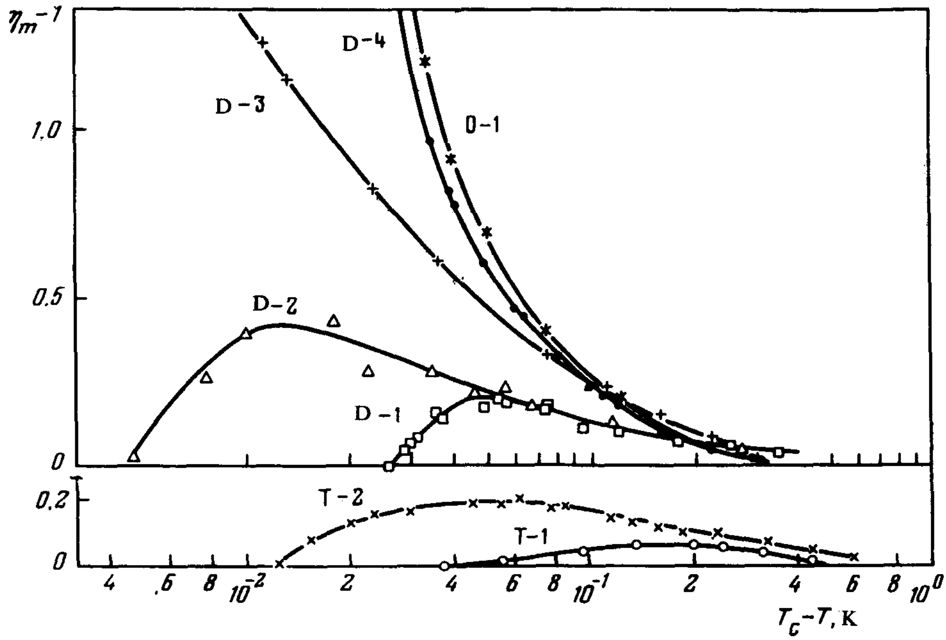

FIG. 2. Temperature dependence of $\eta_{\max}$ for bridges of different length (see Table I).

ation induces a superconductivity current (curves 1,2), and for $T \lesssim T_c$ greatly increases it (by 3–5-fold) (curve 3). With further decrease in temperature $\eta_{\max}$ decreases. In the VAC of such a bridge the curved characteristics are not observed at $V \approx 0$, the Josephson phases are absent, and there is a step-like transition to a resistive state at $P \neq 0$ (i.e., a type 1 phase transition) even at high temperatures when no hysteresisis is observed in VAC without irradiation. Analogous features are observed in very long bridges of the type 0-1 and in the long T-3 bridge with a varying thickness.

The difference between the nature of stimulation of I_c in short and long bridges is especially evident in the temperature dependence of $\eta_{\max}$, shown in Fig. 2. In short bridges with $L < 1$ μm stimulation immediately near T_c is absent. It appears at some interval from T_c, becoming greatest for temperatures when $L \sim \xi(T)$ and then again decreasing, which is consistent with the results reported elsewhere.,[4] Thus, for the bridge T-1, $\eta_{\max}$ is observed when $T_c - T = 0.16$ K, at $\xi(T) = 0.5$ μm, which is very near the bridge length $L = 0.6$ μm. For the bridge T-2, $T_c - T = 0.06$ K, corresponding to $\xi(T) = 0.8$ μm and $L = 0.7$ μm. It should be noted also that for the shortest sample T-1 the increasing and decreasing portions of the function $\eta_{\max}(T_c - T)$ are almost linear on a logarithmic scale with a slope of 1/5, which is also in good agreement with theory[4] for which $\eta_{\max} \sim (T_c - T_1)^{1/4}$. Theory[4] specifies a limit to the contact size $\xi(T)\ (1 - T/T_c)^{1/4} \ll L \ll (D/\omega)^{1/2}$, where $D = 1/3 l v_F$. For tin with $v_F = 0.65 \times 10^8$ cm/sec, $l = 1000$ Å, $T_c - T = 0.2$ K, and $f = 9$ GHz giving 0.2 μm $< L < 0.62$ μm. Experimentally the nature of stimulation changes at $L \lesssim 0.8$ μm, which is relatively close to theory.

Figure 2 also clearly shows that with increased bridge length a boundary for the occurrence of stimulation shifts toward T_c. The curves for $\eta_{\max}(T)$ for bridges of constant thickness D-1 and D-2 lies nearer T_c than for bridges of varying thickness (T-1, T-2) but the same length. This apparently occurs because in D-bridges the region of the nonequilibrium state extends over some distance from the edge of the bridge increasing its effective length. Simultaneously with the shift toward T_c there is an increase in the parameter $\eta_{\max}$ (bridge D-2), and finally at $L \gtrsim 1\ \mu\text{m}$ the nature of the temperature dependence of stimulation changes: maximal stimulation of I_c is observed for $T \approx T_c$ with a smooth decay at decreasing temperatures. Subsequently, increasing L of all narrow long bridges yields a dependence of $\eta_{\max}(T)$ which is (within experimental accuracy) similar to the dependence for D-4 (for example, the curve for bridge 0-1 of length 1.36 mm).

Thus, the data obtained show that with decreasing bridge length there is a transition from the stimulation mechanism of Eliashberg[2,3] to the mechanism investigated by L.G. Aslamazov and A.I. Larkin.[4]

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