UHF METHODS FOR THE INVESTIGATION OF THE DYNAMIC CHARACTERISTICS OF THIN SUPERCONDUCTING FILMS

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Several methods for investigating experimentally the uhf dynamic characteristics of thin superconducting films are proposed. By means of these methods, it has been established that the recovery rate of destroyed superconductivity in thin lead films is $1 \times 10^9 - 2 \times 10^{10}$ sec^{-1}.

INTRODUCTION

THE study of the dynamics of change of the characteristics of superconductors makes possible a deep understanding of the phenomenon of superconductivity itself and a more perceptive approach to the problem of its practical use. In this connection, there is increased interest in the theoretical and experimental studies of relaxation processes in superconductors.

In the studies carried out to date, the case is usually considered of the condensation of excited quasiparticles for small deviation of their density from equilibrium.[1-6] Under these conditions, the rate of condensation is proportional to the stationary equilibrium density of the quasiparticles, and is therefore strongly temperature dependent. The smallness of the excitation leads to the result that the reabsorption of phonons by Cooper pairs is practically nonexistent in this case. However, in practice one frequently has to deal with strong excitations of the equilibrium density of quasiparticles in a superconductor, and then it is hard to expect the condensation process to remain as before. In particular, the temperature dependence of the rate of condensation should practically disappear, and a significant role will be played by the reabsorption of phonons.

We have undertaken the study of the recovery rate of superconductivity in thin films whose superconductivity had been completely destroyed by a uhf current.[7,8]

INTERACTION OF AN AMPLITUDE-MODULATED UHF SIGNAL WITH A THIN SUPERCONDUCTING FILM

1. In the consideration of dynamic processes in superconductors, it should be kept in mind that the presence of the energy gap in the spectrum of excitations and the principle of detailed balancing lead to a dependence of the rate of change of the ordering parameter w on the direction of the process:

$$w_\downarrow / w_\uparrow \approx \exp[2\Delta / kT],$$

where $w_\downarrow$ is the rate of condensation of the excited quasiparticles, $w_\uparrow$ the rate of their excitation, and 2Δ the width of the energy gap. Therefore, in the general case, a single characteristic rate (time) for the description of the dynamical properties of the superconductor is shown to be insufficient.

In the interaction of the uhf current with a superconducting film, as the kinetic energy of the electrons ϵ_k increases during the first half of each half period (but under the condition that the total free energy of the condensed state F remains negative) the relatively slow process of thermal excitation of Cooper pairs takes place. Then, in the second half of this half period, the much more rapid process ($w_\downarrow \gg w_\uparrow$) of their condensation begins with decrease of ϵ_k. Under these conditions, the characteristic rate of the interaction process of the superconducting film with the uhf current is the rate of the thermal excitation as the slowest process. Here the departure of the density of Cooper pairs from the equilibrium value in the uhf current ($\omega \gg w_\uparrow$) will be determined not by the mean square current but by a quantity that is smaller by the factor $\omega / w_\uparrow$ and will therefore be quite insignificant.

However, if the quantity ϵ_k increases so much in the first half period of uhf that the condition $F_s \geq 0$ is achieved at some moment of time, a new, very rapid mechanism of excitation of Cooper pairs by the uhf current is initiated, as a result of the action of which a destruction of the superconducting state takes place.[7] The rate of this new mechanism of excitation is no longer determined by the process of thermal excitation, but by the rate of relaxation of the normal electrons (τ^{-1}), which is very large in sufficiently thin films ($\tau^{-1} \gg w_\downarrow$). In this case, the dynamic characteristics of the superconducting film will be determined by the rate of condensation of the Cooper pairs.

Thus, the dynamic characteristics of the film undergo a sharp change upon increase in the uhf power acting on the thin superconducting film, up to some definite threshold value (corresponding to $F_s = 0$): the rate of their interaction with the uhf field is greatly enhanced.

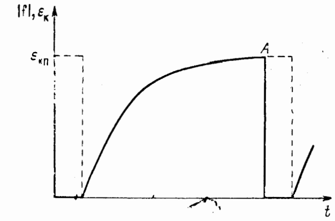

FIG. 1. Recovery of destroyed superconductivity in a film with square wave modulation of the uhf signal (f(t) is the free energy of the electrons in the absence of current, ϵ_k the kinetic energy of the electrons, the point A is the "threshold."). The continuous curve is the dependence f(t), the dashed curve, $\epsilon_k(t)$.

2. If, after the destruction of superconductivity in the film by the uhf current, the uhf power falls rapidly to a very low value, sufficient only for control of some parameter of the film (for example, the impedance), then one can directly observe the time sequence of the entire process of establishment of superconductivity on the oscilloscope (Fig. 1).

However, the possibilities of such a method are limited by the bandwidth of the apparatus used, and it is suited in practice for the investigation of the dynamics of the processes which take place at rates no higher than 10^6/sec.

3. For the study of more rapid processes in the superconducting films, the following circumstance can be used.

If the peak power level of the uhf acting on the film at very slow (50 Hz) amplitude modulation is raised to the threshold value, then a characteristic "step" is produced on the envelope of the signal.[8] In the non-oscillatory regime, it will have a nonsymmetric shape (Fig. 2). One edge of it will be found at the maximum power point (P_1, according to [8]), and the other at a lower power level (P_2, according to [8]). The shape of this step is changed upon superposition of a high-frequency amplitude modulation of the uhf power by rectangular pulses with a comparatively low repetition rate ($\Omega \ll w_\downarrow$): it becomes symmetric (Fig. 3). This takes place as a consequence of the fact that at 100% modulation the process of recovery of destroyed superconductivity is completely concluded by the instant of arrival of the next uhf pulse.

However, at repetition rates that are comparable with the rate of condensation ($\Omega \gtrsim w_\downarrow$), the observed picture changes. Under these conditions, the process of recovery of superconductivity is no longer completed by the instant of arrival of the next uhf pulse (Fig. 4). Therefore, the symmetric shape of the "step" is again destroyed; one of its edges (the "tail" in time) becomes lower, i.e., it shifts to the region of lower uhf power levels. By measuring the ratio of the power level at the "leading" and "trailing" edges of the "step" at different repetition rates, one can construct, point by point, the dependence of the threshold kinetic energy of the electrons ϵ_{k-th} on the repetition rate. On the basis of these data, and with the help of the Ginzburg-Landau equation, we can compute the time dependence

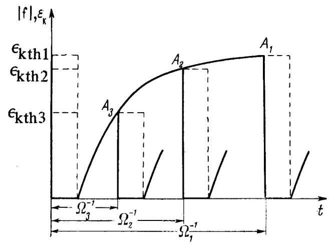

FIG. 4. Dependence of the threshold kinetic energy of the electrons on the repetition frequency of the square pulses of uhf (the point A is the "threshold). The continuous curve–f(t), the dashed curve–$\epsilon_k(t)$.

of the density of the superconducting component and determine the characteristic rates and times.

The possibilities of such a method of investigation of the dynamic characteristics of superconducting films are limited only by the fact that the length of the fronts of the destroying uhf pulse must be much shorter than the length of the process studied. Therefore, such a method of investigation can be used for the investigation of processes which take place with rates no higher than 10^8 sec^{-1}.

4. To overcome the limitations mentioned above, which are connected with the shape of the uhf pulses, and to increase the resolving power of the method with respect to the rate of the processes studied, a uhf signal can be used whose power is modulated according to the usual cosinusoidal law:

$$P = P_0(1 - \delta \cos \Omega t).$$

In principle, such a modulation method of investigation of the dynamic characteristics of thin conducting films is completely analogous to the case considered above of amplitude modulation of the uhf power by rectangular pulses. There are only two singularities in this case.

In cosinusoidal amplitude modulation, the "threshold" (the point A in Fig. 5) is not fixed at the vertex of the cosinusoid, but is shifted somewhat relative to it with increase in modulation frequency. However, calculation shows that this shift is small: no greater than 35% for $\Omega \approx 0.3\, w_\downarrow$, less than 15% for $\Omega \approx 0.2\, w_\downarrow$, and of the order of 1% for $\Omega \approx 0.1\, w_\downarrow$. Therefore, we can assume that the point A is always found at the peak of the cosinusoid with a sufficient degree of accuracy.

The second, more significant feature of such a shape of modulation is that the effect of the uhf power on the film is continued into the time of recovery of the destroyed superconductivity.

To account for this latter circumstance, we consider the process of recovery of destroyed superconductivity in a thin film for a cosinusoidal amplitude modulation. For this purpose, we use the Ginzburg-Landau equation, which describes the behavior of such films quite satisfactorily, at least in the temperature range $0.5 < t < 1.0$.[8]

We shall assume that $\delta \approx 1$ and $a\omega\tau \ll 1$ ($a = \rho_1/\rho_s$,

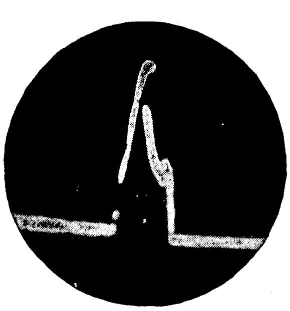

FIG. 2

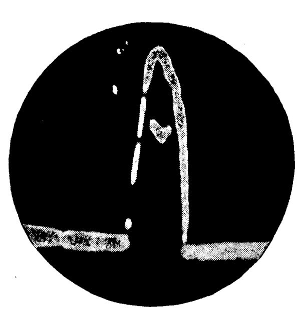

FIG. 3

FIG. 2. Unsymmetric "step" in the absence of high-frequency amplitude modulation.

FIG. 3. Symmetric "step" in the superposition of high-frequency amplitude modulation.

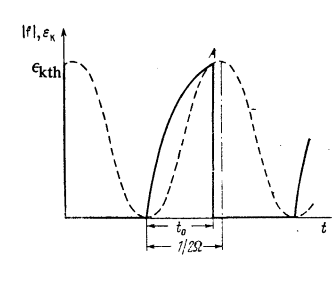

FIG. 5. Recovery of destroyed superconductivity in a film for cosinusoidal amplitude modulation of the uhf signal (point A–"threshold"). Continuous curve–f(t), dashed–$\epsilon_k(t)$.

ρ_1 is the density of the conduction electrons, ρ_{th} the density of the superconducting component at $F_s = 0$, τ^{-1} the relaxation rate of the normal component) and therefore the recovery of destroyed superconductivity begins practically at zero power level of the uhf.[7] By determining the density of the superconducting component at the point A, i.e., where $F_s = 0$, we find at the same time the value of the density achieved at a time t_0 after the initiation of the recovery process. If we assume that the point A is located at the cosine vertex, then $t_0 = 1/2\Omega$.

To determine the density of the Cooper pairs at the point A, we use the Ginzburg-Landau equation, according to which the instantaneous stationary value of this density[7] is

$$x_{st} = \frac{\alpha - \varepsilon_k}{\beta\rho_{th}}, \quad \varepsilon_k = \frac{mv^2}{2},$$

where $x = \rho/\rho_{th}$ is the dimensionless density of the superconducting component, ρ_{th} the density of the superconducting component at $F_s = 0$ and $\Omega \to 0$, v is the instantaneous value of the velocity of the superconducting component, α and β are the coefficients of the Ginzburg-Landau equation.

It can be shown that in the case of a uhf signal modulated by the cosinusoidal law we have

$$\varepsilon_k = k\frac{1+b^2}{1+\delta}\varepsilon_{kth}\frac{1-\delta\cos\Omega t}{b^2+x^2},$$

$$x_{st} = \frac{3}{2}\left[1 - \frac{k}{3}\frac{1+b^2}{1+\delta}\frac{1-\delta\cos\Omega t}{b^2+x^2}\right],$$

where $k = P_0/P_1$, P_1 is the uhf power level at which $F_s = 0$ for $\Omega = 0$, P_0 is the same level for $\Omega \neq 0$, $b = a\omega\tau$, $\epsilon_{k\text{-}th}$ is the kinetic energy of the electrons for $F_s = 0$. Therefore, under the condition

$$\delta \approx 1, \quad a\omega\tau \ll 1$$

we obtain

$$x_{st} \approx \frac{3}{2} - \frac{k}{4}\frac{1-\cos\Omega t}{x^2}.$$

At low modulation frequencies ($\Omega \to 0$), the value of x at the "threshold" (for $F_s = 0$) is obviously equal to unity. However, upon increase in the frequency of modulation, this quantity becomes different from unity by reason of the finite rate of the process of condensation of the excited quasiparticles. Therefore, in the general case,

$$x_A = \frac{\alpha - 2\varepsilon_k}{{}^1\!/_2\beta\rho_{th}} = 2\frac{\alpha - \varepsilon_k}{\beta\rho_{th}} - 2\frac{\varepsilon_k}{\beta\rho_{th}} = 2x_{cr} - \frac{\varepsilon_k}{\varepsilon_{kth}} = 3 - k\frac{1-\cos\Omega t}{x_A^2}$$

and, if we assume that the point A is at the vertex of the cosinusoid, then

$$x_A = 3 - 2k/x_A^2.$$

Consequently, the density of the superconducting component can be determined from the equation

$$x_A^3 - 3x_A^2 + 2k = 0,$$

or, by introducing $y = x_A - 1$,

$$y^3 - 3y - 2(1-k) = 0.$$

This equation has three real roots, but, since $k < 1$ and $y < 0$ in real situations, there is physical meaning to only one of them:

$$y = -2\cos\left[\frac{\pi}{3} + \frac{1}{3}\arccos(1-k)\right].$$

With accuracy better than 4%, we have

$$y = -\frac{\pi}{3} + \frac{2}{3}\arccos(1-k),$$

and for $k > 0.3$,

$$y \approx -\frac{2}{3}(1-k).$$

Therefore, for the range of values $0.5 \leq x_A \leq 1.0$, with accuracy to within 10% (in x_A), one can use the expression

$$x_A = {}^1\!/_3(1+2k),$$

and for the calculation of smaller values of x_A ($x_A < 0.5$ but $x_A \gg a\omega\tau$), the following more accurate expression should be used:

$$x_A = {}^2\!/_3 \arccos(1-k).$$

Thus, by changing the modulation frequency anf fixing the ratio of the power levels at both edges of the "step," we can obtain the dependence $k(\Omega)$ and then, by means of the expressions obtained above, calculate $x(t)$ and find the characteristic rates and times.

EXPERIMENTAL RESULTS

Investigations were carried out on thin (100–400 Å) lead films in the three centimeter wavelength region at a temperature of 4.2°K. The technology of sample preparation and the construction of a resonator with the film have been described in a previous paper.[8] The experimental arrangement consisted of a helium cryostat, the source of the uhf signal and a detector with an oscilloscope. A low-frequency modulation (50 Hz) could be applied to the uhf signal for observation of the region of generation and of the resonance curve on the screen of the oscilloscope. High-frequency square wave and cosinusoidal amplitude modulation of the uhf signal, with frequencies up to 200 MHz, were obtained by means of a waveguide modulator with a twin-T bridge. To obtain the cosinusoidal amplitude modulation at much higher frequencies (up to 1000 MHz), the method of beating of oscillators from two uhf sources tuned to half the modulation frequency was used.

2. A few dozen lead samples were studied. By means of amplitude modulation of the uhf signal by square wave pulses with direct observation of the screen of the oscilloscope, the dynamics of recovery superconductivity could be studied. It was found that the rate of this process is higher than 10^6 sec^{-1}. Study of the dependence of the threshold uhf power levels on the repetition frequency of the square wave pulses made it possible to establish the fact that this rate exceeds 10^8 sec^{-1}. Therefore, for the investigation of the condensation rate in these samples, cosinusoidal amplitude modulation of the power of the uhf signal was employed. Here it was found that in all the lead films studied, the symmetric form of the step was maintained up to modulation frequencies of 400–450 MHz.

At higher frequencies ($\Omega \geq 500$ MHz), the symmetry of the "steps" was destroyed. However, these frequencies were already comparable with the transmission band of the resonator, the use of which in our experiments was due to the necessity of compensation of the reactive part of the impedance of the superconducting film. Without this compensation, it is impossible to obtain sufficient "steps" for observation on the envelope of the signal reflected from the film. Therefore, one can only assert that the rate of recovery of destroyed superconductivity was no lower than 10^9 sec^{-1} in our experiments.

3. If the rate of condensation is sufficiently great ($w_\downarrow \approx \omega$), then there is a possibility of its determination by means of an unmodulated uhf signal.

At high frequencies ($\omega > w_\downarrow$), an unsymmetric "step" should be observed, in the nonoscillatory regime, on the envelope of the uhf signal reflected from the resonator with the film for a power level higher than threshold.[8] However, upon lowering of the frequency and achievement of the level $w_\downarrow > \omega \gg w_\uparrow$, as also for cosinusoidal amplitude modulation in the case $\Omega < w_\downarrow$, the shape of the "step" should become symmetric. Therefore, by reducing the frequency ω of the uhf signal from $\omega > w_\downarrow$ and fixing its value for which the nonsymmetric earlier "step" becomes symmetric, one can determine the rate of the condensation process in the film.

From this viewpoint, the nonsymmetric shape of the "step" observed in our experiments at frequencies of 10^{10} Hz (λ = 3 cm) in the absence of modulation indicates that the rate of condensation of excited quasiparticles in the lead samples we investigated does not exceed $(1-2) \times 10^{10}$ sec^{-1}, i.e., it is found in the range $1 \times 10^9 - 2 \times 10^{10}$ sec^{-1}.

The defect of the latter method is the necessity of retuning of the resonator with the film and the uhf source over a wide range of frequencies. However, the absence of the amplitude modulation of the uhf signal in this method makes it possible to use resonators of high Q, so that measurements are materially easier and the possibilities of the investigation of the dynamic characteristics of thin superconducting films are broadened. In particular, we claim that with this method we could study condensation processes in thin films that occurred with rates up to 10^{10} sec^{-1} and possibly even higher.

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