Observation of microwave Josephson radiation in thin-film superconducting bridges

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We report direct observation of microwave Josephson radiation in thin-film superconducting bridges.

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1. Among the various types of weakly-coupled superconductors, thin-film bridges offer the advantage of permitting a correct estimate of the electromagnetic parameters and of controlling the geometry of weak-coupling bridges. So far, however, the Josephson properties of bridges were investigated by using indirect attributes (effect of the magnetic field on the critical current, behavior of the bridges in a microwave field, etc.). We report here direct observation of Josephson radiation from autonomous thin-film bridges. This appears to be the first observation of this radiation in the microwave band.

We investigated microwave generation in tin bridges of "variable" thickness, in which the thickness d of the bridge film was much smaller than the thickness d_0 of the film at the "banks." As shown earlier,[1,2] in such a structure it is easier to attain greater localization of the weak-coupling region in comparison with the "flat" bridges of Dayem[3] and to realize concrete effects under the influence of the transport current I.

2. The investigated bridges were rectangular in shape with length $l_0 = 0.5-1$ μ and width $w = 1-3$; the bridge-film thickness was $d \approx 800$ Å. The sequence of the preparation operation was the following. A thread, whose diameter determined the eventual width w, was first stretched along the substrate (optically polished crystalline quartz), after which a layer of silicon monoxide (SiO) of thickness ~300 Å was evaporated. After removing the thread and obtaining the channel in the SiO, a thick tin film ($d_b \approx 5\times10^3$ Å) was evaporated ($p \approx 1\times10^{-6}$ Torr, evaporation rate ~100 Å/sec). The tin film was then cut with a razor blade in a direction perpendicular to the channel, and by the same token was removed over the entire width of the substrate, including the film in the channel; the width of the cut determined the value of l. This procedure yielded bridges with reproducible parameters ($R_{300K}/R_{4.2K} = 20 \pm 5$), and had the following advantages over the "double scratching" procedure described in[4]: the bridge cross section was a rectangle, and the value of d could be adjusted by varying the thickness of the SiO layer. We present here the results for one of the bridges.

To perform the microwave experiments, the sample was inserted into the central conductor of a two-half-wave coaxial 3-cm resonator at its midpoint. For a better microwave contact, the transition from the bulky central conductor to the film of the bridge was produced at a distance $\lambda/4$ from the end. The coupling between the resonator and the waveguide was made adjustable by a coupling post and a plunger located at the end of the waveguide. The loss resistance in the resonator, referred to the bridge ($R_0 = 0.3-0.1$ Ω) and the resistance of the coupling with the microwave channel referred to the bridge ($R_c = 0.1-1$ Ω) were determined by measuring the coefficient of reflection of a weak signal ($\lesssim 10^{-9}$ W) from the resonator. The resonator Q was ~200. The generation was observed with a P5-10 receiver tuned to the resonant frequency $f_{res} = 9510$ GHz.

3. At temperatures close to T_c, the characteristic depth of penetration of a magnetic field normal to the film plane and the coherence length were larger than w and l. Satisfaction of these conditions justifies a comparison of the experimental results with the "resistive" model,[12] in which the current in a weak-coupling region is assumed to be equal to the sum of the currents of the superconducting ($I_0 \sin[(2e/\hbar)\int V\,dt]$) and normal ($V/R_N$) electrons. The validity of this comparison is confirmed primarily by the absence of periodic changes in the differential resistance with increasing I (Fig. 1), which occurs in bridges of "variable" thickness with large dimensions[2] and are connected with the motion of the vortices in the weak-coupling region. The temperature dependence of the critical current I_0 of the bridges in the range $\Delta T = T_c - T = 0.05-0.2$ °K was linear, in accord with[5].

Application of an external signal with $f = f_{res}$ produced Josephson steps on the current-voltage characteristics. The oscillatory dependences[1)] of I_0 and of the current steps on P_{mic} (Fig. 2), and the changes in the waveforms and periods of the oscillations of $I_{0,1,2,3...}$ with increasing I_0 as T is lowered, agree qualitatively with these calculated from the "resistive" model. The reduction of the plot of $I_{0,1}(P_{mic}, T)$ in accordance with[6],

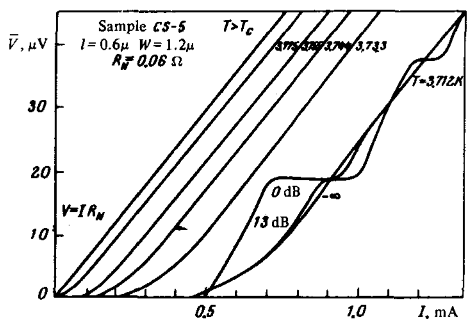

FIG. 1. Family of current-voltage characteristics with changing temperature. Current-voltage characteristics at different levels of the microwave power are shown for $T = 3.712$ °K. The frequency of the applied signal was f_{res} (9510 GHz).

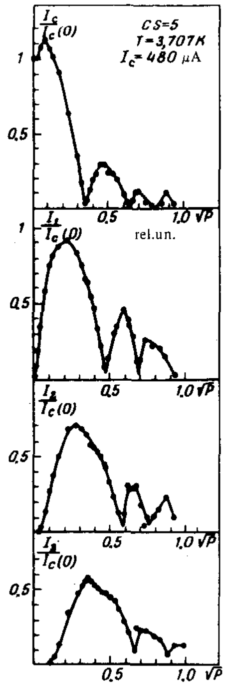

FIG. 2. Plots of $I_{0,1,2,3}$ against the level of the incident microwave power (P_{mic}).

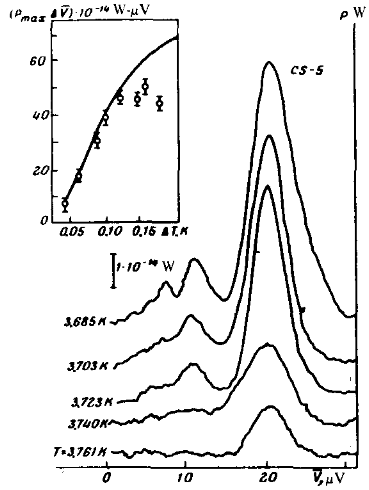

FIG. 3. Family of bridge oscillation spectra with varying temperature. The insert shows plots of $P_{max}\Delta\overline{V}$ at the first harmonic of the radiation against T (solid line—theory,[5,6] points—experiment).

and a comparison of the results with $I_0(T)$, offer evidence that at $\Delta T = 0-0.1$ °K the "resistive" model can be used also for a quantitative description of the Josephson microwave properties of bridges, at any rate at not too large values of the time-averaged voltage V and $I - I_0$. The correctness of this description is confirmed by the symmetry of the first current steps relative to the current-voltage characteristics of the autonomous bridge in the case of a weak external signal (Fig. 1).

It should be noted that simultaneously with the Josephson properties, we observe in a number of cases in the bridges an effect of superconductivity stimulated by the microwave field. This effect was manifest in a small increase of I_0 under the influence of a weak signal. This effect was observed, at any rate, in the range $\Delta T = 0-0.2$ °K. We did not study it in detail.

4. The generation spectra of the autonomous bridge as a function of $\overline{V}$ are shown in Fig. 3. We see that the maxima of the central radiation density P_{max} are observed as values of $\overline{V}$ connected with f_{res} by the Josephson relation $\overline{V} = (\hbar/n2e)f_{res}$, where $n = 1, 2, 3, \ldots$ are the radiation harmonics. At a given level of the fluctuations (fluctuation-current amplitude $I_f \leq 10$ μA), the value of R_N, which is small in comparison with $(R_0 + R_C)$, precluded a noticeable influence of the possible anomalous features of the microwave impedance of the bridge[7] on the character of the $P(V)$ relation. With decreasing temperature, the integral radiation power $P_{max}\Delta\overline{V}$($\Delta V$ is the width of the radiation band at the $P_{max}/2$ level) increases in accordance with the calculation.[5,6] At $\Delta T = 0.05-0.15$ °K there is quantitative agreement between the theoretical and experimental plots of $P_{max}\Delta\overline{V}$ against T for the first harmonic of the radiation (see the insert in Fig. 3). Further increase of ΔT leads to the appearance of a thermal voltage jump on the current-voltage characteristic of the autonomous bridge in the region $\overline{V} \approx 20$ μV. This in turn causes a sharp decrease in the integral first-harmonic power registered by the receiver. Attempt to decrease $\Delta\overline{V}$ by adding a low-resistance shunt ($R_{sh} \approx 0.01$ Ω) did not yield the desired result, probably because of the appearance of the low-frequency relaxation oscillations described in[8].

Thus, our experiments offer direct proof of the existence of the Josephson radiation in superconducting thin-film bridges, and the employed weak-coupling geometry leads to an enhancement of the observed coherent effects.

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1) Similar plots of $I_{0,1,2,3}$ against P_{mic} were obtained for bridges with dimensions $l \approx 1$ μ and $w \approx 3$ μ, prepared in accordance with the technology described in[2].

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