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PHYSICAL REVIEW B VOLUME 4, NUMBER 7 1 OCTOBER 1971

Destruction of Superconductivity by Laser Light

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(Received 27 January 1971)

Superconductivity is destroyed by laser light in Pb films of thickness comparable to the optical penetration depth δ and less than the superconducting coherence length ξ. Thermal effects, which have been independently determined, cannot account for this. For films of thickness greater than δ and ξ, only the thermal effect is observed. In a proposed explanation it is shown that the electron gas may be heated from 3 to 18 °K above the lattice temperature by the light absorption in these experiments.

I. INTRODUCTION

Several experimental[1] and theoretical[2] studies of the behavior of superconductors in high-frequency electromagnetic fields have been reported recently.

The destruction of superconductivity by laser light in thin Pb films is reported in this paper. This paper deals mainly with the description of the anomalous effect and the experiments to establish the magnitude of the heating caused by the laser pulse.

II. EXPERIMENTAL

To determine unambiguously the heating of the film produced by the laser illumination, the film resistance was used to measure the film temperature. This requires a temperature coefficient of resistance $d\ln R/dT$ of at least several parts per thousand at temperatures just above T_c for films of thickness comparable to the optical penetration depth (~ several hundred Å). Only a few metals will satisfy this requirement. One of the most satisfactory is lead.

Films were obtained by argon getter sputtering of high-purity Pb at 4–6 Å/sec onto polished single-crystal sapphire substrates.[3] Sample shapes suitable for standard four-terminal resistance measurements were obtained by scribing away thin lines of the Pb films on the substrate face. Sample dimensions were usually 2–4 (between potential probes)$\times$0.5 mm.

For most of the experiments, film thicknesses of about 275 Å were used. Several films 1500–2000 Å were also studied. In all cases the films had an electrical resistivity at 300 °K (~ 25×10^{-6} Ω cm) roughly equal to that of bulk Pb. Resistivity ratios $\rho(300\,^\circ\mathrm{K})/\rho(8\,^\circ\mathrm{K})$ were ~3 to 4 for the thinner films.

The sapphire substrates were plates approximately 1 cm$\times$0.5 cm$\times$0.7 mm (thick). These plates were ultrasonically soldered with gallium to a block of oxygen-free high-conductivity (OFHC) copper roughly 1$\times$2 cm. The arrangement is shown in Fig. 1.

Two lasers were used. Both were argon multicolor multimode lasers. About half the power from the laser was multimode at 5145 Å, one-third the power was single-mode multicolor, and the remainder was single mode at 5145 Å. The outputs were a 40-μsec pulse at 2 W and a 6-μsec pulse at 5 W. The light was focused to circular spots at the sample of ~4 and $2\frac{1}{2}$ mm diameters for the two lasers, respectively. Estimating an optical loss of 50%, for the lens, mirror, and window, a sample reflectivity of 60%, and a (measured) transmittance[4] of ~0 to 10% gives the energy fluxes shown in Table I.

Note that even for the 275-Å films (~10% transmittance[4]) the optical penetration depth was com-

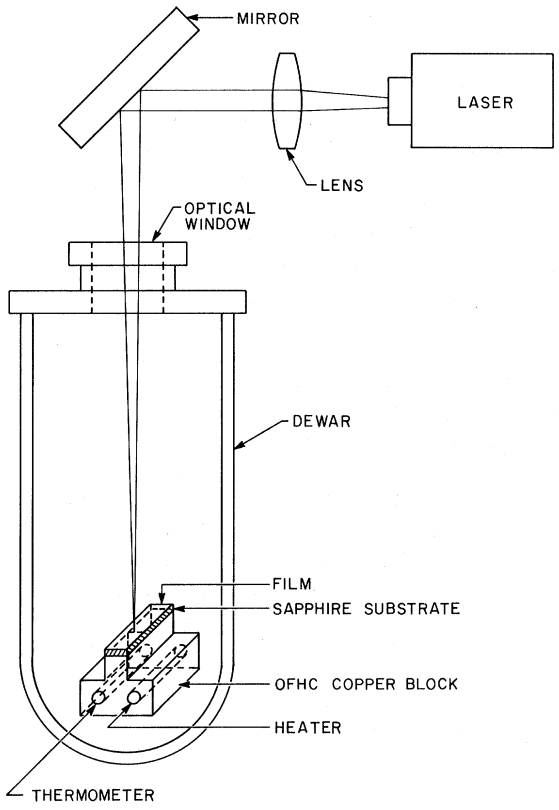

FIG. 1. Experimental arrangement. The sapphire substrates were ultrasonically soldered with gallium to the copper block.

parable to, or less than, the film thickness. The samples, therefore, were not uniformly illuminated in thickness.[5] Also, for Pb, the BCS coherence length ξ_0 is approximately equal to 830 Å, and the penetration depth $\lambda \approx 390$ Å. The electron mean free path was estimated[3] to be $l \approx 220$ Å for the thinner films from which follows a Ginzburg-Landau parameter $\kappa \approx 1$ and a temperature-dependent coherence length (for the dirty limit $\xi_0 \gg l$) $\xi = 0.85 \times (\xi_0 l/\tau)^{1/2}$ where $\tau = (T_c - T)/T_c$.

III. RESULTS AND DISCUSSION

A. Film Heating by Laser Light

Measurements of the film heating were made by observing the change in film resistance during laser illumination at temperatures above T_c. Figure 2 shows the change in *IR* drop for a 275-Å film at 7.84 °K during illumination with the full power output of the 40-μsec-pulse laser. The temperature increase was determined by raising the temperature of the film until the *IR* drop just before the onset of the laser pulse (i.e., with no light) increased by the same amount as that caused by the illumination. For the film of Fig. 2 the heating was 0.45 °K. This heating varied linearly with laser power (from full power to half-power) and was independent of the measuring current (for variations in the latter of a factor of 8).

The heating showed an initial time response $dT/dt \approx 0.027$ °K/μsec (partly influenced by the rise time of the laser pulse) which lasted for about 8 μsec. This was followed by a slower response, initially $dT/dt \approx 0.005$ °K/μsec, for the remaining 32 μsec. (This behavior may reflect the separate time constants of the substrate and copper block but analysis is hampered by the unknown thermal contact resistances.) With the laser light off the initial cooling rate, $dT/dt \approx 0.02$ °K/μsec, was roughly similar to the initial heating rate. The time constant for cooling was ≈ 50 μsec.[6] For heating the time to reach steady state was greater than the pulse duration. A characteristic of the thermal response for heating, which is important for the analysis of the superconducting behavior, is that the film temperature cannot follow the exact shape of the laser pulse. This can be seen in Fig. 2 which also shows the laser pulse recorded by a fast silicon photodetector.

The thermal response was also measured at 10.8 °K. To within an uncertainty of ~10% the results were the same as those found at 7.8 °K (Fig. 2). On this basis it is assumed that the normal thermal response at temperatures ~1–2 °K below T_c (= 7.2 °K) was not grossly different than

TABLE I. Laser light and heating magnitudes and T_c reduction.

Laser pulse width (μsec)	Light absorbed by sample: Power (W)	Power/area (W/cm²)	Energy (10^{-6}J)	Initial heating rate, Full power (°K/μsec)	Initial cooling rate, Full power (°K/μsec)	Observed heating at full power (°K)	T_c reduction[a]: Full power (°K)	Half-power (°K)
40	0.3	3	12	0.027	0.020	~0.45	~3.2	~1
6	0.75	17	4.5	0.15[b]	0.11[b]	~1	$\gtrsim$6	~2.5

[a] T_c (light off) − T_c (light on). Temperatures measured at beginning of light pulse. This quantity includes the heating effect.

[b] Calculated.

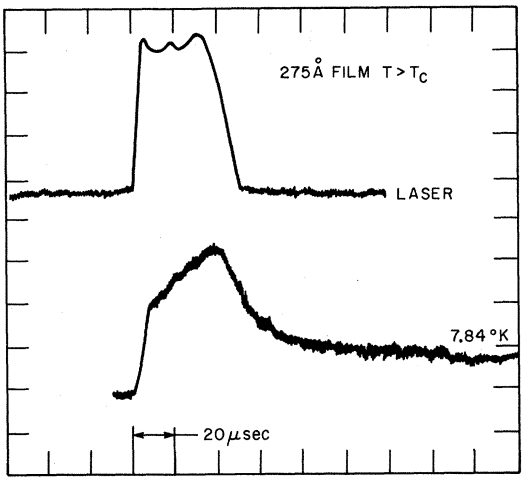

FIG. 2. 275-Å-thick sample resistance at 7.84 °K and laser output vs time. Horizontal scale 20 μsec/div. Vertical scale for sample resistance is $dR/R = 0.85 \times 10^{-3}$/div or, equivalently, $\Delta T_{\text{heating}} = 0.14$ °K/div. The laser output was recorded by a fast photodetector.

that shown in Fig. 2. This assumption was confirmed by the results of the thick film experiments (see below).

About four samples with thickness 250–300 Å were measured. All showed temperature increases of 0.3–0.5 °K with full power illumination from the 40-μsec-pulse laser. This is the magnitude and uncertainty of the heating effects obtained in these experiments.

Two samples of thickness 1500–2000 Å were also measured. Heating values in the range 0.3–0.5 °K were also obtained. This result shows that the thermal response of the film to the laser light is not dependent on the film thicknesses used in these experiments. (The heat capacity of such thin films is of minor importance in determining the thermal response of the system.) This fact will be used in distinguishing optical from heating effects in the superconducting behavior.

For the 6-μsec-pulse laser the measured temperature rise in a 270-Å film at 7.7 °K was ~1 °K. This is consistent with the results of the 40-μsec-pulse laser when account is taken of the difference in power/area at the sample in the two cases (see Table I). Because of a much higher electrical noise level from the 6-μsec-pulse laser the exact shape of the sample heating curve could not be observed. The values of the initial heating and cooling rates, given in Table I, have been calculated by scaling the results of the 40-μsec-pulse laser. These calculations are supported by the consistency in the measured total temperature increases for the two lasers.

B. Measurements below 7.2 °K

Below 7.2 °K (T_c with no light) an *IR* drop across the sample is observed with the 40-μsec-pulse laser whose pulse shape is a nearly exact replica of the laser light output recorded by the photodetector. This behavior requires a response time of $\lesssim 5$ μsec which is a factor of $\gtrsim 10$ faster than the thermal response time observed at 7.8 °K.

For the 40-μsec-pulse laser (where $\Delta T_{\text{heating}} \sim 0.45$ °K) the *IR* drop is observed at temperatures as far as 3 °K below T_c (no light). This is well beyond the range in temperature where the heating effects should be observed. The *IR* drop at 4.4 °K and the laser pulse shape are shown in Fig. 3.

Evidence that this is not a new form of the thermal effect observed at 7.8 °K lies in the fact that for T between T_c and $T_c - \Delta T_{\text{heating}}$ both the fast response and the slow thermal response can be observed. This is shown in the photograph reproductions in Fig. 4. Note that at $T = 6.8$ °K $\approx T_c - \Delta T_{\text{heating}}$, a slight asymmetry appears in the pulse with the trailing end slightly larger in amplitude than the leading end. This is the shape expected for the contribution due to heating (see Fig. 2). Furthermore, the temperature at which this occurs agrees well with that expected for the heating effect. As the temperature is raised the trailing edge (heating peak) increases rapidly but the leading edge peak can be discerned separately up to $T \approx 7$ °K.[7]

The last pulse in this sequence, at $T \approx 7$ °K, allows a further comparison with the expected results for heating. The laser pulse should increase the sample temperature at the trailing

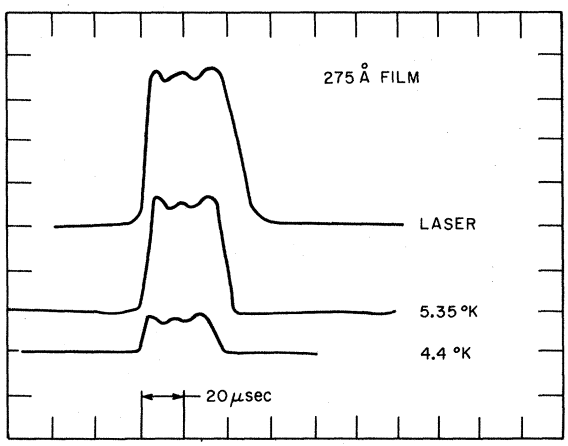

FIG. 3. 275-Å-thick sample resistance (lower curve) and laser output (upper curve) vs time. Horizontal scale 20 μsec/div. For $T = 4.4$ °K the sample resistance during laser pulse is $0.06 R_N$. For $T = 5.35$ °K the sample resistance during laser pulse is $0.15 R_N$.

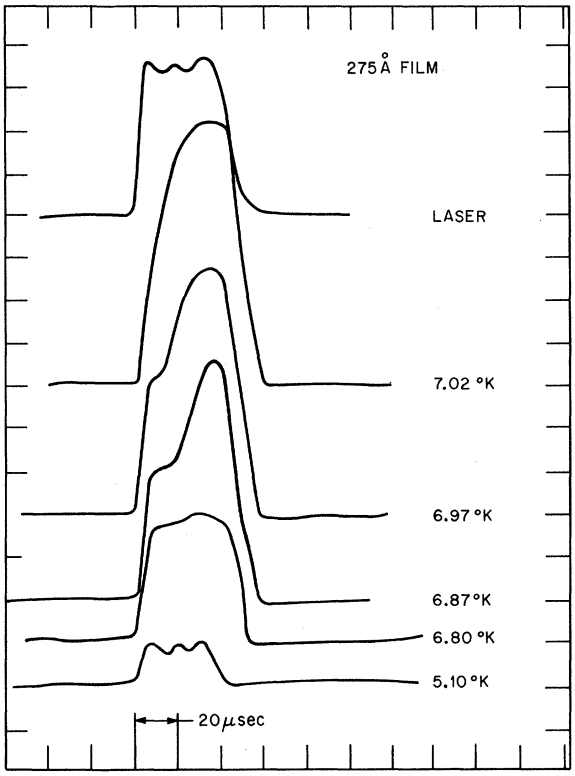

FIG. 4. 275-Å-thick sample resistance vs time (20 μsec/div). Normal-state resistance is 6 vertical units.

end of the pulse to 7.47 °K. With an initial cooling rate of 0.02 °K/μsec (see Fig. 1 or Table I) the sample should remain in the normal state for ≈ 13 μsec after the completion of the laser pulse. This is confirmed in the results.

The most important evidence elucidating this effect comes from the thick-film experiments. For film thicknesses $d \sim 1500$–2000 Å, one has $d \approx 2\xi$ and $d \approx 8\delta$, where ξ and δ are the superconducting coherence length and optical penetration depths, respectively. For these films superconduction will occur along the "back" half of the film thickness presumably uninfluenced by the direct interaction with light or with the effects of light carried over the coherence length. However, as found in the "heating effect" measurements above T_c, the temperature rise of these films due to the laser pulse is similar to that for the 275-Å films.

The thick-film experiments show no effects below 7.2 °K other than those expected for heating. This can be seen in the photo sequence of Fig. 5. For this film (2000 Å thick) the temperature increase due to the laser pulse was measured to be 0.35 °K. The first appearance of an *IR* drop occurred near $T = 6.85$ °K. At 6.88 °K about one-third the normal-state resistance is found and at $T = 7.02$ °K the film is driven fully normal for most of the duration of the laser pulse. At 7.08 °K the laser pulse raises the sample temperature to 7.43 °K and the sample must remain in the normal state for a time necessary to achieve a cooling of 0.23 °K or 0.23 °K/0.35 °K of the total temperature rise. From the thermal behavior shown in Fig. 2 this time is ≈ 50 μsec, which is in reasonable agreement with the results in Fig. 5.

Note also from Fig. 5 that below 7.2 °K the response is slow and first appears at the trailing edge of the laser pulse as expected for heating effects.

An important conclusion of these results is that the heating effects for $T > T_c$ are also found for $T < T_c$. This excludes as possible explanations (i) changes in the Kapitza thermal boundary resistance at the film-substrate interface between the normal and superconducting states and (ii) other anomalous temperature dependences of the thermal properties which would cause the heating below T_c to be grossly different than the heating above T_c.

C. Nonlinear Effects

Although the transition in zero light is only a few millidegrees wide, the photoinduced resistive state shows a very broad superconducting to full normal-state transition. This is shown in Fig. 6 which gives the ratio of normal-state resistance, R/R_N, observed during the 40-μsec-pulse laser as a function of the initial temperature. Note that for the full laser output the resistive state with fast time response appears just above 4 °K and is observed up to ≈ 6.8 °K where the heating peak

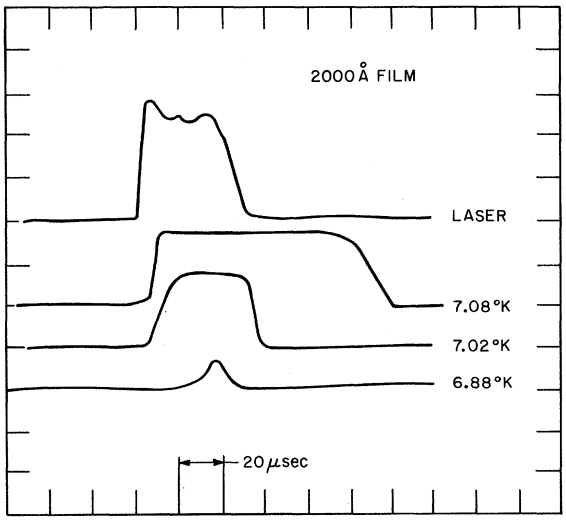

FIG. 5. 2000-Å-thick sample resistance and laser output vs time (20 μsec/div). Normal-state resistance is 1.8 vertical divisions.

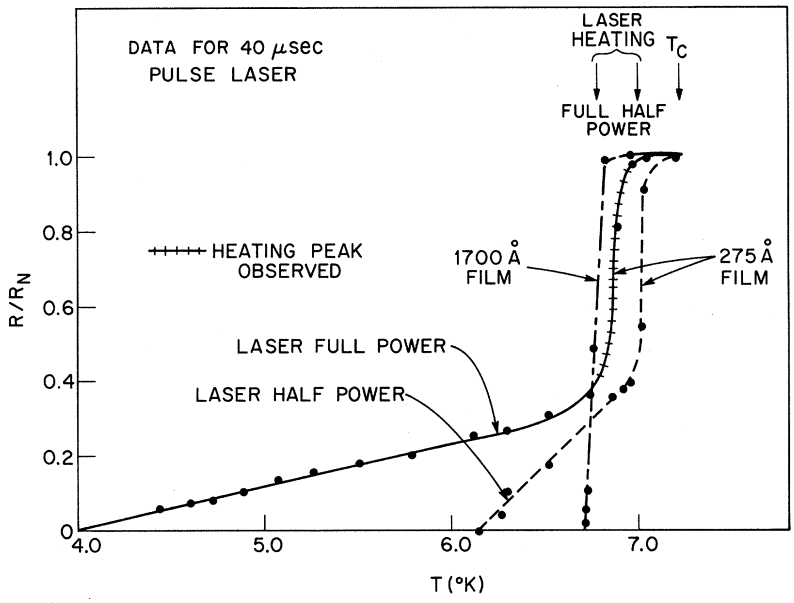

FIG. 6. Sample R/R_N versus temperature during illumination by the 40-μsec-pulse laser beam. Temperatures are those recorded in zero light.

appears. The transition to the full normal state occurs abruptly after this.

When the intensity of the 40-μsec-pulse laser is reduced by 50% (by a calibrated transmission filter) the data represented by the dashed line are obtained. Both the measured temperature rise above T_c and the range of the heating peak below T_c are reduced by a factor of 2. However, the range of the anomalous photoinduced resistive state is reduced by more than a factor of 2. In the range of the anomalous behavior the slope of the data line for the full laser output is one-fourth that obtained for the 50% laser output. The anomalous depressions of T_c (i.e., corrected for the heating effect) are in the approximate ratio 3.5/1.

The shape of the curve, R/R_N vs T, however, is influenced somewhat by the transverse nonuniformity of the laser light intensity over the sample length. This was due in part because the laser beam diameter was only slightly larger than the length of the measured sample. A further complication arises from (~ 500–1000 Å) polishing grooves on the surface of the sapphire substrate within which oblique illumination will occur. The measured R/R_N is therefore an average value for the sample between the potential probes. An estimate of the nonuniformity of illumination is given by the width of the superconducting transition which is induced only by the heating effect of the laser beam. For the thick film, and for the thin film where the heating "peak" could be discerned, the width of the transition is ~0.1 to 0.15 °K, which should be compared with a mean $\Delta T_{\text{heating}}$ ~ 0.4 °K and a transition width of several millidegrees in zero light.

Also shown in Fig. 6 are the results for a thick film different from that discussed above. Again only the heating effect is observed below T_c.

D. 6-μsec-Laser Results

The sample voltage signals obtained with the 6-μsec-pulse laser showed "ringing" at the leading edge and a peak at the completion of the laser pulse.[8] These are electrical pickup transients from the laser power supply. There was also a slight delay (< 1 μsec) of the sample signal relative to the laser pulse which was introduced by the signal amplifier.

With the full power of the 6-μsec-pulse laser the near full normal-state resistance was induced at temperatures down to < 3 °K (see Fig. 7). (The laser pulse heating at 7.7 °K was ~ 1 °K.) Only for $T \gtrsim 6.2$ °K did the sample remain in the normal state for a short time after the completion of the laser pulse. This behavior for $T > 6.2$ °K was consistent with that expected for heating and calculated from the initial cooling rates shown in Table I.

With the intensity of the 6-μsec-pulse laser reduced by a factor of 2 the onset of the resistive state occurred at about 4.5 °K. In this case one could study the photoinduced resistive state where $R/R_N < 1$. A puzzling result of this study was the occurrence of delay times of several microseconds between the beginning of the laser pulse and the onset of the resistive state. This is shown in Fig. 8 for $T = 5.15$ °K ($\Delta T_{\text{heating}} \sim \frac{1}{2}$ °K).

No evidence of the resistive state persisting after the completion of the light pulse was found until $T \sim 6.85$ °K where the heating effect was expected to occur (see Fig. 8). Figure 9 shows the

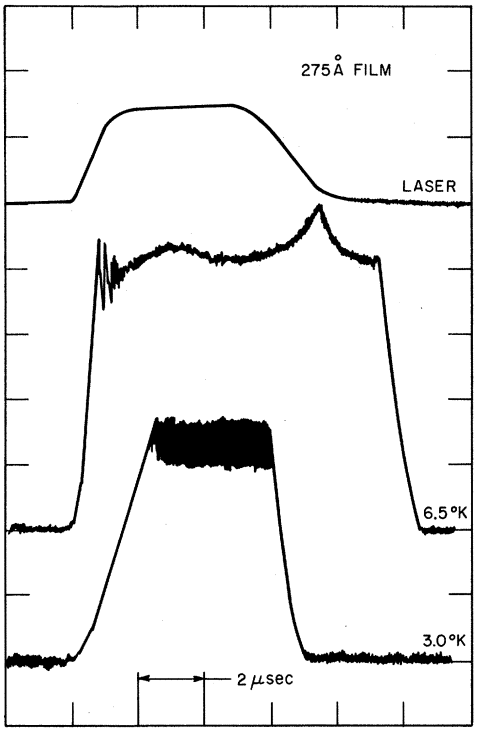

FIG. 7. 275-Å-thick sample resistance and laser output vs time (2 μsec/div). Sample normal-state resistance is 4 vertical divisions.

sample resistance vs temperature for two power levels of the 6-μsec laser.

IV. SUMMARY AND CONCLUSIONS

Laser light induces a resistive state in thin films of Pb at temperatures below the usual T_c. The effect is not due to normal heating.

The response times in the resistive state are shorter than the thermal response times and the "width" of the resistive transition is much larger than the transition in no light.

The magnitude of the anomalous depression of T_c varies nonlinearly with the laser power.

The photoinduced resistive state is only found in films of thickness comparable to or less than the optical penetration depth and the superconducting coherence length. For thicker films only the thermal effect is seen. This would preclude explanations based on a change in the Kapitza thermal boundary resistance of the film between the normal and superconducting states.[9]

A delay time of several microseconds between the laser pulse and the onset of the resistive state is observed.

No explanation for these effects is known.[10] The magnitude of the laser power is not exceptionally large (photon flux ~ 10^{19}/cm^2 sec).[11] The electric and magnetic fields (in air) of the light pulse are 50 V/cm and 0.5×10^{-2} Oe, respectively. These are small compared with the critical values of these quantities for the destruction of superconductivity.[12]

The laser light used in this experiment had a coherence time of ~ 10^{-9} sec. The importance of the coherent nature of the light could be established by performing similar experiments with light of coherence time, say, $<\hbar/\Delta$ (~ 4×10^{-2} sec for Pb), where 2Δ is the superconducting energy gap. No measurements have been made with light sources other than the lasers described above.[13]

Phenomenologically one can explain the results by a "bottleneck" in the conversion of optical energy, absorbed by the electrons, to phonons ultimately sent to the heat sink. This effect could arise if the electron-phonon relaxation time after the optical-absorption process was much longer in the superconducting state than in the normal state. An estimate of the heating of the electron gas above the lattice temperature is made as follows. Let τ be the time necessary for the electron gas to reach a steady-state condition after the light is turned on. If P is the input light power then the energy of the illuminated electron gas is increased by ~ $P\tau$ in reaching the steady state. Approximating the light absorption as uniform over the film thickness d (≈ optical penetration depth)

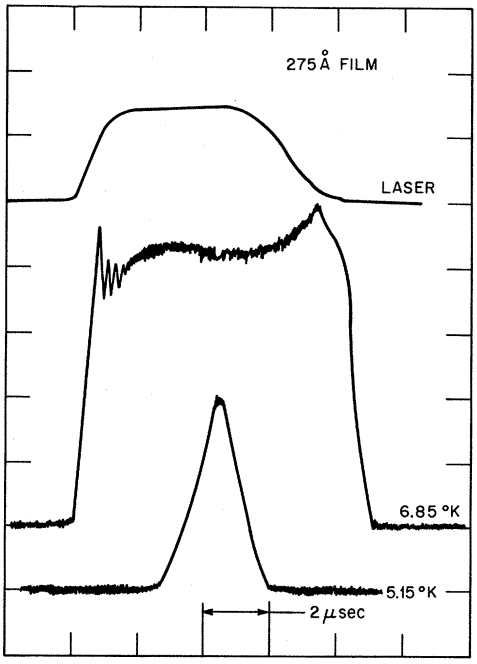

FIG. 8. 275-Å-thick sample resistance and laser output vs time (2 μsec/div). Sample normal-state resistance is 8 divisions for $T = 5.15$ °K and 4 divisions for $T = 6.85$ °K.

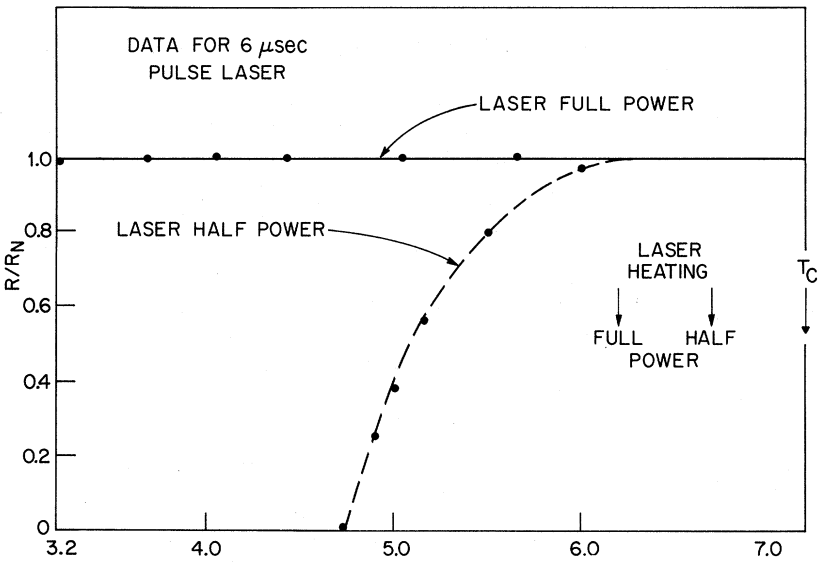

FIG. 9. Sample R/R_N versus temperature during illumination by the 6-μsec-pulse laser beam. Temperatures are those recorded in zero light.

and taking n as the carrier concentration and A as the area of the laser beam, then the *average* increase in energy per carrier after time τ is $\sim P\tau/nAd$. For the experiments described above P/A = 3 to 17 W/cm^2, $\tau \sim 10^{-6}$ sec (the delay time observed with the 6-μsec-pulse laser), $n = 2.54 \times 10^{22}$ cm^{-3}, [14] $d = 275$ Å, and one calculates an increase in energy for the electron gas of ~ 3 to 18 °K due to the absorption of the laser beam. This, presumably, leads to the destruction of the superconducting state.

Physically one might expect the energy of the absorbed 2-eV photon to be shared initially with other electrons very rapidly, say, in a time τ_{ee}, followed by a conversion to phonons over a longer time τ_{eP} and finally transmitted as heat to the surroundings in a thermal response time. (Regarding the assumption $\tau_{eP} > \tau_{ee}$ it is noted that the highest single phonon energies are ~ Debye temperature ~ 0.01 eV for Pb compared to ~ 2 eV for the photons.) Normally one expects τ_{ee} and $\tau_{eP} \ll 10^{-6}$ sec and very little heating of the electron gas above the bath temperature occurs. In the superconducting state longer lifetimes are expected[15] for quasiparticles excited (by ~ millivolts) across the superconducting gap 2Δ. Experiments[16] show that these quasiparticles decay (at least in part) by emission of phonons of energy $\lesssim 2\Delta$ even when the excitation energies are several times 2Δ. Our experimental $\tau \sim 10^{-6}$ sec may be the decay time τ_{eP} in the optical-absorption process which describes the conversion of the excited electron energy (after being shared by many carriers) to phonons, somewhat similar to quasiparticle decay. [17] Shortly after photon absorption, then, the optical energy may be shared by a number of carriers all of which are excited by 2Δ. These "pumped" electrons would be quite numerous, amounting to 10–50% of the total number of free carriers. The destruction of superconductivity would occur when the number of excited electrons exceeds some critical value.

ACKNOWLEDGMENTS

The author is indebted to J. J. Hauser for preparation of the films, A. G. Chynoweth for helpful suggestions related to the proposed explanation, and William Royer for technical assistance.

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[4] The transmittance was measured for white light at room temperature. Some changes may occur at low temperatures (partly from the increase in electrical conductivity) but changes in the optical parameters due to superconductivity should be negligible at these frequencies.

[5] For thinner films the resistance ratio $\rho(300\,°\mathrm{K})/\rho(8\,°\mathrm{K})$ decreases and the magnitude of $d\ln R/dT$ for T just above T_c becomes too small to allow an accurate measurement of the film heating during laser illumination.

[6] This is of the order of magnitude of the thermal response time expected for the copper block (see Fig. 1).

[7] The amplitude of the leading edge peak is obviously

being increased by the heating contribution as T increases.

[8]The shape of the sample signal obtained with the 6-μsec-pulse laser showed some irregularities which could not be accounted for by transient pickup or the electronic circuitry. A complicating feature of these experiments is that the mean free path of thermal phonons in the sapphire substrate was ~1 cm. Ballistic phonon effects (complicated by a possible dimensional resonance in the substrate) may occur. These effects also hinder a calculation of the thermal response time of the system. The thermal diffusion distance for sapphire in 10 μsec is ~ sapphire phonon mean free path and this is comparable to or greater than the dimensions of the substrate. These phonon effects may be important for the superconducting state of the film and the effects discussed in this paper.

[9]A Kapitza thermal boundary resistance which depends on light intensity, of course, is not precluded.

[10]One may also question the assumption, so far implicit, that the observed effect in the normal state is due to ordinary heating.

[11]Within the skin depth the photons are absorbed at a rate $\sim 10^{24}$–$10^{25}/\mathrm{cm}^2$ sec. If each photon were absorbed by an electron whose excited state lifetime was greater than several microseconds the equilibrium carrier concentration would be altered by less than 1% during the 6-μsec laser pulse. A greater change would occur if each photon led directly or indirectly (e.g., by phonon emission) to much more than one excited electron state. (See further discussion in Sec. IV.)

[12]For a free electron in the alternating electric field of the laser the amplitude of the oscillatory velocity would be ~1 cm/sec. The dc critical velocity for the destruction of superconductivity is $\sim 10^5$ cm/sec.

[13]It would also be important to determine whether ballistic phonons in the sapphire substrate (from the heat pulse) are involved in this effect.

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Dislocation Inertial Effects in the Plasticity of Superconductors*

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It is shown that radiation damping is weak enough so that all dislocation segments in superconductors are underdamped at low enough temperatures. Consequently, a dislocation impinging on a barrier in the superconducting state overshoots its static-equilibrium position, exerting an additional force on the obstacle, thereby increasing the plasticity. The inertial model gives a quantitative account of available observations on the size of the effect and its dependence on temperature, magnetic field, deformation, and purity.

I. INTRODUCTION

In the past several years, striking observations have been made of an increased plasticity of materials entering the superconducting state.[1–14] These measurements, beginning with the work of Pustovalov *et al.*[1] and Kojima and Suzuki,[3] have recently been reviewed by Alers, Buck, and Tittman.[15] As yet there appears to be no satisfactory quantitative or qualitative explanation. We give here an inertial model[16] of dislocation motion in superconductors and show that it can give a quantitative account of the so-far-available data.

The following are facts which must be explained by an adequate theory:

a. Direction. When a superconducting material is switched into the superconducting state, the plasticity is increased. For constant strain-rate tests, the stress required drops. For creep measurements at constant stress, the strain rate increases dramatically (Soldatov *et al.*[7]). For stress-relaxation experiments at constant strain, the stress drops suddenly (Suenaga and Galligan[10,12]).

b. Magnitude. The stress-change effects observed are typically of the order of from 0.1 to 10%. However, effects as large as 53% have been reported.[5] The effects are strong for Pb, weak for Sn, with Tl and In in intermediate positions (Startsev *et al.*[14]).

c. Universality. The effect appears to be universal. Its existence is independent of crystal structure, appearing in Pb (fcc), Nb (bcc), In (fct), Sn (bct), and Tl (cph). It is found in pure, impure,