Steplike structure produced on the superconducting transition of a tin film by microwave radiation

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(Submitted August 11, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 6, 488–491 (20 September 1977)

Experiment has revealed a steplike structure, due to the action of microwave radiation, on the plot of the superconducting transition of a film. It is proposed that the observed structure is due to the disequilibrium and inhomogeneity of the state of this film in the microwave field.

PACS numbers: 74.30.Gn, 74.40.+k, 74.70.Gj, 73.60.Ka

It is known that under certain conditions microwave radiation can increase the critical current I_c,[1,2] the energy gap Δ,[3] and the critical temperature T_c of a superconducting film[2,4] Experiment has revealed a small increase of T_c, by an amount $\sim$0.02 K, whereas theory predicts an appreciable increase of T_c.[5,6] One of the causes of the limitation of the growth of T_c may be heating of the film lattice by the radiation.[7] Another possible cause is the instability of the nonequilibrium superconducting state, which occurs under the action of microwave radiation and results in the transition of the superconductor to the normal state or to some other resistive state.[8,9] In this article we report observation of steps produced on the curve of the superconducting transition of a tin film under the influence of microwave radiation, and discuss the connection between this phenomenon and the factors that limit the growth of T_c.

Radiation of frequency 9.4 GHz was fed through a standard waveguide to the investigated sample, which was located either in liquid or in gaseous He (to this end, the sample was placed in a inverted glass vessel immersed in liquid helium). The samples were narrow (1–2 μm wide) strips of Sn, of length 30–60 μm and of thickness 1000–2000 Å, deposited at 77 K on a crystalline-quartz substrate. The sample temperature was measured with a Ge thermometer imbedded in the substrate and screened against the microwave radiation. The accuracy of the measurement of the absolute temperature was $\sim$10 mK and the relative accuracy was $\sim$1 mK. The measurement was performed at a current 1 μA through the sample. Low-pass filters were placed in all four conductors leading to the sample.

Figure 1 shows a number of plots of the resistance $R(T)$ of one of the samples against temperature at different radiation powers W. The initial small jump on $R(T)$ corresponds to the transition of the broad electrodes of the bridge ("shores") into the superconducting state. As seen from Fig. 1, radiation of relatively low power (attenuation $\sim$20 dB) shifts the transition into the region of higher temperatures and decreases its width Θ defined as the difference of the temperatures between the $0.9R_n$ and $0.1R_n$ levels (usually $\Theta \lesssim 10$ mK). The shift δT_c of the superconducting transition at the $0.1R_n$ level, for samples in contact with liquid helium, was approximately double the value of δT_c for samples in gas, and reached 30 mK, which in turn is more than three times larger than the width Θ of the superconducting transition.

It turns out also that a given W the reverse transition from the superconducting to the normal state has a jumplike form and takes place at higher temperatures than from the normal to the superconducting state (Fig. 1). The hysteresis of the transitions is due apparently to "overheating" of the superconducting states in the microwave field.[6,10]

Starting with a certain W (20 dB attenuation in Fig. 1), the transition stops shifting towards

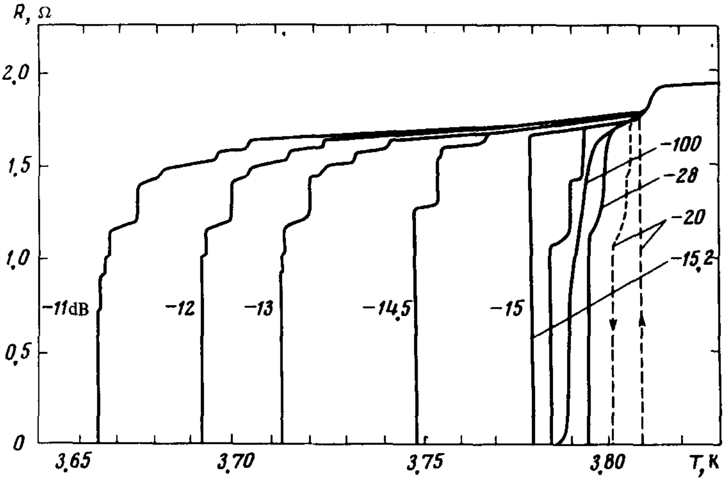

FIG. 1. Dependence of the resistance of film No. 48-1 on the temperature at certain fixed values of incident-radiation power. Film dimensions $0.15\times1.5\times47$ μm.

higher temperatures and begins to return to the low-temperature region. Simultaneously, the transition curve begins to reveal a steplike structure, which becomes more strongly pronounced with increasing W (the 15.2-dB curve). Next, in a narrow power interval ($\approx$0.5 dB) near a definite value of the power (15 dB for the samples in question), a change takes place in the form of the steplike structure. The initial system of steps corresponding to the region of small W vanishes; the transition becomes jumplike, followed by a formation of another system of steps, which retains qualitatively its form up to the largest W at which we performed the measurements ($\approx$3 dB). In this region of W, the smallest step on the $R(T)$ corresponds to a transition to the superconducting state of a bridge section of $\approx$2 μm length. The states of the film on the horizontal sections of $R(T)$ are stable. Part of the bridge is in this case in the normal state and part in the superconducting state. If the bridge temperature is raised starting from this intermediate state, then "local" hysteresis is also observed for each step.

The dependence of δT_c on W relative to the transition temperature at $W=0$ is shown in Fig. 2 for the cases of rising and dropping temperature. The difference between the curves is due to the already mentioned hysteresis in these transitions. For transitions starting from the superconducting state, the intercept with the abcissa axis takes place at larger radiation powers. We note the similarity between these curves and the plots of I_c of the bridges against W, cited in[8], where it was shown that the possible cause of the decrease of I_c is heating of the lattice in the bridge.

The functions $R(T)$ were plotted for 7 different samples and qualitatively similar results were obtained for all of them. However, the number of steps and their heights changed from sample to sample. Among the 7 samples were two pairs of bridges with nearly equal dimensions. The paired bridges had identical thickness and widths and practically equal lengths (difference 1–2 μm). The system of steps for these nearly equal samples turned out to be quantitatively different, thus apparently pointing to a connection between the observed steplike structure and the inhomogeneities of the samples. On the other hand, as seen from Fig. 1, there are no steps on the superconducting-transition curves at $W=0$. Nor did we observe at $W=0$ on the transition curves obtained with larger measurement currents, up to 1 mA, any steplike structures similar to that of Fig. 1. All this seems to suggest that the appearance of steps on $R(T)$ at $W\neq0$ and at small measuring currents is

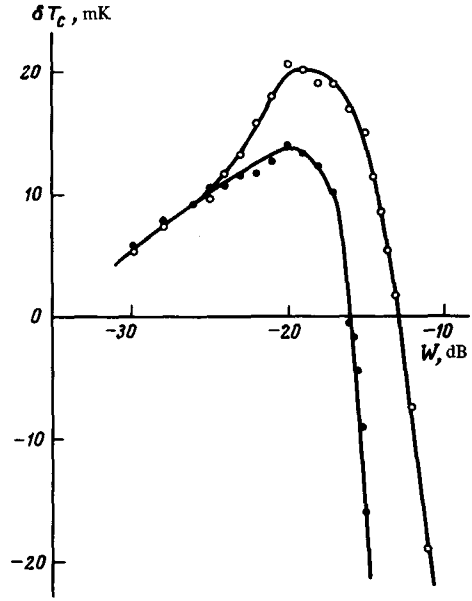

FIG. 2. Shift of superconducting transition of film No. 48-1 against the power of the incident radiation. The light circles correspond to a rising temperature at a given power, while the dark circles correspond to a dropping temperature.

due to the action of the microwave radiation and is connected somehow with the inhomogeneities of the samples.

Several hypotheses can be advanced concerning the mechanism of the observed phenomena. The samples investigated by us are in all likelihood inhomogeneous, i.e., the T_c of their individual sections differ from one another by ~10 mK.[11] When such samples are acted upon by radiation of relatively low power, stimulation of superconductivity is observed. As shown by theory[6] and by the experimental $I_c(W)$ plots,[7] the action of the radiation leads to a greater growth of the critical parameters (T_c, Δ, and I_c) on the bridge sections with smaller T_c and correspondingly smaller Δ than on the section with high T_c. It follows therefore that at the same time that the critical parameters of all the sections increase, they should also become equalized. These processes correspond to the experimentally observed shift of the superconducting transition towards larger T and to the narrowing of this transition. With further increase of W, it appears that factors that compete with the mechanism that stimulates the superconductivity come into play and limit the shift of T_c; these factors are instability of the nonequlibrium superconducting state[8,9] and thermal effects. Both factors contribute to a breakdown of the bridge into superconducting and normal sections, the formation of which is also influenced by the inhomogeneities of the sample. The observed steplike structure on the superconducting transition is apparently the result of the existence of such a nonequilibrium and inhomogeneous of the bridge.

The authors are most grateful to A.F. Volkov and B.I. Ivlev for a useful discussion of the results.

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