Nature of the resistive state of granular aluminum films

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The effect of external 10-GHz electromagnetic radiation on the current-voltage characteristics and $R(T)$ of thin ($d<\xi$) and wide ($w>\lambda_\perp$) aluminum films has been investigated in the region of the superconducting transition. It was found that, in the resistive region, the specimens under investigation exhibited properties characteristic of a system of *S-N-S* weak links. Synchronization effects in the statistical set of junctions are related to the dynamics of fluxoids of different polarity, which have been detected experimentally in such films by the flux transformer method in the absence of an external magnetic field.

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In an earlier study[1] of thin aluminum films, it was found that (a) the $R(T)$ curve for a superconducting junction had a two-step form and (b) the electrical conductivity $\sigma(U)$ of the specimen had an oscillatory form near T_k. The resistance of the films was substantially lower than the quantum limit $[R_\square^N \ll \hbar/e^2 = R_c = 4.11\ \mathrm{k}\Omega]$. To elucidate the mechanisms responsible for the observed effects, we have carried out experiments designed to investigate the interaction between an external electromagnetic field and aluminum films near the critical transition temperature.

1. The specimen under investigation was an aluminum film with $d = 3\times10^{-6}$ cm, $w = 0.03$–0.1 cm, and $L = 0.5$–1 cm, i.e., we examined specimens with $d<\xi(T)$ and width $w>\lambda_\perp$; their resistance was $R_\square^N = 8$–$12\ \Omega$. The films were deposited at the rate of 20 Å/s on a warm ($\simeq 300$ K) glass substrate in a "poor" vacuum of 10^{-4} Torr. For measurements in liquid helium, the films were mounted in a cryostat shielded from external magnetic fields.

Data on the conductivity of the films as a function of the applied voltage and temperature were obtained by using the well-known modulation method. The current used in these measurements did not exceed 1 μA at 1 kHz. An *xy* plotter was used to record automatically all the required characteristics, namely, $I(U)$, dU/dI vs U, and $R(T)$. In the last case, the temperature probe was a carbon resistance thermometer. Occasionally, more detailed information on the superconducting junction was obtained by determining the function $dR/dT(T)$ using the generation and detection of second sound in helium II. The specimen was irradiated in a direction parallel to the terminating piston in a three-centimeter waveguide.

2. The presence of two singularities on the $R(T)$ curve is characteristic for a system of weak links and is usually[2] interpreted as a transition to the superconducting state T_k of the "banks" and the establishment of a coherent state T_{2D} of the links (Fig. 1). The broad resistive region $T_{2D}<T<T_k$ is interesting. The current-voltage characteristics in this region indicates the presence of an excess current that increases linearly with decreasing temperature. A critical current is observed below T_{2D} and the current-voltage characteristics assume a "disruptive" character due to the inhomogeneous entry of vortex strings.[3]

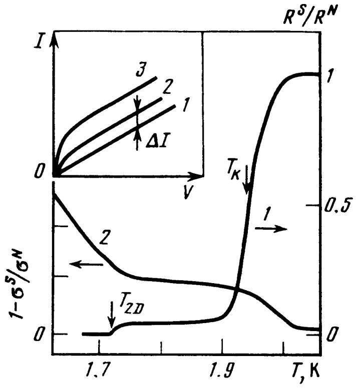

FIG. 1. 1—Copies of the recorded film resistance as a function of temperature. 2—Normalized conductivity of the Al-Al_2O_3-Bi tunnel junction in the region in which the aluminum electrode goes over into the superconducting state. The inset shows current-voltage characteristic of the aluminum film with excess current ΔI: curve 1) $T = 4.2$ K, 2) 1.85, 3) 1.74.

Experiments with films in the microwave field were performed at temperatures $T\simeq T_k$ at which there were no intrinsic oscillations in the conductivity.[1] Irradiation gave rise to a structure on the d^2U/dI^2 *versus* U characteristics with strictly periodic maxima (Fig. 2). When the external field frequency was increased (reduced) at constant power, the

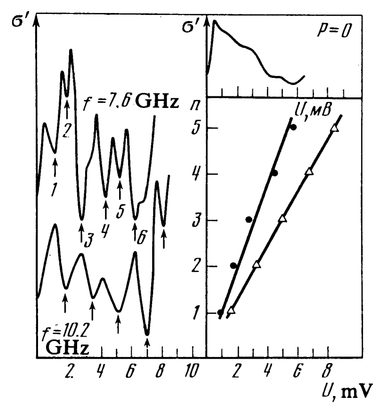

FIG. 2. $\sigma'(U) = d^2I/dU^2$ as a function of U, and the running number of oscillation period as a function of the bias voltage under microwave illumination at $T = 2.05$ K, $P = 10^{-5}$ W (●—$f = 7.6$ GHz, △—10.2 GHz).

period of the oscillation was found to increase (decrease). The dependence of the position of the maxima along the voltage scale on their running number is linear, and the ratio of the oscillation periods is equal to the frequency ratio of the electromagnetic fields applied to the film. The effect is observed only in a narrow temperature range near T_k. The relationship between the irradiation frequency and the period of the oscillations can be used to estimate from the Josephson relation the number of coherent sources $n = 2eU/\hbar\omega$ contributing to the response of the system. The value $n \sim 100$ was found to remain unaltered for a given geometry of the specimen. As the temperature was reduced, intrinsic-generation and self-detection effects were found to "mask" the effect of the microwave signal on the specimen. The function $\sigma'(U)$ then reflected the presence of different subharmonic components of the natural oscillations of the system. The fact that an oscillating microwave field structure can be induced is clearly a manifestation of the coherence properties of the system and of response times that are characteristic for Josephson contacts. These effects should also be reflected in the so-called inverse Josephson effect, i.e., the transformation of microwave radiation into a constant voltage.[4] In fact, a voltage was recorded across the film when the current circuit was opened. An increase in the microwave signal led to an increase in the potential difference and reached $U = 1$ mV for a completely open attenuator ($P \simeq 20$ mW).[1)] It was found that the effect was observed only in the temperature range $T_{2D} < T < T_k$, i.e., in the region corresponding to the resistive superconducting transition in the film. We also note that the vortex structure whose generation is not related to external fields and measuring currents in the specimen was also recorded in this temperature range.[5]

The microwave field had an appreciable effect on $R(T)$. For power levels $P = -13$ dB relative to the generator power, the resistance of the film was found to decrease throughout the range $T_{2D} < T < T_k$, and the value of T_{2D} was found to shift towards higher temperatures ($\Delta T \simeq 0.01$ K). Further increase in the power was accompanied by an increase in the resistance of the film, which substantially exceeded the value corresponding to $P = 0$ (Fig. 3). The position of the first step

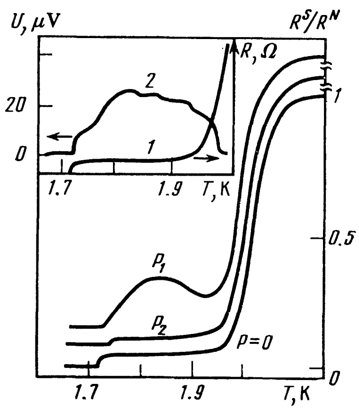

FIG. 3. Effect of 10-GHz microwave power on $R(T)$ of the aluminum film. $P_1 = -8$ dB, $P_2 = -13$ dB (the superconductivity curves are shifted along the ordinate axis). The inset shows the voltage across the specimen, induced by the microwave radiation, as a function of temperature.

on the $R(T)$ curve near T_k was found to be the same for all microwave-signal strengths. We have thus detected an enhancement of the superconducting properties of wide films by the application of microwave radiation—an effect that was previously observed[6] only for narrow channels with $w \sim 1\ \mu$m.

All the foregoing data suggest that a system of weak-link contacts, or the so-called Josephson medium, was established in the films that we investigated. Qualitative ideas on the structure of weak links were deduced from the temperature dependence of the conductivity $\sigma(T)$ of the Al-Al_2O_3-Bi tunnel junction under zero bias. The point is that, near T_k, the conductivity $\sigma(T)$ is determined by the change in the gap Δ and satisfies the relation[7]

$$1-\frac{\sigma_S}{\sigma_N}=\frac{\langle\Delta(\mathbf{r},T)\rangle^2}{(k_B T_k)^2}B,$$

for any Cooper pair-breaking mechanism, where B is a constant determined by the particular mechanism.

In contrast to the usual linear behavior of $\sigma(T)$ in homogeneous systems, our films were found to have nonlinear $\sigma(T)$ in the region of the $R(T)$-transition spread, which clearly indicates an inhomogeneous modulus of the order parameter in the Al electrode. We note that this behavior of the film is not due to edge or thickness effects, but is connected with the structure of the specimen. Electron microscopy of the films showed the presence of a considerable spread of the linear size of crystallites forming the film (50–200 Å). Bearing in mind the known dependence of the critical parameters T_k of aluminum films on the mean size of granules,[8] it may be considered that a structure of the form *S-N-S*, i.e., a set of superconducting regions in a normal host, appears in low-resistance films with $R_\square^N \sim 10\ \Omega$. The presence of *S*-regions in an *N*-host is responsible for the large ($\Delta T \gg (R_\square^N/R_c)T_k$) width of the semiconducting junction, which reflects the spatial inhomogeneity of the order parameter.

The data of Fig. 2 and the well-known Josephson relation enable us to determine the number of weak-link contacts that are responsible for the coherent response of the system to microwave radiation. However, there is a considerable discrepancy between the results of simple estimates and the proposed number of weak links with $d \gtrsim \xi(T)$. We consider that the nonlinear properties of the films that we have found are related to the dynamics of fluxoids of unlike polarity that appear in the absence of the magnetic field as a result of thermodynamic fluctuations.[9] In that case, their electromagnetic size $\lambda_\perp$ is much greater than the size of an individual link, so that the area trapped by a vortex will contain a large number of Josephson microjunctions. The structural inhomogeneity of the system will then have very little effect on the properties of the fluxoids and, as they move, the individual links will synchronize along the flow lines of the vortex supercurrent. The resonant interaction between external microwave fields and the system of these moving vortices results in the observed features of the current-voltage characteristic. The short response time $\tau \sim 10^{-10}$ s to the electromagnetic radiation may be regarded

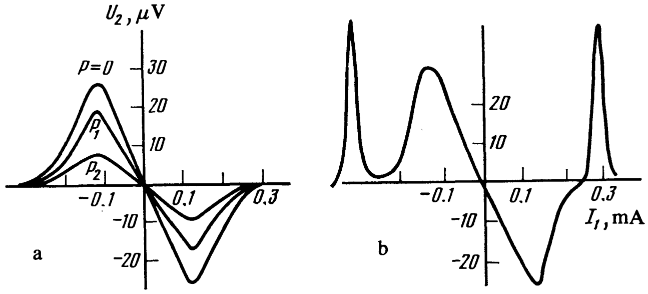

FIG. 4. a) Amplitude of the signal from the flux transformer, $U_2(I_1)$, as a function of the microwave power, b) anomalous behavior of the characteristic of the flux transformer.

as evidence for the high mobility of the vortices, the creation of which turns out to be possible in the system of weak links.

In this series of experiments, we also used the superconducting flux transformer: in the presence of the microwave field, we recorded the voltage U_2 induced by the motion of vortices in the film as a function of the transport current I_1 in the generator film. The shift of T_{2D} on the $R(T)$ curve toward higher temperatures upon irradiation was accompanied by a reduction in the signal amplitude from the transformer (Fig. 4). We think that the last effect is due to the stimulation of the supercurrent across the microjunctions, i.e., an increase in the contact link energy, responsible for the corresponding increase in vortex pinning.[10] This, in turn, affects the reduction in the resistance of the film throughout the temperature range $T_{2D} < T < T_k$. Further increase in the microwave power leads to an increase in the effect of the microwave currents on the vortices, the dynamics of which governs dissipative processes in the resistive region.

In the course of our investigation of the transformer characteristics in zero external field there were several cases in which, in contrast to the vortex drag, we observed on the $U_2(I_1)$ curve singularities that were independent of the polarity of the current I_1 (see Fig. 4). It seems reasonable to relate them to processes of generation and detection of internal electromagnetic fields in the resonant strip system that constitutes the film transformer.

3. The study of the so-called Josephson media, i.e., systems of random junctions, is attracting considerable attention at present. The greatest advances—both experimental and theoretical—have been achieved by studying regular structures.[11] Nevertheless, the problem of internal synchronization of a large ensemble of junctions with different properties remains unsolved. Essentially, the results reported here and the natural oscillations in the conductivity reported previously[1] suggest the presence of a nonstationary Josephson effect in thin and wide films of aluminum with $R_{\square}^{N} \ll \hbar/e^2$ in a certain temperature range near T_k. The synchronization of an enormous number of weak links forming the film may be due to the dynamics of thermally-generated vortex structures.

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[1)]The inset in Fig. 3 shows the temperature dependence of the induced potential difference across the film under exposure to microwave power $P = 5 \times 10^{-6}$ W.

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