THIN SUPERCONDUCTING FILMS IN A UHF FIELD. II. NONLINEAR PROPERTIES OF THIN SUPERCONDUCTING FILMS IN A UHF FIELD

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The nonlinear properties of thin ($d < \lambda_L(0)$, $d < \xi_0$) lead, tin and indium superconducting films are studied experimentally in UHF fields (10^{10} Hz) at temperatures between 1.5 and 4.2°K. The results, which can be explained by excitation of Cooper pairs through the energy gap by a UHF current, agree well with the pair excitation mechanism considered in the first part of[1], despite the fact that the results were obtained with films having a nonuniform current distribution over the length of the film. The results also indicate a possibility of observing the behavior of the principal superconductor parameters and of measurement of their relaxation rate.

INTRODUCTION

EXPERIMENTAL studies of the superconductivity at high and ultrahigh frequencies (UHF) have been carried on for a long time. A special place in these investigations is occupied by experiments on the study of nonlinear properties of superconductors by means of UHF. Fundamentally, these experiments were carried out on thin films, which permit the achievement of greater current densities than on bulk samples, without appreciable heating. Effects have been studied that are connected with the passage of UHF signals through the thin film[2,3] and the dependence of the frequency of a resonator with a superconducting film on its transparency to the UHF magnetic field.[4-8] The latter are more strongly evident in semi-transparent (to the UHF magnetic field) films and therefore films of thickness $d = \lambda_L(0)$ (or thinner) were used for observation.

We have studied the behavior of much thinner ($d < \lambda_L(0)$, $d < \xi_0$) superconducting films in UHF fields.

METHOD OF EXPERIMENT

The UHF impedance of a superconducting film was studied by the resonator method. For this purpose, resonant systems of two types were used: 1) a superconducting film of half-wavelength thickness deposited on mica, forming a plane resonator; 2) the same film, deposited on mica and pressed to one of the faces of a rutile dielectric resonator.

The experimental arrangement consisted of a resonant system with adjustable coupling, a helium cryostat, a source of UHF (31-IM radar tester), a spectrum analyzer (IV-66), and a receiver with an oscilloscope. In the course of the experiments, the dependence of the shape of the envelope and the spectrum of the reflected signal on the power level of the UHF were studied, as well as the dependence on the constant magnetic field, the temperature, and the thickness of the film.

The films were vacuum-sputtered (at 10^5–10^{-6} mm Hg) on a thin (0.01 mm) mica substrate. For good coupling with the substrate, freshly cleaved mica was used. The temperature of the substrate was about 300°K in all sputterings. The thickness of the films was estimated from their electrical resistance. Furthermore, for the determination of the effect of the thickness on the experimental results, sets of films were used, sputtered under completely identical conditions, and differing only in the duration of the evaporization process.

The greater part of the results set forth below was obtained on lead films. Some experiments were repeated on tin and indium films. The lead films were rapidly oxidized in air. Therefore, immediately after sputtering, they were brought into the cryostat and tested. The tin and indium films could be stored in air longer.

All the measurements were made in the 3-cm wavelength range over the temperature interval 1.5–4.2°K.

EXPERIMENTAL RESULTS

Several hundred superconducting films were studied. At a low UHF power level ($\lesssim 10^{-6}$ W) they all behaved in the same way: the Q of the resonators with the film was practically independent of the power level, and no anomalies were observed in the shape of the resonance curve and in the spectrum of the signal reflected from the resonator.

In resonators with low Q, an increase in the power up to some threshold value P_1 (10^{-5}–10^{-6} W) produces a jumpwise change in the reflection coefficient, corresponding to a sharp increase in the damping of the resonator (by an order of magnitude or greater). The subsequent jumpwise decrease of the power restores the initial value of the reflection coefficient only at a power level $P_2 \le P_1$, i.e., a hysteresis effect is observed. Upon reduction in the coupling of the resonator with the waveguide, the ratio P_1/P_2 increases and in a strongly mismatched regime can reach a value of 10 and higher.

In the regime of frequency modulation of the UHF source, jumps in the reflection coefficient are observed on the resonance curve of the resonator at points corresponding to the power levels P_1 and P_2 (Fig. 1).

The first jump (P_1) appears at the vertex of the resonance curve at a point corresponding to the maximum power input to the resonator. Similar jumps can

FIG. 1. Resonance curve of unmatched resonator in the klystron generation band; jumps of the reflection coefficient in the absence of oscillations of the reflection coefficient.

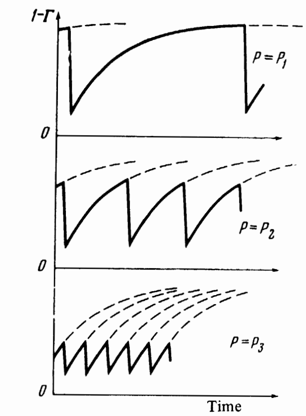

FIG. 3. Dependence of waveform of the relaxation oscillations of the reflection coefficient Γ on the UHF power P ($P_3 > P_2 > P_1 \approx P_t$).

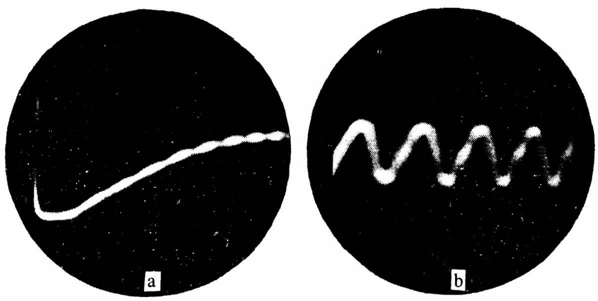

FIG. 2. Oscillations of reflection coefficient: a – near threshold, b – prior to the interruption (the brightness markers represent 0.1 μsec each).

be observed far away from the fundamental resonance at waveguide-system resonances due to random reflection in it.[7]

2. In our experiments, there was the possibility of changing the loaded Q of the resonator by regulating its coupling with the waveguide. An increase in the Q of the resonator system leads to the appearance of periodic amplitude modulation of the reflected signal by relaxation-type oscillations in certain films, at powers above the threshold (Fig. 2). This explains the appearance of additional frequencies in the spectrum of the signal reflected from a resonator with a superconducting film.[7]

For sufficiently high Q of the resonator, the period of these relaxation oscillations changes, with increase in UHF power, from an infinite to a minimum value that is characteristic for the given film. Lowering of the Q causes the period of the relaxation oscillations to differ from zero at their threshold. The change of the form of relaxation oscillations, originating upon increase in power, is shown in Fig. 3. After the termination of the oscillations, the damping in the resonator is much higher than prior to their formation.

Figure 4 shows the formation of oscillations of the reflection coefficient on the vertex of the resonance curve of the resonator. When a narrow-band receiver is used, the onset and end of the oscillatory regime are recorded in the form of "steps"[7] on the resonance curve (Fig. 5). In certain cases, the described process is repeated several times upon change of power, indicating that various portions of the film take part in it and the dimensions of each of them are small. This explains the large number of "steps" observed previously.[7]

3. For one and the same film, the threshold power P_1 depends on the Q of the resonator (Q_0), the frequency of the UHF signal (ω), and the reflection coefficient (Γ) in such a way that the energy of the UHF field in the resonator corresponding to it,

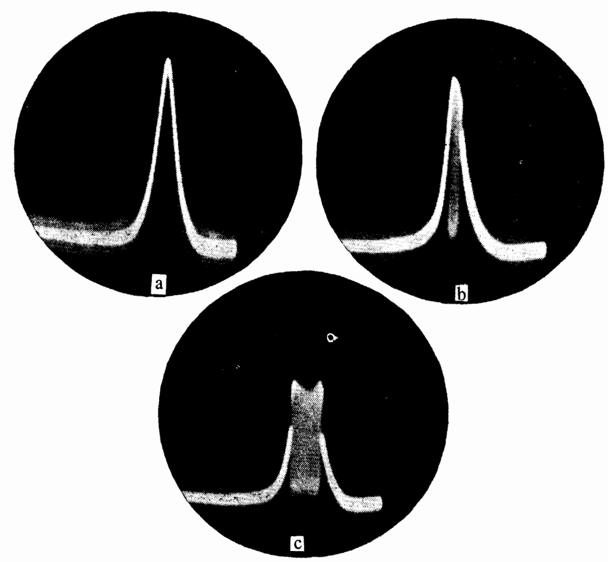

FIG. 4. Resonance curve of unmatched resonator in the oscillation mode at different power levels: $P_a < P_1 < P_b < P_c$ (broad-band receiver).

$$W_1 = (1 - \Gamma^2) P_1 Q_0 / \omega$$

remains constant.

The dependence of W_1 on the constant magnetic field perpendicular to the UHF current was studied on lead films. In a field perpendicular to the plane of the film, a rapid decrease of W_1 (by an order of magnitude in fields of 300–500 G) is observed. In a field parallel to the plane of the film, the decrease of W_1 takes place much more slowly. Thus, on films of d ≈ 100 Å, the change in W_1 becomes appreciable only in fields greater than 5 kG.

The temperature dependences of Q_0 and of the threshold energy W_1 have been studied on tin films with d = 120 Å (Figs. 6 and 7). The maximum temperature at which the measurements were made was 3.73°K. The critical temperature (T_x = 3.96°K) was determined from the change in the losses in the film. In the temperature range 3.73–3.96°K, the observations of W_1 were made difficult because of the significant weakening of the effect.

4. As has already been noted above, each film is

characterized by some limiting maximum frequency Ω_m (minimum period) of the relaxation oscillations.

The lowest value of Ω_m (~ 1 MHz) has been obtained on indium films, and much higher frequencies (2—75 MHz) are observed on tin and lead films. In all materials, the highest frequencies were observed for the thinnest films.

In thin (60—200 Å) films of lead (in the temperature range 1.5—4.2°K) and of tin (in the temperature range 1.5—3.0°K), no change in the value of Ω_m was observed. In much thicker films of lead (d $\gtrsim$ 400 Å), indium (d $\gtrsim$ 100 Å), and tin (d $\gtrsim$ 400 Å) the vibrational regime is observed only in resonant systems of the second type (film pressed against the boundary of the dielectric resonator) at $Q_0 > 10^4$. Since the film is held in this case between the mica substrate and the dielectric resonator, the heat transfer from them is difficult and the oscillatory regime becomes unstable. Therefore the dependence of Ω_m on the temperature has not yet been studied for these films.

The effect of the magnetic field on Ω_m was studied for lead films. When such a film was placed in a magnetic field parallel to its plane, the frequency increased with the field by at least a factor of two, and then the amplitude of the oscillations fell off rapidly to the noise level. The magnetic field not only affects the value of the threshold energy W_1 and the maximum frequency Ω_m of the relaxation oscillations, but also changes the form of the dependence of the amplitude of the neighboring frequencies in the spectrum of the reflected signal on the UHF power. The character of these changes is shown in Fig. 8.

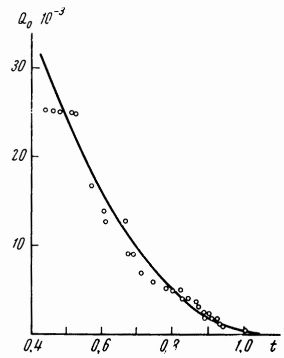

FIG. 6

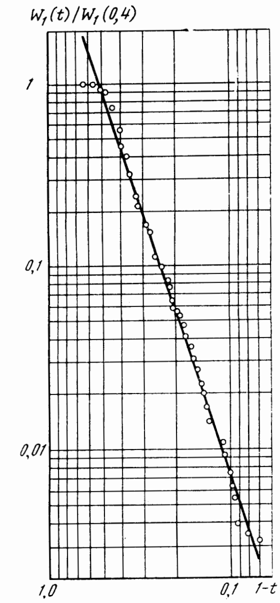

FIG. 7

FIG. 6. Dependence of intrnisic Q of the resonant system (of the second type) on the temperature. Sn, d = 120 Å.

FIG. 7. Dependence of threshold energy on the temperature. Sn, d = 120 Å.

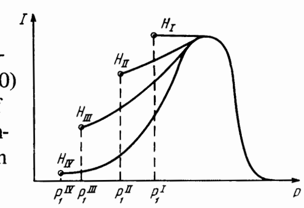

FIG. 8. Influence of constant magnetic field ($H_{IV} > H_{III} > H_{II} > H_I = 0$) on the character of the dependence of the amplitude of the sideband frequencies in the reflected-signal spectrum on the UHF power.

DISCUSSION OF RESULTS

1. The UHF current in a strip resonator can be computed from the formula

$$I \approx [2PQ_0/\rho]^{1/2}, \tag{1}$$

where P is the power introduced in the resonator, Q_0 the Q of the resonator itself, and ρ the wave resistance of the resonator. Therefore, we obtain $I \approx 4 \times 10^{-2}$ A for films of thickness 60 Å and width 1.7 mm. at T = 4.2°K, $P = 10^{-5}$ W, $Q_0 = 5 \times 10^3$, and $\rho = 70$ ohms. In contrast with the direct current, the UHF current will be distributed uniformly in the plane film and consequently the current 4×10^{-2} A in this film corresponds to a density $J \approx 4 \times 10^5$ A/cm². Such values of the threshold current density were also obtained in the resonant system of the second type.

The computed current densities are close to the critical constant current densities in cylindrical films, where the current distribution is also homogeneous.[9] This allows us to assume that the threshold power P_1 in our experiments corresponds to the achievement of the critical values of density of UHF current in the superconducting film.

The absence of any appreciable changes in the Q of the resonant system up to the very threshold, observed in our experiments, is possible only for insignificant changes of concentration of the superconducting electrons. Under these conditions, its sudden change can indicate only the appearance of a new mechanism of destruction of the superconductivity. The closeness of the current in the film to its critical value gives us grounds for assuming that there is a disruption of the Cooper pairs, which acquire the kinetic energy exceeding the value of the energy gap (see[1]). The equality of the experimental and computed dependence of the Q and of the threshold energy on the temperature also testifies in favor of this assumption.

If we take the free energy density

$$F_s = -f_1(\rho_s) + f_2(v_s^2, \rho_s), \tag{2}$$

where

$$f_1(\rho_s) = -\alpha\rho_s - {}^1/_2\beta\rho_s^2, \tag{2a}$$

$$f_2(v_s^2, \rho_s) = {}^1/_2 m v_s^2 \rho_s, \quad v_s = v\cos\omega t,$$

v the amplitude of the velocity of the superconducting

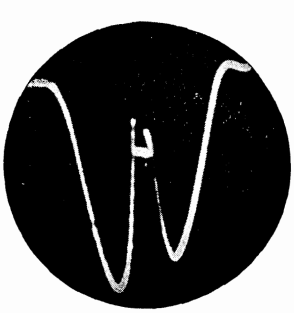

FIG. 5. Resonance curve of unmatched resonator in the oscillatory mode at the klystron generation band (narrow-band receiver).

electrons, then at $v = v_t$, i.e., at the threshold value of the velocity, we obtain

$$\alpha + \beta\rho_t + {}^1/_4 m v_t^2 = 0,$$

$$\alpha + {}^1/_2\beta\rho_t + {}^1/_2 m v_t^2 = 0,$$

from the condition of vanishing of the peak value and the variation of the mean square value F_s, where ρ_t is the concentration of superconducting electrons when the condition $F_s = 0$ is attained. Hence

$$ {}^1/_2 m v_t^2 = {}^2/_3|\alpha|, \quad \rho_t = {}^2/_3|\alpha| / \beta.$$

In this case

$$Q_0 \sim (\rho_t / \rho_{t,0})^2 \sim \alpha^2$$

and

$$\frac{W_1}{W_{10}} = \frac{v_t^2}{v_{t0}^2}\left(\frac{\rho_t}{\rho_{t0}}\right)^2 \sim \alpha^3.$$

Here W_{10}, v_{t0} and ρ_{t0} are the threshold values of the energy, drift velocity, and density of superconducting electrons at $T = 0$.

Since[9] $\alpha \sim (1 - t)$, where $t = T/T_c$, it follows that $Q_0 \approx (1 - t)^2$ and $W_1 \sim (1 - t)^3$.

It is seen from Fig. 6 that the function $Q_0(t)$ over a wide range of values is very well described by a parabola with vertex at the point $t_0 = 1.05$, while, in accord with the specified model, $t_0 - 1 \approx a(\omega\tau)^2$, where $a = \rho/\rho_t$, ρ the total density of conduction electrons, and τ the time of free flight of the superconducting electrons in the film (see[1]). A deviation from a parabola is observed only for $t < 0.5$, where the Q of the system approaches the Q of the dielectric resonator. The straight line corresponding to the slope $(1 - t)^3$ is also in agreement with the experimental points of the dependence $W_1(t)$ in the temperature range $0.5 < t < 1.0$ (Fig. 7). The discrepancies at $t < 0.5$ can indicate that the expression for $f_1(\rho_s)$ in the form (2a) is not valid in this temperature range.

Thus, from the change of W_1 we can assess the dependences of F_s, ρ_s and Δ on the external parameters.

So far as the dependence $W_1(H)$ mentioned above is concerned, it can be explained by the fact that the field increases the total current on one of the sides of the films.

2. The hysteresis effect in the resonant system with a superconducting film in the absence of an oscillatory regime can also be explained with the help of the mechanism of pair excitation, considered in the first part. The increase in the UHF power up to the threshold value (P_1) leads to a destruction of the superconductivity of the film, as a consequence of which the damping of the resonator increases and the UHF current in the film decreases. If this current (I_{min}) is always greater than critical (I_c), then for the establishment of superconductivity it is necessary to decrease the power furnished to the resonator to the level $P_2 < P_1$.

3. If the condition of stability at the threshold $I_{min} > I_c$ is not satisfied, periodic transitions of the film from the superconducting state to the normal state and conversely take place at a power level higher than threshold. We observed such oscillations with a frequency up to 150 MHz (in a magnetic field) and, judging from the spectrum of the reflected signal, they preserve the relaxational form at these frequencies. This indicates that the rate of destruction of superconductivity in this mechanism is at least higher than $10^9\ \text{sec}^{-1}$.

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