Some rf properties of thin films near the superconducting transition

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A study is made of the rf properties of thin superconducting aluminum films under unidirectional irradiation near the phase transition on the *T-H* plane and, in particular, of the linear and nonlinear behavior of the anomalous absorption of an rf magnetic field near T_c (Refs. 1 and 2). Third-harmonic generation is observed, and it is shown that the nonlinear processes in the superconducting films near the critical temperature have a threshold character. An electrodynamic model incorporating the change in the transparency of the film for the rf field is proposed; this model can explain a number of the properties of the anomalous absorption.

I. INTRODUCTION

The rf properties of thin ($d<\lambda,\xi$) superconducting films are quite well understood as a result of both experimental and theoretical studies. Nevertheless, a number of studies[1] have revealed an anomalous magnetic-field dependence of the microwave absorption. In a certain field interval around the critical magnetic field of the film the absorption in the superconducting state exceeds the absorption in the normal state.

We have previously[2] observed such an anomalous magnetic-field dependence of the rf absorption in the resistive state produced in a film by intense microwave irradiation and found that the effect has an upper frequency limit. Above this limit the usual picture was observed, with the absorption in the superconducting (or resistive) state always being smaller than in the normal state. When the frequency was below this limit, we observed[2] an anomaly in the rf absorption near the entire line of $S \rightarrow N$ phase transitions on the *T-H* plane. An anomalous temperature dependence of the microwave absorption has also been found[3] in granular films of aluminum in the 3-cm range.

The cause of the anomalous absorption peak has not been explained. It is also unclear whether the response studied in Refs. 1–3 is linear, since a possible explanation for the absorption peak is hysteretic loss due to the irreversible motion of vortices created in the film by the electromagnetic wave itself.[4] It is not clear why the absorption peak arises near the superconducting transition and generally in films which are quite thin and dirty. One wonders whether the explanation will have to incorporate fluctuation effects, since it is known that the onset of fluctuational vortex-antivortex pairing[5] in helium films gives a sharp burst of energy dissipation in the region of the superfluid transition.[6]

We have therefore made a detailed study of the linear and nonlinear rf properties of aluminum films of various thicknesses and investigated the resistance in the neighborhood of the superconducting transition. We show that many of the experimental results on anomalous absorption can be explained in terms of a simple electrodynamic model.

II. EXPERIMENTAL TECHNIQUES

We have previously[7] described the technique used to measure the rf absorption in the films, so here we shall discuss at length only the details related to the study of the nonlinear properties.

A block diagram of the apparatus is shown in Fig. 1. Part of the apparatus (units 1–7) was used to measure the rf absorption. A second part of the apparatus (8–16) was used to receive both the signal transmitted through a film on an insulating substrate at the irradiation frequency ω and the signal of the harmonics $n\omega$ generated by the film.

To receive the third-harmonic signals we used a modulation technique. The signal from the oscillator was sent to a modulator 9. At the output of the modulator there was an rf voltage at both the frequency ω and its harmonics. After an attenuator 2 and low-frequency filter 19 the rf power at frequency ω entered a resonance circuit. The signal at frequency 3ω was received by a three-turn coil of diameter ~ 3 mm placed on the opposite side of the film. After passing through preamplifier 11 the signal was mixed with a 3ω reference signal from the output of modulator 9 and was sent to the input of a superheterodyne receiver 14 and then to a synchronous detector 15. The working apparatus assembled on this design permitted a linear detection of the signal at frequency 3ω with a sensitivity of $\sim 10^{-16}$ W.

We studied aluminum films deposited thermally on glass substrates in a diffusion vacuum (10^{-5} torr), with thicknesses of 300–700 Å and resistances $R_\square = 1$–$20\ \Omega$. The

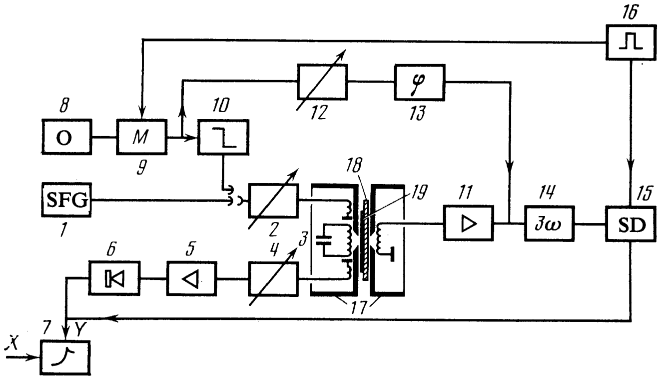

FIG. 1. Block diagram of apparatus: 1—sweep-frequency generator; 2, 4, 12—attenuators; 3—resonance circuit; 5, 11—amplifiers; 6—peak detector; 7—*xy* recorder; 8—oscillator, 9—modulator; 10—low-frequency filter; 13—phase shifter; 14— 3ω superheterodyne receiver; 15—synchronous detector; 16—pulse generator; 17—copper shield; 18—substrate; 19—film sample.

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substrates were at room temperature during the deposition. The films had T_c values from 1.3–1.6 K, so that all the measurements could be done in superfluid helium. The temperature was measured by a semiconductor thermometer.

A special feature of the construction of the absorbing cell was that the film was separated from the resonator by a copper shield 17 with an iris of diameter 2–3 mm, preventing the passage of rf currents along the edges of the film at typical film dimensions $\sim 1 \times 1$ cm. The output power of the oscillator was varied over the range 10^{-2}–10^{-8} W. Measurements of the amplitude of the rf magnetic field on the surface of the film gave ~ 5 Oe per watt of output power.

III. EXPERIMENTAL RESULTS

To study the linear rf properties we decreased the power of the oscillator until the width and shape of the superconducting transition no longer changed, usually to $\sim 10^{-7}$ W.

Figure 2 shows the magnetic-field dependence of the power absorbed by the film for various angles θ between the field and the plane of the film. Below $H_c(\theta)$ the anomalous absorption peak is clearly seen. In the region of intermediate angles in small fields another absorption peak develops and grows rapidly in height with increasing θ. Growing and widening, this peak gradually covers up the narrow feature near $H_c(\theta)$, so that at $\theta \sim 90°$ only a single large absorption peak remains. The critical field $H_c(\theta)$ is defined as the point at which the absorption goes to a constant.

Both peaks are of a linear character at low power levels, as is confirmed by the absence of harmonic generation. Therefore, to explain these peaks it is evidently necessary to abandon the hysteretic-loss mechanism that has been invoked to interpret similar behavior of bulk type II superconductors in low-frequency alternating fields.

The absorption peaks appear only at frequencies lower than a certain boundary frequency f_b. At higher frequencies the field dependence of the absorption is normal—below $H_c(\theta)$ the absorption falls off monotonically with decreasing field. The boundary frequency for our films lay in the range 400–700 MHz.

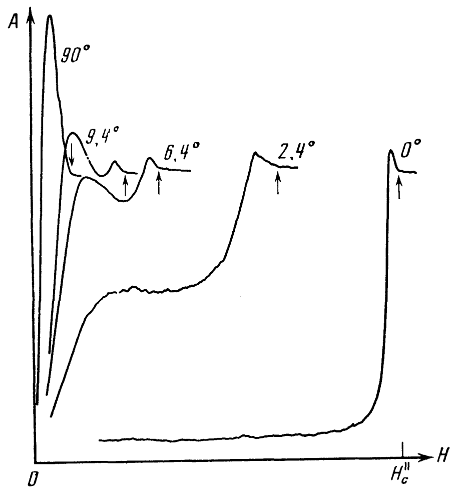

FIG. 2. Dependence of rf absorption A on the magnetic field at various angles θ between the field and film plane. For $\theta = 90°$ the scale along the abscissa is enlarged 5 times. The arrows indicate the position of $H_c(\theta)$.

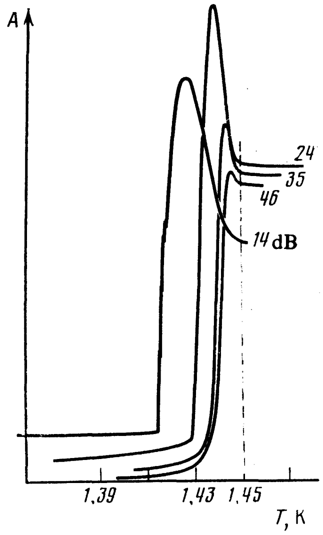

FIG. 3. Dependence of rf absorption A on the temperature at various rf power levels. The numbers on the curves give the attenuation in dB from the level $P_0 = 10^{-2}$ W; $f = 172.5$ MHz.

Below this same boundary frequency, the temperature dependence of the rf absorption in the absence of magnetic field also exhibits a narrow absorption peak. Figure 3 shows some typical temperature curves for the absorption of a thin film at various levels of the rf power entering the resonator. At low power levels the temperature of the peak differs from T_c, the point at which the absorption goes to a constant, by a quantity of order of several mK. With increasing power the peak broadens and increases in amplitude. There is no decrease in T_c with increasing power, indicating that the heating of the film is negligible.

From the data shown in Fig. 3, one can obtain the normalized maximum absorption $A_{\max}/A_N$ as a function of the irradiation power. This function is shown in Fig. 4. We see that at low power levels there is a linear region in which the relative absorption ($A_{\max}/A_N$) and the width and position of the peak are independent of the irradiation power. With increasing power a logarithmic increase is observed in $A_{\max}/A_N$; this increase begins practically in a threshold manner in terms of the power.

A study of the generation of harmonics of the irradiation frequency by the film shows that the radiation of harmonics is not observed in the linear region (where $A_{\max}/A_N$

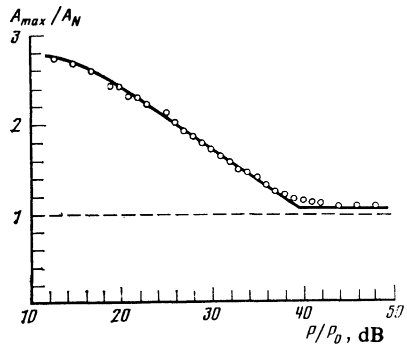

FIG. 4. Maximum absorption $A_{\max}/A_N$ versus the rf power.

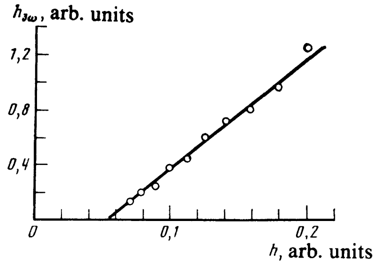

FIG. 5. Maximum amplitude $h_{3\omega}$ of the third harmonic versus the rf field amplitude h.

is independent of the power) and arises of a threshold manner in power a level corresponding to the logarithmic growth of $A_{\max}/A_N$. The temperature interval in which harmonic generation is observed is correlated with the width of the anomalous absorption peak.

Figure 5 shows the maximum amplitude $h_{3\omega}$ of the third harmonic as a function of the amplitude h_0 of the exciting field. It must be noted that only the generation of odd harmonics is observed. The even harmonics arise only when a transport current is passed through the film.

Studies of the passage of the exciting rf field through the film reveal the following basic qualitative patterns:

a) A film found in the normal state introduces a weak attenuation (of the order of several decibels) into the signal transmitted from the exciting to the receiving coil, if $f < f_b$.

b) For $f < f_b$ the superconducting film completely screens the rf field.

IV. DISCUSSION OF THE RESULTS

1. Linear rf properties of the films

Data on electromagnetic absorption during unidirectional irradiation of thin films are usually analyzed in the simplest and most convenient geometry—with the rf field parallel to the film. In this case the temperature dependence of the absorption is completely determined by the temperature dependence of the resistive component of the impedance of the film:

$$R=\mathrm{Re}\,(\sigma d)^{-1},\quad \sigma=\sigma_N,\quad T\geqslant T_c,\quad \sigma=\sigma_1-i\sigma_2,\quad T<T_c, \tag{1}$$

where σ and d are the conductivity and thickness of the film.

It has been shown,[1] however, that in the region of temperatures and magnetic fields in which $\omega < \Delta(T,H)$ (Δ is the energy gap in the superconductor) and under the condition that the impedance of the film is lower than the impedance of the vacuum, A_S is always smaller than A_N, even when the analysis is based on an expression more general than (1) which takes into account the partial passage of the field through the film. In our case $\omega < \Delta(T)$ in the temperature interval $T_c - T \gtrsim 10^{-4}$ K.

For this reason we propose to consider a more realistic picture of the field distribution, where the rf magnetic field can also have a component normal to the film. The penetration of this component is characterized by the dimension $\delta_\perp = \delta^2/d$, where δ is the skin depth of the film material. If the transverse dimensions of the film are much greater than $\delta_\perp$, the perpendicular component of the field will be screened by rf ring currents in the film and the field will remain parallel to the film. In the opposite case the presence of a normal component of the field will mean that field lines pass through the film. This situation is illustrated in Fig. 6, which shows a short coil having a fringing field around it with components normal and tangential to the film. The transparent film case corresponds to having a voltage source across the film, and the absorption in the film will be proportional to Reσ. In Fig. 6 this corresponds to small values of the conductivity (it is assumed that the thickness of the film and the frequency of the field are fixed).

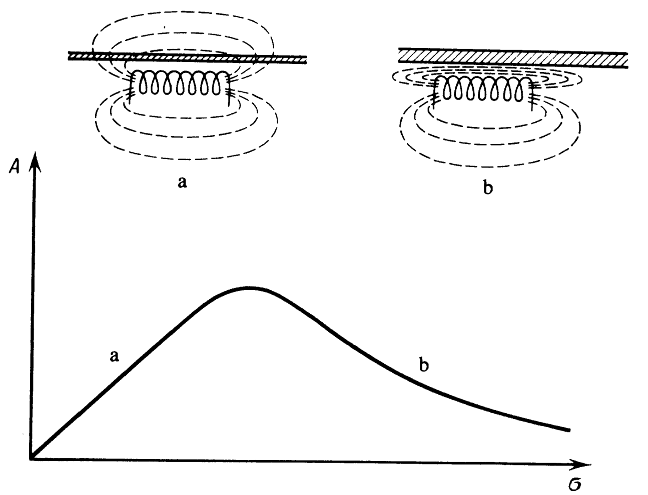

FIG. 6. Qualitative behavior of the rf absorption in a thin film in the normal state as a function of the conductivity, and the configuration of the magnetic field lines in the induction coil of the resonance circuit (schematic) for the cases: a—transparent film, b—opaque film.

The case when the rf field is screened by the film corresponds to having a fixed current in the film, and the absorption is proportional to R [Eq. (1)]; this corresponds to large σ in Fig. 6.

In our experimental situation, where the film is separated from the rf source by an irised shield, the role of the film dimension is played by the iris diameter a. The maximum absorption should be observed at a conductivity corresponding to the condition $\delta_\perp \approx a$.

We have measured the rf absorption in normal films by depositing films with different resistances $R_\square$ and have actually observed a nonmonotonic dependence of the absorption on the resistance of the film, with a maximum at $\delta_\perp \approx a$. These results are shown in Fig. 7. The condition $\delta_\perp \approx a$ should also determine the boundary frequency if σ and d are fixed.

After transition to the superconducting state, all the qualitative arguments given above still hold if δ is replaced by the penetration depth λ of the magnetic field into the superconductor. The quantity $\lambda_\perp = 2\lambda^2/d$ plays the role of an effective penetration depth of the perpendicular magnetic field into the film.[8]

It is clear from this discussion what the origin of the

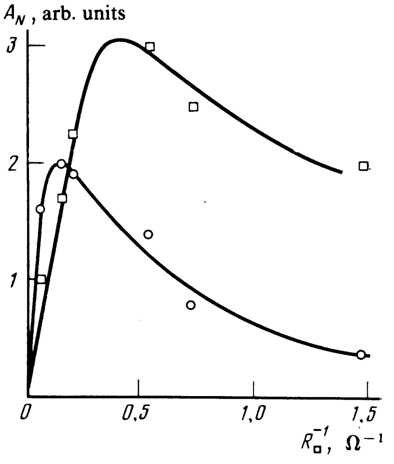

FIG. 7. Dependence of the rf absorption in a thin film in the normal state on the resistance of the film: □—$f = 170$ MHz, $a = 0.3$ cm; ○—$f = 850$ MHz, $a = 0.2$ cm.

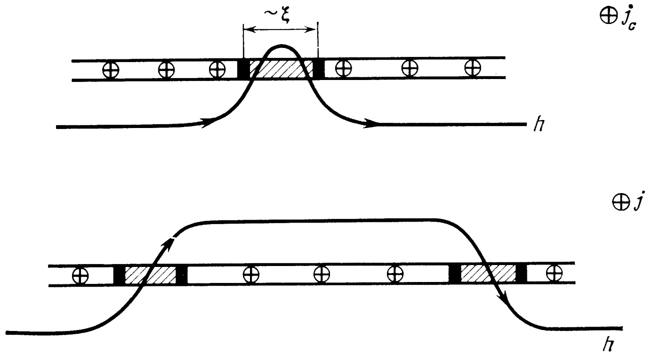

FIG. 8. Schematic illustration of the stages of the penetration of an rf field through an edgeless superconducting film when the critical rf current density is reached in the film.

absorption peak at the superconducting transition is. If the film under study has values of σ and d which correspond to a position to the left of the maximum on the $A(\sigma)$ curve (Fig. 6) at the frequency f in the normal state, the absorption will increase after the transition to the superconducting state on account of an increase[9] in σ_1, so long as $\lambda_\perp > a$. Using the parameters of the film whose absorption curves are shown in Figs. 2 and 3, viz., $R_\square = 7\Omega$, $d = 3\cdot10^{-6}$ cm, $f = 1.7\cdot10^8$ Hz, and $a = 0.3$ cm, we get $\delta_\perp/a = 4$, i.e., we are to the left of the maximum in Fig. 6. The growth of the absorption stops when $\lambda_\perp \approx a$; this, together with the expression $\lambda_\perp = 8.3\cdot10^{-5} R_\square (T_c - T)^{-1}$, puts the position of the peak at $T_c - T \approx 2\cdot10^{-3}$ K, in good agreement with experiment. For $T_c - T \gtrsim 10^{-2}$ K we have $\lambda_\perp \ll a$; the film is no longer transparent, and $A_S \to 0$.

The arguments we have given are easily generalized to the case where the absorption depends on the parallel magnetic field by introducing field dependences $\sigma_1(H^\parallel)$ and $\lambda_\perp(H^\parallel)$ through $\Delta(H^\parallel)$.

In a perpendicular magnetic field the film is in the mixed state and, if the frequency of the rf field is higher than the pinning frequency (see Ref. 1), the electrodynamics of the film is governed by the real conductivity σ_f (Ref. 10) and by the skin depth associated with the viscous motion of the vortices. Because σ_f changes from σ_N for $H = H_c^\perp$ to $\sigma_f \to \infty$ for $H \to H_{c1}$ and because H_{c1} in the films is small, the transition through the maximum, as in Fig. 6, will be observed here in pure form.

2. Nonlinear rf properties of the films

It has been shown[11] that at the temperature corresponding to the beginning of the sharp increase in the absorption (the 14 and 24 dB curves in Fig. 3), the current density in the film reaches a value equal to the depairing current density j_c. Our experiments show that at this instant the generation of odd harmonics by the film begins, and a signal transmitted through the film appears. The penetration of the rf field through the film in this case can be pictured as follows. At the place where the critical depairing current density is reached, the potential barrier for the injection of a vortex vanishes, and a "normal" region arises with dimensions of the order of the coherence length; the field lines of the rf magnetic field enter this region, forming a pair of vortices of opposite sign in the film. The Lorentz force due to the rf current flowing along the film tends to separate the vortex-antivortex pair, overcoming the force of attraction and the viscous drag. This situation is illustrated schematically in Fig. 8. If it is assumed that the behavior is completely adiabatic, vortices will be injected in both the positive and negative half-periods of the field, giving rise to odd harmonics in the radiation transmitted through the film.

The density of vortices injected into the film will increase with increasing temperature. It can be assumed that dissipative processes in such a dynamic mixed state created by the rf field itself are similar to those in the mixed state created by a static field, and the absorption peak can be explained along the lines of the discussion in Sec. IV.1. That this is the case follows from the fact that the height of the absorption peak at the largest rf field amplitudes (Fig. 4) is close to the height of the peak in a perpendicular field (Fig. 2).

Thus the scheme set forth above can explain most of the experimental facts. However, there are at least two results which we believe do not fit in.

First is the appearance of two absorption peaks on the $A(H)$ curve at intermediate angles (Fig. 2). Second is the existence of a power threshold for the onset of the nonlinearity (Figs. 4 and 5). In fact, as the temperature approaches T_c, the critical current and H_{c1} go to zero, so that for any nonlinearity mechanism, given a finite amplitude of the rf field, one could bring the temperature close enough to T_c that the nonlinearity would arise. The existence of a power threshold could be explained by assuming that the critical current and/or H_{c1} (depending on the nonlinearity mechanism) arises discontinuously at a temperature very close to T_c. Such a discontinuity is possible for phase transitions in two-dimensional systems,[12,13] but simple estimates by the formulas given in Ref. 5 show that the corresponding fluctuation region for our films is too narrow. Furthermore, the possible discontinuity in j_c is two orders of magnitude smaller than would be necessary to explain the value of the threshold power.

In conclusion, it is our pleasant duty to thank G. I. Leviev and K. K. Likharev for helpful discussions. One of us (S.K.T.) also wishes to thank A. L. Kasatkin, S. I. Mukhin, and V. F. Taborov for many discussions. We are grateful to V. A. Berezin for assistance in making some of the measurements and to V. M. Pan for his interest and cooperation in this study.

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