Influence of microwave irradiation on high-frequency absorption by thin superconducting films (superconductivity stimulation)

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An investigation was made of the influence of microwave (9.4 GHz) irradiation on the temperature dependences of electromagnetic absorption at frequencies 10–1000 MHz in thin wide aluminum films. A considerable reduction in the absorption was observed near T_c and the onset of the absorption was shifted by an amount up to 10^{-2} K. The results were interpreted as enhancement of superconducting properties predicted by a theory of stimulation by a microwave field.

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1. INTRODUCTION

Considerable attention has been given recently to the influence of microwave irradiation on the properties of superconductors. This interest has arisen largely out of the results of experimental and theoretical investigations of stimulation of superconductivity by a microwave field. A mechanism of this effect proposed by Éliashberg[1] is as follows: microwave irradiation alters the distribution function of quasiparticles in a superconductor and this can, under certain conditions, increase the energy gap Δ. Consequently, there should be an increase in the superconducting transition temperature T_c, as well as in the critical magnetic field H_c and in the critical current j_c.

An increase in the critical current in film microbridges was first reported in Refs. 2 and 3. Since then the effect of stimulation of the critical current by microwave irradiation has been observed for practically all types of weakly coupled superconductors and the main features of the phenomenon have been studied (see, for example, the review in Ref. 4).

It is much more difficult to detect directly the increase in the energy gap Δ under the influence of microwave radiation in a tunnel experiment.[5–7] These difficulties have given rise to critiques[8,9] expressing doubts about the correctness of the interpretation of the increase in j_c and of the shifts of the singularities of the tunnel current-voltage characteristic under the action of microwave radiation as due to an increase in T_c and Δ.

One must also point out that superconductivity stimulation (an increase in the critical current and gap) have been observed only for special film devices (microbridges, microscopic short circuits, long narrow channels, etc.) characterized by a rigid requirement of narrow width (usually $< 10\mu$). In spite of the fact that many reasons can be adduced to account the condition of a small width (better heat removal, feasibility of a homogeneous distribution of currents and fields), it is clear that the superconductivity stimulation mechanism does not by itself impose any restrictions on the film width.

It follows from the above discussion that it would be interesting to investigate the influence of microwave radiation not only on the critical current and on the energy gap, but also on some other parameter of a superconductor. The first investigation of this kind was reported by Pals and Dobben[10] who determined the influence of microwave irradiation on the quantization of the flux in a thin-film cylinder. Sridhar and Mercereau[11] showed that a convenient parameter is the active component of the surface impedance of a film, which is very sensitive to the form of the distribution function of quasiparticles in a superconductor. Moreover, in this case one would expect to observe the predicted[11] microwave-induced reduction in the surface resistance of real wide superconducting films.

We shall report the results of an investigation of the influence of microwave (3-cm) radiation on the absorption of electromagnetic waves of frequencies 10–1000 Mhz in wide (~1 cm) superconducting aluminum films.

2. EXPERIMENTAL METHOD

The apparatus (basically similar to that used in our earlier investigations[12,13]) was based on a sweep spectrometer system and its block diagram is shown in Fig. 1. A frequency-modulated signal generated by a sweep oscillator 1 excited, by inductive coupling, a resonance circuit 2 in the form of a single-layer coil L (diameter ~4 mm and length ~5 mm,

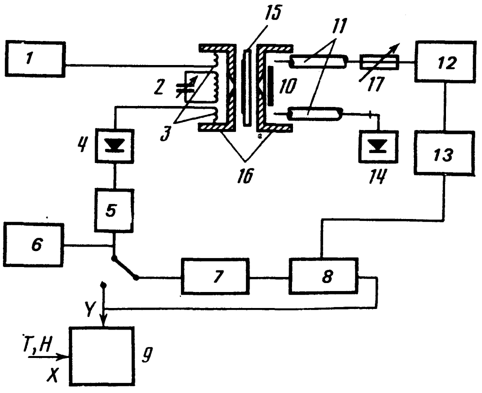

FIG. 1. Block diagram of the apparatus: 1) sweep frequency oscillator; 2) resonant circuit; 3) devices for coupling to the circuit; 4) detector (30–1000 MHz); 5) peak detector; 6) reference voltage source; 7) narrow-band amplifier; 8) phase detector; 9) plotter; 10) strip resonator; 11) coaxial lines; 12) klystron; 13) pulse generator; 14) microwave detector; 15) substrate and film; 16) copper shields; 17) attenuator.

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consisting of 10–15 turns of copper wire of the type used in radio engineering) connected in parallel with a variable capacitor C. The operating frequency was altered by changing the capacitance of C directly in liquid helium. The inductance coil was surrounded by a copper shield 16 with an aperture of diameter 2 mm near which a film on a substrate 15 was placed parallel to the coil axis. The dimensions of the film were of the order of 1×1 cm and the use of the shield with an aperture made it possible to study the relatively small central part of the film and thus avoid the influence of its edges, which are normally far from perfect. The frequency-modulated signal was converted into an amplitude-modulated one by the passage through the resonator containing the film and it then reached a peak detector 5. The detected signal was compensated by a source 6 of a reference voltage and it was applied to the Y input of a plotter 9. The X input of the plotter received the voltage from potential contacts of a semiconductor thermometer or a Hall probe connected in the same circuit as the current source.

The use of frequency modulation in combination with peak detection made it possible to avoid dispersion and to record a signal proportional to the change in the Q factor of the LC circuit by varying either the temperature or the magnetic field. In the case of small changes of the Q factor the signal was proportional to the change in the power absorbed by the film and this, in its turn, was proportional to the change in the active component of the film impedance, since the parameters of other parts of the absorption cell were constant in the investigated range of temperatures and magnetic fields.

The influence of microwave radiation was investigated by placing—on the opposite side of the film—a second copper shield 16 with an aperture 3 mm in diameter so that the centers of both apertures were on the same axis and the plane of the apertures were parallel. A half-wave copper strip resonator 10 excited by a klystron (30 mW) was placed inside this shield parallel to the planes of the aperture and film. The microwave power in the channel was varied by an attenuator 17. The use of two coaxial apertures of different diameters made it possible to study the central part of the irradiated spot of the film and thus reduce somewhat the influence of the inhomogeneities of the field at the edges of the irradiated region.

The output power of the klystron was either kept constant or 100%-modulated by rectangular pulses of 20–100 Hz frequency. In the latter case the measurement procedure was as follows. The modulation frequency in the high-frequency channel was selected to be about two orders of magnitude higher than that in the microwave channel. A narrow-band amplifier 7 was connected after the peak detector and this amplifier selected the signal at the klystron modulation frequency. The signal was subjected to lock-in detection and it was recorded by the plotter. After such detection its magnitude and sign were proportional to the relative change in the high-frequency absorption under the action of microwave radiation.

We investigated aluminum films of thickness 500–1000 Å prepared by condensation in 10^{-5} Torr vacuum on 0.1-mm thick glass substrates kept at room temperature. The investigated films were characterized by the resistance ratio $R_{300}/R_{4.2} = 2$–6 and by a superconducting transition temperature T_c in the range 1.4–1.6 K, which made it possible to carry out all the experiments by pumping out helium vapor.

The measurements were usually carried out as follows. The helium cryostat was pumped out to the minimum temperature (~ 1.27 K), the circuit was subjected to a compensation procedure, and then the temperature dependence of the high-frequency absorption was recorded during heating. Since the specific heat of a glass substrate carrying a film was low at helium temperatures, and since the rate of heat loss to superconducting helium was high, it was possible to establish an equilibrium in the substrate-helium system at a low heating rate. Therefore, a thermometer placed in the helium path recorded the film temperature. This was confirmed also by the absence of hysteresis between the absorption curves recorded during heating and cooling.

Whenever necessary, the magnetic field was created by an external electromagnet and the terrestrial magnetic field was not compensated. All the high-frequency absorption measurements were carried out at a relatively low (10^{-4}–10^{-5} W) level of the power entering the measuring cell and this was done in order to avoid overheating effects.

3. RESULTS AND DISCUSSION

Figure 2 shows typical records of the temperature dependences of the absorption exhibited at the frequency of 143 MHz by an aluminum film for several microwave (9.4 GHz) powers. The numbers alongside the curves give the relative attenuation (in decibels) in the microwave channel.

In the absence of microwave radiation (curve denoted by ∞) the temperature dependence of the absorbed power shows clearly a narrow peak located slightly below T_c. It is clear from the figure that the absorption at the maximum is much stronger than the absorption by the film in the normal state. It should be pointed out that the high-frequency absorption peak appears only if the frequency is less than a certain characteristic value. In the case of films investigated by us this characteristic frequency was about 300 MHz.

It is clear from Fig. 2 that an increase in the microwave radiation power results in a considerable reduction (the re-

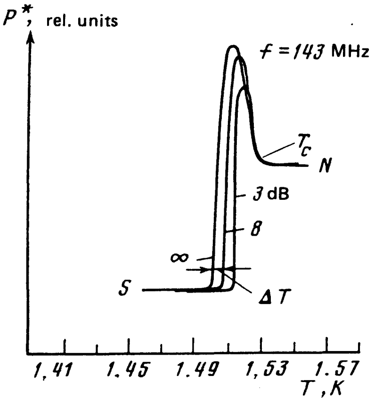

FIG. 2. Temperature dependence of the high-frequency power P^* absorbed by a superconducting film subjected to microwave irradiation of the different powers.

duction is practically to zero when measured relative to the absorption in the normal state) in the high-frequency absorption at temperatures slightly below T_c and it also causes some increase in the absorption in the direct vicinity of T_c. Consequently, the whole absorption curve shifts toward higher temperatures. However, we observed no significant increase in T_c, which was regarded as the point at which the absorption curve reached a plateau.

Beginning from a certain critical microwave radiation power, the temperature dependence of the high-frequency absorption shows an abrupt destruction of the pure superconducting state and a transition to a high-absorption state. The temperature at which this abrupt jump occurs decreases on increase in the microwave radiation power. Such abrupt changes in the superconducting regime were observed by us earlier[13,14] when the microwave radiation frequency was about 1 GHz. The nature of the jump was clearly related to the transition of the film to a spatially inhomogeneous state. We concluded that jumps of similar origin were observed in studies of stimulation of superconductivity and manifested as an abrupt vanishing (at some incident radiation power) of the critical current in narrow channels and microbridges[15,16]; this was attributed to an instability of a strongly nonequilibrium superconductor relative to a transition to an inhomogeneous state.[17,18]

Since at microwave radiation powers above the critical value we observed only an increase in the high-frequency absorption and a corresponding shift of the absorption curve to the left, we shall not consider this range of powers further; all the results given below apply to powers below the critical value.

Figure 2 can be used to obtain the dependence of the temperature shift ΔT of the onset of a strong rise of the absorption on the microwave radiation power. This is easily done using only the temperature dependences of the high-frequency absorption obtained for different microwave radiation powers when ΔT is sufficiently high ($\Delta T \gtrsim 4 \times 10^{-3}$ K), i.e., at relatively high microwave radiation powers. The values of T found in this way are represented in Fig. 3 by points with the associated experimental errors. At low powers (and correspondingly low values of ΔT) the method of direct determination of the shift of the absorption curve is not sufficiently sensitive or accurate.

In this case the change in the high-frequency absorption under the action of microwave radiation can be investigated conveniently by amplitude modulation of the microwave signal. We can then observe a cross-modulation effect, i.e., the action of amplitude-modulated microwave radiation results in modulation of the properties of an investigated superconductor and this causes modulation of the absorption (an also of the reflection and transmission coefficients) of an electromagnetic wave of frequency other than that of the microwave radiation. As pointed out in Sec. 2, the use of lock-in detection makes it possible to determine in this case the sign and the relative magnitude of the change in the high-frequency absorption.

Figure 4 shows examples of the temperature dependences of the relative change in the high-frequency absorption P^* at the frequency of 143 MHz obtained for the same sample as that for which the temperature dependences are plotted in Fig. 2; the results are given for several powers of microwave radiation of the same frequency 9.4 GHz as before. The negative parts of the curves correspond to the reduction in the high-frequency absorption, whereas the positive parts indicate enhancement of the absorption. If at some fixed microwave radiation frequency the maximum reduction in the high-frequency absorption is set in correspondence to the temperature shift ΔT found by the direct method (from the dependences in Fig. 2), a certain scaling coefficient is obtained. This coefficient allows us to convert the measured (by the modulation method) maximum reduction in the high-frequency absorption into the temperature shift ΔT of the absorption curve. Naturally, this operation is valid only at low values of the maximum change in the high-frequency absorption. This shifts ΔT obtained in this was are represented in Fig. 3 by points without the associated experimental errors. The scaling is carried out at the point identified by a square in Fig. 3.

It is clear from Fig. 3 that the dependence of ΔT on the microwave radiation power P is linear at low powers but saturates on increase in P, well below the critical value when the superconducting regime is destroyed as described above.

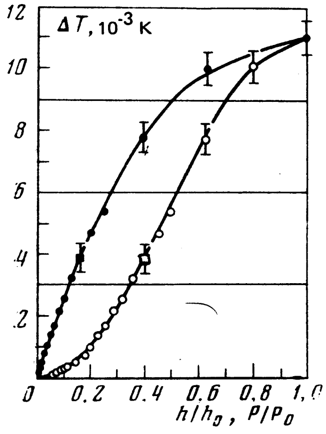

FIG. 3. Dependences of the temperature shift of the onset of strong absorption on the relative magnitudes of the microwave radiation power P (O) and microwave amplitude h (●).

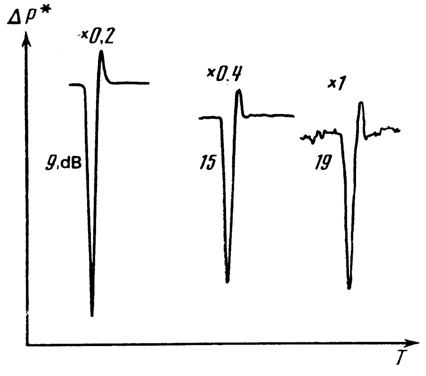

FIG. 4. Temperature dependences of the relative change in the high-frequency power ΔP^* absorbed in the presence of microwave radiation of different powers.

This corresponds to a value of the ratio P/P_0, somewhat smaller than unity.

We can explain the results obtained by considering first the factors that determine the temperature dependence of the high-frequency absorption in thin superconducting films.

If the amplitude of an electromagnetic wave is infinitesimally small, the temperature dependence of the absorption of this wave is governed by the temperature dependence of the active component $R(T)$ of the surface impedance. In the case of thin "dirty" films we have the local relationship $R(T) = \mathrm{Re}[1/\sigma(T)]$ where $\sigma(T) = \sigma_1 - i\sigma_2$ is the complex conductance. At the frequencies employed (about 100 MHz) the dependence $R(T)$ is practically a vertical step, i.e.,

$$R(T)=1/\sigma_N, \quad T>T_c; \quad R(T)\approx 0, \quad T<T_c.$$

In fact, the step becomes smeared out because of the influence of inhomogeneities of the film and because of the fluctuations.

In reality, the amplitude of an electromagnetic wave may be small but it is always finite. At the powers employed by us an estimate of the amplitude of the magnetic field of an electromagnetic wave reaching the film surface gives $\sim 10^{-2}$ Oe. This means that on approach to T_c from the low-temperature side we can expect sooner or later considerable nonlinear effects which cause a strong rise in the absorption before manifestation of the broadening of the superconducting transition by inhomogeneities. In the case of wide films we can distinguish two groups of nonlinear phenomena.

The first group is the generation in the film of vortices with axes perpendicular to the film plane. These vortices appear at film edges because of the action of the perpendicular (to the film) component of the magnetic field of the wave[19] and they move toward the center of the film. These nonlinearities appear when $w > \delta_\perp$, where w is the film width and $\delta_\perp$ is the depth of penetration of the perpendicular magnetic field. In our case the condition $w > \delta_\perp$ is obeyed. Penetration of the vortices into the film occurs when the amplitude of the perpendicular component of the magnetic field of the wave exceeds $H_{c1}^{\perp}$.

The second nonlinearity mechanism is associated with the suppression of the superconducting properties by the electric component of the wave field.[20] In this case a steep rise of the absorption occurs in fields $E \geqslant E_{\mathrm{cr}} = \Phi_0\sqrt{2}/\xi\lambda$, where E is the electric field in the film, Φ_0 is a flux quantum, ξ is the coherence length, and λ is the wavelength of the electromagnetic wave. The expression obtained in Ref. 20 for E_{cr} is generally valid only in the case of zero-gap superconductors, but because of its simple physical meaning (the energy acquired by an electron in a field E_{cr} becomes of the order of the condensation energy during the characteristic time of the change in the field ω^{-1}), an analogous condition should also exist in the general case. This corresponds to the case when the current induced in the film reaches a value of the order of the depairing current.

We shall assume that in our case the penetration of vortices into the film does not occur until the critical value of E is reached ($E \geqslant E_{\mathrm{cr}}$) and, therefore, the second nonlinearity mechanism applies. This hypothesis is based on the assumption that in our case the experimental geometry is selected so that the action of the high-frequency field does not extend to the edges of the film, i.e., to those places where the concentration of the current and nucleation of vortices usually occur.[19] The spot irradiated with microwaves is surrounded by a considerable part of the superconductor where the high-frequency currents do not flow and, therefore, it follows that vortices can penetrate into the irradiated spot only by overcoming a considerable potential barrier. Moreover, as pointed out above, the high-frequency power P_k at which a steep rise is observed in the temperature dependence of the absorption is proportional to $(H_{c1}^{\perp})^2$ and, consequently, the temperature dependence is[19] $P_k \propto (1-t^4)^2$, where $t = T/T_c$. Our earlier experiments[13] carried out on the same aluminum films and in the same geometry demonstrate that $P_k \propto (1-t)^3$ near T_c. This dependence follows from the mechanism of destruction of the superconductivity by the electric component of a low-frequency electromagnetic wave[20] (this is the case in our experiments).

All this allows us to assume that the temperature of the onset of a strong rise in the absorption (curve ∞ in Fig. 2) corresponds to the attainment of $E = E_{\mathrm{cr}}(T)$ in the film. The subsequent form of the temperature dependence of the absorption is governed by the more complex nonlinear dissipative processes, when during a part of the electromagnetic field period the film is in the superconducting state and during another part of the period it is in the resistive state. The anomalous absorption maximum is associated with these processes. However, we shall not consider such processes in greater detail, because this maximum and the associated nonlinear phenomena will be discussed in a separate communication.

According to Éliashberg,[1)] the action of microwave radiation on a film stimulates superconducting properties (increases Δ) and, consequently, enhances all the critical parameters of a superconductor including E_{cr}. Therefore, at a given amplitude of the high-frequency field the temperature at which the absorption rises strongly in the presence of microwave radiation is higher than in the absence of such radiation. This shifts the onset of the absorption curve by ΔT, which is found from the condition

$$E_{\mathrm{cr}}(T, 0) = E_{\mathrm{cr}}(T+\Delta T, P) = E,$$

where E is the electric field of the wave in the film. It is clear from Fig. 2 that the microwave irradiation also alters somewhat the form of the absorption curve, i.e., it influences also the properties of a superconductor in the resistive state.

We demonstrated that the reduction in the high-frequency absorption in a superconducting film under the action of microwave radiation is observed not only at the frequencies corresponding to the anomalous absorption peak: this was done by investigating the effect also at ~ 1 GHz. At these frequencies the temperature dependence of the absorption had the usual form for the superconducting transition curve. In this case we also found that below T_c there was a range of temperatures where microwave irradiation reduced strongly the high-frequency absorption and that in the direct vicinity of T_c the absorption rose somewhat. We can therefore say that the influence of microwave radiation on the high-frequency absorption in thin aluminum films is of general nature and represents manifestation of superconductivity stimulation in real wide superconducting films.

We investigated also the influence of a static magnetic field parallel to the film plane on the temperature dependences of the change in the absorption under the action of microwave radiation. We found that at a fixed microwave power an increase in the magnetic field resulted in a monotonic fall of the maximum reduction in the high-frequency absorption. The application of a magnetic field of ~ 0.5 kOe destroyed completely the temperature interval where the absorption decreases; only the region near $T_c(H_0)$ was retained and there the irradiation caused the absorption to rise. Such behavior may be associated with the influence of the magnetic field on the density of states in a superconductor, but this problem requires an additional study.

We shall conclude by noting that for one reason or another our hypothesis of the dominant role of the electric component of the high-frequency field on the onset of the strong rise of the absorption may be incorrect and the rise of the absorption may be due to the penetration of vortices by a mechanism suggested in Ref. 19 or by some other mechanism. However, in the interpretation of the shift ΔT of the absorption curve under the action of microwave radiation causing superconductivity stimulation this is of no importance because the existence of ΔT in this case denotes an increase in H_{c1} and, consequently, it again represents superconductivity stimulation.

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