# Experimental investigation of the nonequilibrium state of superconductors excited by lasers

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The superconducting properties of Pb and $Nb_3Sn$ films irradiated by a pulsed laser are studied. A GaAs laser with pulse intensities up to 50 W and pulse durations between 0.1 and 10 $\mu$sec was used. The dependence of the signal due to the appearance of resistance on the sample temperature and on the intensity and duration of the laser pulse is studied. A spatially nonuniform distribution of the excitations is observed. The phenomenon resembles the formation of Keldysh exciton drops in semiconductors.

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## INTRODUCTION

To resolve the question as to the possibility of high-temperature superconductivity under nonequilibrium conditions, it is important to investigate the properties of nonequilibrium superconductors. The present paper reports on a study of the properties of superconducting films of Pb and $Nb_3Sn$ that were irradiated with a laser. As a result of the investigations, it was established for the first time that a spatially nonuniform distribution of excitations is formed in the superconductor under the action of the laser radiation. The phenomenon is similar to the formation of a spatially nonuniform distribution of excitons in semiconductors (Keldysh drops).

## EXPERIMENT

1. The investigated layers were obtained by evaporation in vacuum on polished ruby substrates, which guaranteed their high homogeneity. The measurements were carried out on ten Pb films and four $Nb_3Sn$ films. Their parameters are given in the table. Most of the measurements were made on films of Pb of thickness 1000 Å and films of $Nb_3Sn$ of thickness 2000 Å.

As a source we used a GaAs semiconductor laser with a radiated pulse power of up to 50 W, wavelength 0.85 $\mu$, and pulse durations from 0.1 to 10 $\mu$sec. The voltage pulses to the laser were obtained from a G5-15 generator by means of a current amplifier. The radiation was incident on the sample through a quartz-rod lightguide, giving a uniformly radiated spot of diameter 4 mm. The radiation that emerged from the other side of the laser, was incident on a Ge-Au photoresistor, which served am receiver for investigation of the magnitude and shape of the laser pulses. The sample was fastened to a copper block by means of an indium gasket. An Allen-Bradley thermometer was located inside the block. The thermometer resistance was measured by means of an F-30 digital voltmeter. The entire system, including the sample, lightguide, laser and photoresistor, was placed inside a helium cryostat. The resistance of the sample was measured by the four-contact method. A subcritical constant current (from 3 to 10 mA for Pb, and from 0.8 to 3 mA for $Nb_3Sn$) was passed through the sample. The values of the critical currents for the films studied are given in the Table.

The voltage that is developed between the potential contacts of the sample during the laser pulse, was applied to the input of a two-channel S7-8 oscilloscope. The signal from the photoresistor was applied to the other input. The oscilloscope had an output to a PDS-021 x-y recorder, which made it possible to record both the shape of the signal from the sample and also the form of the laser pulse. We studied the dependence of the magnitude and shape of the resulting voltage pulses (U) on the temperature T, the radiated power W, and the laser pulse duration $\tau$. The measurements were carried out repeatedly on all 14 prepared samples.

2. We first consider the results for the Pb samples. At a sufficiently high power of the laser radiation, a signal was generated at temperatures which were considerably below critical. Figure 1 (curve 1) shows that such a signal appears even at T = 5.2°K and amounts to about 30% of the value $U_N$ of the signal corresponding to the complete transition of the sample to the normal state. With increasing temperature, the magnitude of the signal increases, however, only at T = 6.9°K did it reach the full value of $U_N$. The temperature at which this value is reached depends on the radiated power and the sample thickness.

The power dependence of the signal (Fig. 2) has a threshold character. The threshold power decreases with increasing temperature and increases with increasing thickness. For Pb films with thickness of 1000 Å at 5.75°K, the threshold power amounted to 17 W. Under our experimental conditions, this corresponded to an absorbed power density of 30 W/cm². At low radiated powers, a signal developed on the sample only in the immediate neighborhood of $T_c$.

Testardi[1] also studied the effect of laser radiation on the superconductivity of Pb films. However, the laser power used in his experiments was only 5 W (the absorbed power density amounted to 17 W/cm²); therefore, in films of thickness 1000 Å, only the result of heating was observed. And only for films of thickness

Parameters of samples studied

| Parameters | Pb | $Nb_3Sn$ |
|---|---|---|
| Film thickness, A | 1000–2000 | 2000 |
| Width, mm | 1–1.5 | 1–1.5 |
| Distance between potential contacts, mm | 3–3.5 | 3–3.5 |
| $T_c$, °K | 7.2 | 17–18 |
| $\Delta T_c$, °K | 0.01–0.03 | 1–2* |
| $I_c$, A (at T = 4.2°K) | 0.1 | 0.4–1.0 |

*For the $Nb_3Sn$ sample with transition width of 2°K, a small "tail" was observed in the dependence of the resistance R on T, amounting to 10% of the basic transition and terminating at T ≈ 10°K.

  

275 Å did he record nonthermal disruption of the superconductivity.

The picture described above was observed by us as the duration of the laser pulses was varied in the range 0.1–10 μsec. The magnitude of the signal, which was less than $U_N$, increased somewhat with increasing laser-pulse length.

3. The general picture observed in study of the properties of $Nb_3Sn$ films irradiated by a laser resembles the picture for Pb. However, there were certain differences in the shape of the pulses, the magnitude of the signal, and its dependence on the power and temperature (Figs. 3 and 4). These differences are connected basically with the shape of the temperature dependence of the resistance near $T_c$, and with the magnitude of the threshold power. Films of $Nb_3Sn$ had a significantly larger temperature width of the superconducting transition and a higher value of the threshold power. For a film of thickness 2000 Å the threshold power at $T = 4.2°K$ amounted to 30 W (the absorbed power density was 53 W/cm²). At the powers that we used, these differences did not allow us to obtain the full value of the signal for $Nb_3Sn$ and led to a smoother drop of the signal at $T \sim T_c$. To obtain the full values of the signal in our samples of $Nb_3Sn$, it was necessary to use a laser power $\gtrsim 60$ W.

4. We now consider the amount of heating $\Delta T_h$ of the superconducting film by the laser radiation pulse. For Pb, it was measured experimentally by two methods: 1) at $T \gtrsim T_c$, the change in the resistance of the film was measured under the action of a laser pulse of definite power and duration. The amount of heating of the sample was then measured from the temperature

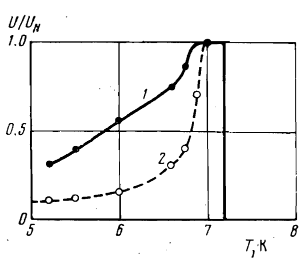


FIG. 1

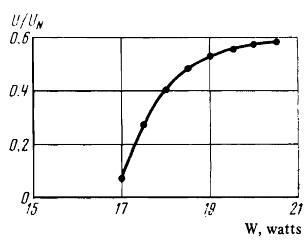


FIG. 2

FIG. 1. Temperature dependence of the magnitude of the signal for Pb: 1–without screen, W = 20 W, 2–with screen, W = 50 W; τ = 10 μsec.

FIG. 2. Dependence of the magnitude of the signal on the power at constant temperature in the case of Pb: τ = 10 μsec, T = 5.75°K.

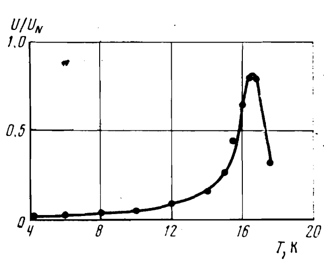


FIG. 3

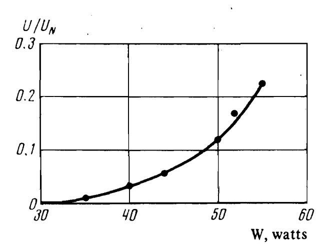


FIG. 4

FIG. 3. Temperature dependence of the magnitude of the signal for $Nb_3Sn$: τ = 5 μsec, W = 40 W.

FIG. 4. Dependence of the magnitude of the signal on the power at constant temperature in the case of $Nb_3Sn$: τ = 5 μsec, T = 4.2°K.

dependence of the resistance. For films of thickness 1000 Å at a laser power of 20 W and pulse duration of 10 μsec, the amount of heating was 0.3–0.6°K; 2) the upper limit of the heating could also be estimated from the temperature dependence of the magnitude of the signal at $T < T_c$. Inasmuch as the signal was still incomplete at $T < 6.9°K$ for Pb, the heating at this temperature amounted to 0.3–0.4°K. This is in good agreement with the value obtained by direct measurement at $T > T_c$.

For $Nb_3Sn$, the absence of a significant temperature variation at a temperature slightly in excess of $T_c$ precludes determination of the heating by method (1). Using the temperature dependence of the resistance for $Nb_3Sn$ films, the second method gave the result that the upper limit of the heating amounted to 1.2°K.

Both for Pb and for $Nb_3Sn$, the signal was observed at temperatures T much lower than $T_c - \Delta T_h$. This indicates that the observed effect is not determined by heating of the sample.

## DISCUSSION

The disruption of superconductivity by laser radiation can be regarded as a consequence of the appearance of excitations with a concentration exceeding some critical value.[2,3] The excitations that first appear have a large energy and lose it rapidly, taking levels near the boundary of the gap. The relaxation time $\tau_\epsilon$ of the nonequilibrium excitations depends strongly on the difference $\epsilon - \Delta$, increasing as it decreases (here $\epsilon$ is the energy of excitation, $\Delta$ the energy gap). The values of $\tau_\epsilon$ can be estimated from tunnel experiments by means of the Éliashberg equation.[4] In our experiments, an important role is played by the long-lived excitations with $\tau_\epsilon \gtrsim \tau$. The number of states for such excitations is equal to $(1-3) \times 10^{19}$ cm$^{-3}$.[5] The number of quanta absorbed by the sample during the pulse amounts to $5 \times 10^{11} - 5 \times 10^{13}$. Taking into account the volume of the sample, we get $10^{18} - 10^{20}$ quanta/cm³. The number of excitations created by the laser increases due to secondary generation. According to the data of Parker and Williams,[6] the multiplication factor is equal to $\sim 10^2$. It is thus seen that during the pulse, not only long-lived but also short-lived states will be filled. Decay of the latter leads to the heating.

An important experimental fact is the presence of the incomplete signal at temperatures below $T_c$. The results obtained for Pb are especially interesting in this connection. The Pb samples had a sharp transition to the superconducting state, of width 0.01°K. In this case, the appearance and peaking of the signal on laser irradiation should take place in a temperature range equal to the transition width. In the experiment, however, this interval exceeded 2°K. Similarly, in films of $Nb_3Sn$, the width of the transition is significantly less than the temperature difference between the beginning of the appearance of the signal and its peaking. Thus, at sufficiently low temperatures the total number of excitations is insufficient for transition of the sample to the normal state in the case of uniform excitation distribution. In this case, the sample should remain in the superconducting state and the signal ought to vanish. An incomplete signal is observed experimentally. The indicated result compels us to assume an nonuniform distribution of the excitations throughout the sample.

This nonuniformity is not connected with the inhomogeneity of the laser radiation. A special experiment was performed. A mask was placed over the sample, covering half of its length. In this case, the nonirradiated part should short-circuit the sample. However, the picture was not changed qualitatively (Fig. 1, curve 2); at $T < T_c$, $U \neq 0$. It then follows that excitations are propagated over a length $\sim 1$ mm. Nor is the observed effect connected with the magnetic field H or with the measurement current I, since $H \approx 0.5-1$ Oe $\ll H_c$, $I \ll I_c$.

The results for $Nb_3Sn$ are similar to the results for Pb. Some difference is connected with the greater value of $T_c$ and the smaller value of the gap $\Delta$ for $Nb_3Sn$ in comparison with Pb ($T_c = 17°K$ for $Nb_3Sn$ and 7.2°K for Pb; $\Delta = 1.0$ MeV for $Nb_3Sn$ and 1.4 MeV for Pb). These circumstances increase the number of thermal excitations in $Nb_3Sn$, and this masks the effect. For observation of the effect in $Nb_3Sn$ with the same sharpness as in Pb, it is necessary to increase the power of the laser radiation.

It follows from our experiments that the excitations are concentrated around certain centers under laser irradiation[7]. The regions where the concentration becomes critical are regions of the normal state. On an increase in the total number of excitations, the dimensions of the regions of the normal state increase, and a signal appears when these regions cover the entire width of the sample. The phenomenon resembles the formation of exciton Keldysh drops in semiconductors.[8] We can say nothing at this point about the shape of the regions of the normal state. They can, for example, have the shape of circles, strips or some other shape.

Assuming that the recombination time of the excitations in the superconducting state is much greater than the relaxation time in the normal state, the formation of regions of the normal state under constant pumping of excitations can turn out to be energetically favorable. The theoretical consideration of this question is an independent problem.

The spatially inhomogeneous distribution of the excitations was observed by us for superconductors in the nonequilibrium state. However, cases are possible in which a similar inhomogeneous state will also exist for an equilibrium superconductor. The inhomogeneous distribution of the excitations should in this case lead to an increase in the ratio $kT_c/\Delta$. The large value of this ratio for superconductors with A15 lattices may be explained in this way.

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