Superconducting aluminum film in a microwave radiation field

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The effect of microwave radiation (850 MHz) on the properties of a superconducting aluminum film is investigated. A transition into a "resistive" state, with an impedance intermediate between the superconducting and normal states, is observed when a critical radiation frequency is observed. The dependences of the critical powers of superconductivity destruction and restoration on the magnetic field and on the temperature are investigated. The dependence of the impedance in the resistive state on the radiation power and on the magnetic field are investigated. Attempts are made to interpret the experimental results.

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In a preceding paper[1] we have reported that a tin film placed in a magnetic field goes over into a "resistive" state when a definite power of the microwave radiation is reached. In this resistive state the impedance of the film was intermediate between the normal and superconducting state, depending on the value of the magnetic field and on the radiation power. The results obtained in Ref. 1 pertained to a temperature region far from the critical temperature T_c. The region near T_c, which lies above the λ point in helium, was inaccessible because of the manner in which the apparatus was constructed. We report here a detailed investigation of the phenomenon observed in Ref. 1 for the case of aluminum films, for which the temperature region near T_c can be investigated.

EXPERIMENTAL PROCEDURE

We investigated the dependence of the active component of the surface impedance of aluminum films at a frequency 850 MHz on an external magnetic field at various levels of microwave radiation at the same frequency. The aluminum films were produced by condensing the metal in a vacuum $10^{-5}-10^{-6}$ Torr on glass and optically polished silicon single-crystal substrates. The film thicknesses were chosen in the range 500 – 700 Å, resulting in superconducting transition temperature T_c in the region 1.5 – 1.6 K, and making it possible to pump-on helium-vapor to obtain the necessary temperatures.

The experimental setup constitutes a flow-through spectrometer system, and its block diagram is shown in Fig. 1. Attenuators 2 and 4 could be used to vary the microwave power fed to the resonator, leaving the power fed to the receiver 5 constant. The signal detected and amplified by the receivers was added to the negative signal from the reference-voltage source 8 and fed to the Y coordinate of the automatic plotter 7. The voltage of the X coordinate came from a Hall pickup. This system made it possible to measure by a null method the variation of the microwave power passing through the resonator with the film when the magnetic field was varied. At a constant input power, with resonator parameters independent of the magnetic field, this change is proportional to the change of the active component of the film impedance.

To obtain the necessary microwave field amplitudes we have used a helical resonator comprising a coil of 2 mm diameter, and 1 mm pitch, made of a piece of radiotechnical copper wire of 0.47 mm diameter and ~$\lambda/2$ long, where λ is the radiation wavelength. The film was separated from the resonator by a copper screen 2 (Fig. 2) with a diaphragm 7 of 2.5 mm diameter, through which the radiation passed. This eliminated the action of the microwave field on the edges of the film. The gap between the generatrix of the coil and the plane of the diaphragm was 0.5 mm. This resonator had a Q of 10^3 at 4.2 K. The microwave and constant magnetic fields were parallel to each other and to the film surface. The absorbing cell was placed in a superfluid-helium bath. The power fed to the resonator ranged from 10^{-7} to 10^{-2} W. The use of such relatively low powers, the independence of the results on the substrate material and of the additional methods used to carry the heat away from the film suggests that

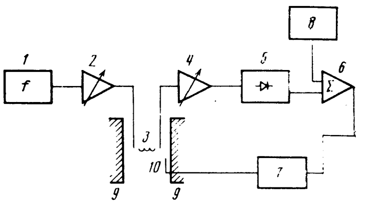

FIG. 1. Block diagram of experimental setup: 1—generator, 2, 4—attenuators, 3—resonators, 5—receiver, 6—adder, 7—automatic plotter, 8—reference-voltage source, 9—electromagnet, 10—Hall sensor.

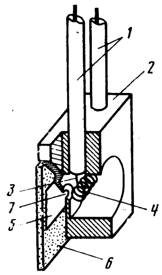

FIG. 2. Construction of absorbing cell: 1—coaxials, 2—copper housing, 3—coupling post, 4—helical resonator, 5—film, 6—substrate, 7—diaphragm.

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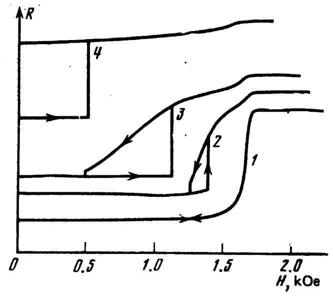

FIG. 3. Typical plots of the film impedance vs. the magnetic field at various microwave-field amplitudes (h in relative units) in the resonator: curve 1—$h=0.01$, 2—$h=0.2$, 3—$h=0.63$, 4—$h=1.05$.

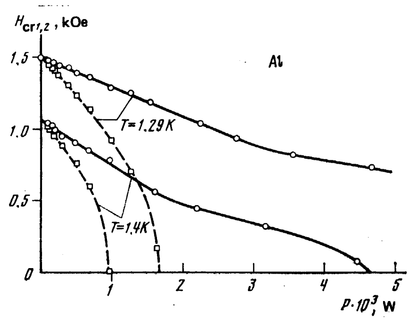

FIG. 4. Plots of the magnetic field of the impedance jump (circles) and of the field of return to the superconducting state (squares) against the microwave power in the resonator. Dashed lines—calculation by formula (5).

the thermal effects are negligible in the phenomena described below.

RESULTS

Figure 3 shows a typical plot of the impedance of an aluminum film with $T_c = 1.50$ K against the magnetic field. A higher number of the curve corresponds to a larger amplitude h of the microwave field on the film surface. For the sake of clarity the curves are shifted vertically relative to one another. At a very small microwave power in the resonator (~10^{-6} W) the film goes from the superconducting to the normal state when a parallel critical magnetic field H_{cr0} is reached, and the impedance changes from its superconducting value R_s to the normal value R_N (Fig. 3, curve 1). A one order-of-magnitude change of the microwave power does not change the character of the superconducting transition, and merely shifts it slightly towards weaker magnetic fields (the shift usually does not exceed 100 Oe). At resonator powers higher than 10^{-5} W an qualitative change of the very form of the transition takes place (curves 2 – 4).

First, in a certain magnetic field $H_{cr1} < H_{cr0}$ an abrupt jump of the impedance takes place, to a value R less than R_N. With increasing microwave field, H_{cr1} decreases and the size of the jump increases.

Second, the jump is followed by a smooth growth of the impedance with increasing magnetic field. In the field H_{cr0} the impedance reaches the value R_N and then remains constant.

Third, whereas at very small powers there was no hysteresis in the impedance as a function of the magnetic field (curve 1), on the section where the impedance varies smoothly ($H > H_{cr1}$), there is no hysteresis at high powers, but it does appear when the field decreases down from H_{cr1}. The impedance of the film returns to the superconducting value with a small jump in a field $H_{cr2} < H_{cr1}$. With increasing microwave power the hysteresis region increases and, starting with a certain power P_{cr2}, the film does not return to the superconducting state even in a zero magnetic field.

Figure 4 shows plots of the jump field H_{cr1} (circles) and of the return field H_{cr2} (squares) against the power fed to the resonator for a film with $T_c = 1.53$ K for two temperatures. The initial sections of the $H_{cr1}(P)$ plots are linear with good accuracy. With increasing temperature, the influence of the microwave field increases [the slopes of the $H_{cr1}(P)$ curves increases]. It is seen from the figure that for each temperature there is a power P_{cr1} at which an impedance jump takes place in a zero magnetic field.

We have investigated the temperature dependences of the powers P_{cr1} and P_{cr2}; they are shown in Fig. 5. It can be stated that P_{cr2} varies linearly with temperature, although in the region near T_c the dependence is stronger. The variation of P_{cr1} in the same region is quite complicated. It should be noted that for temperatures near T_c, where $P_{cr2}(T)$ begins to deviate from linearity, the impedance jump on the plots of the impedance against the magnetic field also vanishes. The same figure shows the temperature dependence of $(R_N - R_s)/R_N$. It is seen that in the temperature interval in which the superconductor impedance changes coincides with the interval in which the functions $P_{cr2}(T)$ and $P_{cr1}(T)$ have a complicated behavior.

It is convenient to represent the experimental results (Fig. 3) in a somewhat different form and obtain the dependence of the film impedance $R(H)$ in a fixed magnetic field on the microwave field amplitude. This is done in Fig. 6 for three values of the magnetic field. With increasing microwave field amplitude, a jump of the impedance takes place in the superconducting state (vertical dashed lines). Further change of the amplitude leads to a smooth change of the impedance (solid lines).

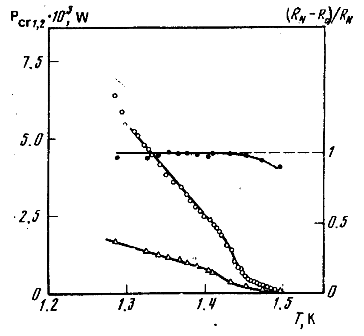

FIG. 5. Temperature dependences of P_{cr1}(○), P_{cr2}(△), $(R_N - R_s)/R_N$(●).

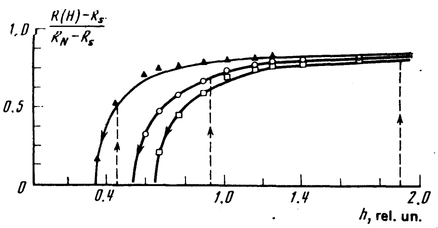

FIG. 6. Dependence of the impedance of an aluminum film on the microwave-field amplitude at several values of the constant magnetic field: □—$H=0$ kOe, ○—$H=0.78$ kOe, ▲—$H=1.30$ kOe.

DISCUSSION OF RESULTS

We propose that the impedance jump is due to destruction of the superconducting state as a result of the increase of the concentration of the nonequilibrium quasiparticle. The mechanism whereby the concentration of the nonequilibrium excitations increases when a superconductor is exposed to an electromagnetic wave of frequency $\hbar\omega \ll \Delta$ is considered in Ref. 2. It is clear that the collapse of the superconducting regime is avalanche-like, since a decrease of the energy gap Δ leads to an increase of the nonequilibrium excitations, which leads in turn to a decrease of Δ. Such a collapse can manifest itself in experiment in the form of an abrupt jump of the impedance when a definite critical radiation-power P_{cr1} is reached on the film surface.

The critical power P_{cr1} is larger the wider the initial equilibrium gap $\Delta(H, T)$ in the superconductor, and consequently the weaker the magnetic field in which the superconductor is placed, since

$$\Delta^2(H,T)=\Delta^2(0,T)(1-H^2/H_{cr0}^2), \quad (1)$$

where H_{cr0} is the critical magnetic field of the superconducting film at the temperature T in the absence of radiation. This agrees with the fact that when the microwave power is increased the magnetic field in which the impedance jump takes place decreases (Figs. 3,4). At a fixed ratio H/H_{cr0}, the critical power will be smaller the lower the temperature, as is also confirmed by experiment (Fig. 4).

It is a rather complicated matter to obtain an analytic solution for the function $P_{cr1}(H, T)$, since it is necessary to know the connection between the amplitude of the microwave field on the film surface (a quantity in fact set in the experiment) and the field inside the superconductor. The latter field is determined by the impedance, which is itself connected with H and T and depends in addition on the radiation power. Such a problem must therefore be solved self-consistently. We propose therefore that the rather complicated temperature dependence of P_{cr1} near the critical temperature (Fig. 5) is due to the temperature dependence of the film (as seen from Fig. 5, it is in this region that the film impedance changes with temperature), as well as with the nonlinearity of the impedance as a function of the microwave power.

We examine now the possible reasons why the film impedance is smaller than R_N after the jump. There are apparently two such reasons.

The first is that when a critical excitation density is reached, a homogeneous superconductor goes over abruptly not into the normal state, but into a spatially inhomogeneous state, such as an alternation of regions of normal and superconducting phases. This can occur, for example, if the local decrease of the quasiparticle-number density in a certain region of space leads to an increase of the order parameter, and this in turn decreases the number of quasiparticles, whereas in the neighboring region, where the excitation density has increased locally, the reverse takes place. These two processes are self-maintaining, and a spatial inhomogeneity develops. An instability of this type was considered earlier[3] for a superconductor under electromagnetic radiation at a frequency $\hbar\omega \ll \Delta$. An indication that such a "phase stratification" takes place in a narrow superconducting channel when a definite microwave power is reached is contained in Ref. 4.

In the case of laser irradiation, these instabilities have apparently been sufficiently well investigated both experimentally and theoretically (see, e.g., Ref. 5). A change in the magnetic field or in the radiation power following the transition into the spatially inhomogeneous state leads to a change in the ratio of the normal and superconducting phase, and this manifests itself by a smooth variation of the impedance.

The second possible reason is the following. When the critical microwave power is reached, the superconductor goes over into the normal state. The order parameter in the normal state is subject to infinitesimally small fluctuations, but their contribution to the conductivity is large and depends on the radiation pow- and on the magnetic field.[6,7] Therefore the impedance of a normal film with infinitesimally small superconducting fluctuations can be significantly smaller than R_N. An unambiguous interpretation of the result calls for additional experimental and theoretical studies.

We discuss now the hysteresis of the impedance when the radiation power or the magnetic field is decreased after the jump. We assume that the cause of the hysteresis is of general character, independent of the state realized in the film after the impedance jump (normal with fluctuations, or stationary and spatially homogeneous in the form of normal and superconducting regions), and consists in the following. In the experiments the amplitude h of the microwave magnetic field on the surface of the film is set beforehand. The electric component E inside the film, on the other hand, is determined by the total impedance Z, and for thin films $E/h \sim Z$.[8]

In the superconducting state the impedance is small and E inside the superconductor is correspondingly small. After the jump, the impedance increases strongly and the field E inside the film increases. If the superconductor changes to a homogeneous normal state, then the distribution of E inside the film is uniform, and if it changes into a spatially inhomogeneous state, then E changes with the period of the structure. All that matters is that the amplitude of the electric component of the microwave field is substantially larger in the normal regions than in the superconducting ones. And if this is the case, the question is now whether the normal state with the field E is stable with respect to a transition into the superconducting space, for if E is strong enough then the Cooper pair, once produced, acquires during the period ω^{-1} of the field a momentum larger than needed for pair breaking. The stability limit in the absence of a field is easily obtained from the nonstationary generalization of the Ginzburg-Landau equations.[9,10] We write the first of them in the form[8]

$$\frac{\partial\Delta}{\partial t}-D\left(\frac{\partial}{\partial x}+ip_s(t)\right)^2\Delta=C_1(T_c-T)\Delta+\frac{C_2}{T_c}|\Delta^2|\Delta, \qquad (2)$$

where D is the diffusion coefficient and C_1 and C_2 are dimensionless positive constants.

In the presence of a constant magnetic together with a high-frequency field

$$p_s(t)=-\frac{2e}{c}A+\frac{2e}{\omega}E\sin\omega t, \qquad (3)$$

where A is the vector potential of the constant magnetic field, and E is the amplitude of the electric component of the microwave field. An analysis of Eq. (2) with the pair momentum in the form (3) yields the following limit for the stability of the normal state:

$$A=A_{\text{cr}0}(1-E^2/E_{\text{cr}}^2)^{1/2}, \qquad (4)$$

where $A_{\text{cr}0}=\Phi_0/2\pi\xi(T)$ and $E_{\text{cr}}=2^{1/2}\,\Phi_0/\xi(T)\lambda$, while Φ_0 is the magnetic-flux quantum $\xi(T)$ is the temperature dependent coherence length, and is the radiation wavelength. Equation (4) can be rewritten in the form

$$H_{\text{cr}2}=H_{\text{cr}0}(1-P/P_{\text{cr}2})^{1/2}, \qquad (5)$$

where P is the power in the resonator and $P_{\text{cr}2}$ is the critical power in the resonator. It is clear that the film becomes superconducting only in fields weaker than $H_{\text{cr}2}$. The value of $P_{\text{cr}2}$ must be determined from experiment, for to obtain in analytic form the proportionality coefficient of E^2_{cr} and $P_{\text{cr}2}$ we must know the connection between the power in the resonator and the field inside the film. A plot of (5) is shown dashed in Fig. 5. It is seen that the agreement between the theory and experiment is very good.

The fact that the film impedance decreases when the magnetic field decreases from $H_{\text{cr}1}$ to $H_{\text{cr}2}$ at a fixed radiation power (Fig. 3) or when the power is decreased from $P_{\text{cr}1}$ to $P_{\text{cr}2}$ at a fixed magnetic field (Fig. 6) can be explained both in the model of a normal film with fluctuations and in the model in which a spatially inhomogeneous state is proposed. In the former case the reason, as shown in Ref. 3, is the increased contribution of the fluctuations to the conductivity. In addition, it was found in Ref. 11 that on this section, notwithstanding the presence of an electric field $E>E_{\text{cr}}$ in the film, superconducting nuclei can be produced and develop, and these contribute to a decrease of the impedance. In the second case, the cause is the already pres- present superconducting-phase regions.

It follows from (4) that $P_{\text{cr}2}$ varies in proportion to (T_c-T) if the coefficient of proportionality of $P_{\text{cr}2}$ and E^2_{cr} does not depend on temperature. As seen from Fig. 5, this is indeed the case at a certain distance from T_c. The deviations from linearity near T_c are possibly due to the screening action of the superconducting fluctuations, an action that can be taken into account in the calculation of the proportionality coefficient and depends most strongly on the temperature precisely near T_c.

In conclusion, we wish to note that despite the qualitative agreement between the experimental results and the existing theories, the nature of the resistive state at microwave frequencies is not completely clear. Nor is the kinetics of the transition from the superconducting to the resistive state and the reverse transition clear. These questions will be the subject of a future study.

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