Effect of microwave irradiation on the current-voltage characteristics of thin-film superconducting tunnel junctions

V. A. Tulin

Institute of Solid State Physics, USSR Academy of Sciences
(Submitted June 13, 1974; resubmitted September 6, 1974)
ZhETF Pis. Red. **20**, No. 8, 554–558 (October 20, 1974)

It is found that microwave irradiation of a superconducting tunnel junction influences the current-voltage characteristics. Depression of the Josephson current and the onset of gapless superconductivity under the influence of the radiation is observed.

Starting with Giaever's work,[1] the investigation of tunnel characteristics of superconductors has become a widely used method of investigating the state density of quasiparticles in superconductors. This rather simple method makes it possible to obtain detailed and fairly accurate information on the behavior of superconductors under the influence of various external factors. The tunnel current of the structure is connected with the density of states in the investigated metal by the expression

$$J = C\int_{-\infty}^{\infty} d\epsilon\, n_1(\epsilon) n_2(\epsilon + eV)[f(\epsilon) - f(\epsilon + eV)],$$

where ϵ is the energy reckoned from the Fermi level in the normal metal, e is the electron charge, V is the potential difference between the electrodes, $f(\epsilon)$ is the Fermi distribution, C is a constant describing the conductivity of the dielectric barrier, and $n_i(\epsilon)$ is the state density referred to the normal metal. Dayem and Martin[2] investigated the influence of microwave photons on the tunnel characteristics of thin-film superconducting structures. Several similar investigations, performed at various microwave frequencies were subsequently published.[3,4] In these studies the tunnel junction in form of two crossed films, was placed in a resonator or a waveguide. As a result, a microwave

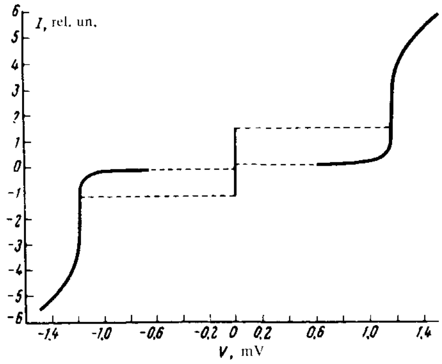

FIG. 1. Current-voltage characteristics of a thin-film junction in the absence of microwave irradiation.

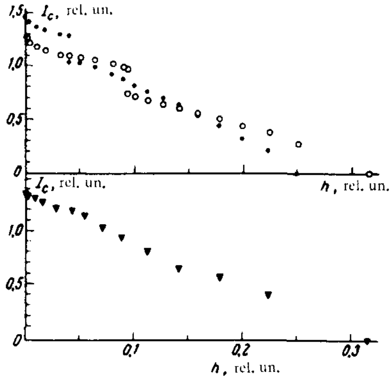

FIG. 2. Change in the amplitude of the Josephson current as a function of the applied high-frequency magnetic field.

displacement current was produced in the region of the tunnel junction, i.e., an oscillating potential difference was produced between the superconducting films, and the treatment of the results is based on this fact.

We have investigated the effect of a uniform microwave current (or microwave magnetic field), flowing in one of the films of the superconductor, on the characteristics of tunnel junctions. The tunnel junction occupied a small area of the irradiated film, and this led, on the one hand, to homogeneous microwave currents, and made it possible on the other hand for the displacement currents to flow far from the tunnel junction, without affecting the characteristics of the latter.

The samples were produced by the usual procedure. A tin film 10 mm wide was evaporated on a glass substrate in a vacuum $\sim(1-2)\times10^{-6}$ produced by an oil diffusion pump. The film was then coated with a dielectric layer (chalcopyrite glass) but a window of area ~0.3 mm^2 remained uncoated. The film was then oxidized by commercial oxygen at a pressure ~300 Torr for two hours. After a subsequent evacuation, a second tin film was evaporated, similar to the first. The thickness of the tin films was of the order of 1000 Å, the junction resistance was several hundredths of an ohm, and the temperature of the superconducting transition was $T \approx 3.8$ °K. The finished structure was clamped to a diaphragm in the midpoint of the narrow wall of a rectangular H_{011}-mode resonator for the 3-cm band, excited by a 30-mW klystron. The diameter of the diaphragm was 4 mm. The entire assembly was immersed in liquid helium, and the current-voltage characteristics were obtained at 1.5 °K by a four-point method at various levels of the power fed to the resonator. The experiments have shown that the influence of the microwave irradiation depends strongly on whether the tunnel junction lies in the area of the diaphragm or not, so that the influence of the leakage of the microwave power through undesirable small channels can be neglected. Various samples were subjected in different manners to the influence of the microwave irradiation, a fact that can be attributed to the considerable scatter of the tin-film thicknesses.

The current-voltage characteristic of one of the junctions[1)] is shown in Fig. 1. This junction had a small current at $V<2\Delta/e$ and a well-pronounced stationary Josephson current. The influence of microwave irradiation of a tunnel structure becomes manifest in a decrease of the Josephson current at $V=0$ and in a change of the current in the entire investigated range of voltages, from zero to more than $2\Delta/e$.

The change in the maximum value of the direct current at zero voltage on the junction is shown in Figs. 2a and 2b. Figure 2a corresponds to the variation of the current as a function of the microwave power for a good sample, while Fig. 2b pertains to a sample with a rather appreciable leakage current at $0<V<2\Delta/e$. It is seen from this figure that the maximum value of the Josephson current decreases with increasing microwave power in the resonator. At a certain value of the power, the maximum current changes jumpwise (in the good sample), and for different current polarities the jump takes place at different values of the power (Fig. 2a). In the poorer sample, the decrease of the current occurs smoothly, without jumps. One can note the absence of a stepwise structure of the current-voltage characteristic in this method of irradiation, whereas such a structure is observed for other methods of placing the tunnel junctions in the microwave field.

Figure 3 shows a family of $J(V)$ curves for different values of power incident on the sample; the values of the attenuation in the microwave channel (in decibels) are shown in the figure. At low values of the power (20 or 17 dB) the altered current-voltage characteristics correspond to a decrease in the gap of one of the tin films making up the junction. At a 15 dB attenuation, the gap for this film vanishes. With further increase of the power, an increase takes place in the single-particle current in the voltage region Δ/e. At an attenuation less than 10 dB, the gap vanishes in the second film (see footnote 1). This is reflected in the common sections of the characteristics, which form a straight line passing through the origin. A state with zero gap in one film corresponds to common sections forming a line conforming with the characteristic of the superconductor—insulator—normal metal structure, which can be clearly traced in Fig. 3. Preliminary investigations have shown that similar films remain superconducting at the same irradiation powers and at the same temperatures.

Thus, a decrease in the stationary Josephson current and a transition of the irradiated film to the gapless state is observed when the described method is used to

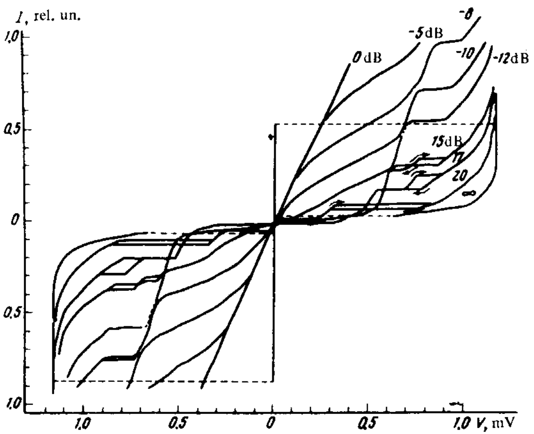

FIG. 3. Change in the current-voltage characteristics of a thin-film junction at $V < 2\Delta/e$ under the influence of irradiation.

irradiate a superconducting tunnel junction. As to the decrease of the Josephson current, the presence of an oscillating current in one of the films of the junction leads to an oscillating phase difference between the superconductors which leads in turn to a conversion of part or all of the Josephson direct current into alternating current. This causes in final analysis a decrease or a total vanishing of the direct superconducting current between the films.

In conclusion, I am grateful to N.V. Zavaritskiĭ and V.N. Grigor'ev for consultations on the preparation of the samples and to B.I. Ivlev for interest in the results.

[1)]In this junction, the thickness of the irradiated tin film is of the order of the penetration depth. Thus, the second film is also in the microwave field, but attenuated by the first film. This illustrates better the difference between the current-voltage characteristics obtained upon irradiation from those given in[3].

[1]I. Giaever, in: Proc. VII Intern. Conf. on Low Temperature Physics, Toronto, 1960, Toronto 1961, p. 327.
[2]A. Dayem and R.I. Martin, Phys. Rev. Lett. 8, 246 (1962).
[3]B. Kofoed, U.K. Poulsen, and K. Saermark, Preprint, Report No. 123, Danmarks Tekniske Hojskole, Lyngby, 1973.
[4]Ch. F. Cook and G.E. Everett, Phys. Rev. **159**, 374 (1967).