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Measurements of microwave-enhanced superconductivity in aluminum strips

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Experiments investigating the influence of microwave irradiation on the critical current and the critical temperature for superconductivity in aluminum strips are presented. The microwave-induced enhancement of the critical current is shown to exist beyond the microwave-power level at which a discontinuous disappearance of superconductivity was previously reported. Microwave-enhanced critical temperatures are found up to 8% above the equilibrium value. It is essential to discern the role of microwave heating in these experiments. The measurements are extended to a lower temperature (40 mK) and to higher frequencies (36 GHz) than previously reported. It is discussed to what extent the observations fit qualitatively into microscopic models for enhanced superconductivity.

I. INTRODUCTION

In recent years much attention has been paid to nonequilibrium properties of superconductors. One of the phenomena in this connection is the enhancement of superconductivity by microwave irradiation. The effect was first observed as an increase of the critical current when microwave radiation is applied to weak-link structures like microbridges,[1–3] proximity-effect bridges,[4] and point contacts.[5] Later on it was observed that this phenomenon was not restricted to weak-link structures only, as continuous superconducting strips were shown to exhibit this effect as well.[6–10] Most of the reported measurements concern aluminum strips, which show an appreciable increase of the critical current in the microwave-frequency region 1–10 GHz. Critical current measurements on tin structures[11,12] have also been reported; in order to get a comparable enhancement the frequency of the microwave has to be roughly an order of magnitude higher. The enhancement of superconducting properties has mostly been demonstrated by means of the increase of the critical current. There is also a reported measurement of the increase of the superconducting energy gap in aluminum under the influence of microwave irradiation.[13] Recently Dahlberg *et al.*[14] did not observe any gap enhancement in aluminum strips at a microwave irradiation which did cause a critical current enhancement in the same strips.

Eliashberg[15,16] gave the first microscopic explanation of the enhancement effect. The microwave photons excite the quasiparticles on the average to a higher energy away from the band gap. With the help of the BCS gap equation it can be seen that this redistribution of quasiparticles results in an increase of the energy gap and of the critical current. Later calculations by Chang and Scalapino[17] showed that Eliashberg's assumption that the phonon system keeps its equilibrium distribution is not always allowed. An effect also not considered by Eliashberg is that the redistribution of quasiparticles to a higher average energy value causes an increased recombination rate into Cooper pairs, resulting in a net decrease of the total number of quasiparticles and consequently an extra enhancement of the energy gap.

The purpose of this paper is to report on a series of measurements on the influence of microwave irradiation on the superconducting properties of aluminum strips. It is shown that it is very important to discern the heating effects which this microwave irradiation may have, especially when the strip is switched to its normal state. The reported measurements give evidence for the correctness of some simplifying assumptions made in the existing microscopic theories.

The sample preparation and the measurement technique with which heating effects can be avoided to a large extent are described in Sec. II. In Sec. III measurements are reported of critical currents of aluminum strips, for temperatures running from 40 mK to the critical temperature. In Sec. IV the combined influence of radiation and electron injection is described. Measurements of enhanced superconductivity above T_c are described in Sec. V, and Sec. VI deals with the influence of heat resistance from the sample to the heat sink. Hysteresis effects in the transition between the normal state and the state of stimulated superconductivity are investigated in Sec. VII. Section VIII discusses the results of the experiments, examining in particular how they fit qualitatively the theoretical predictions.

II. SAMPLE PREPARATION AND MEASUREMENT METHOD

The measurements reported in this paper were made on aluminum strips. The aluminum layers were evaporated in a 10^{-6} Torr vacuum at a rate of 50 Å/sec on a silicon oxide layer of about 1000 Å thickness, covering a 200-μm-thick silicon substrate held at a temperature of 250 °C during the evaporation. The geometry of the aluminum strip was determined by standard photolithographic methods; the strip was 2 μm wide and 40 μm long and had large bonding pads at the ends to which separate voltage and current leads were attached.

Two different kinds of samples were used. Sample *A*, as already described in Ref. 9, consisted of a 750-Å-thick aluminum layer with a critical temperature of 1.29 K. The silicon substrate was a heavily doped n^{++} substrate with a 1.7-μm *n*-type epitaxial layer on top of it. The oxide between the silicon and the aluminum strip had a window in the center of the strip so that 2.5 μm of the strip was in direct contact with the silicon and formed a Schottky barrier diode with the underlying silicon substrate. In this way electrons could be injected locally into the aluminum strip.

Sample *B* had no Schottky diode. The critical temperature of the 1000-Å-thick aluminum layer was 1.25 K. The layer was separated from the silicon by a 1000-Å-thick thermal oxide. The substrate of this sample was low-doped *n*-type silicon and therefore insulating at low temperatures. By phosphorus diffusion a 0.5-μm-thick conducting n^{++} layer was formed at the surface below the oxide layer. This layer was provided with electrical contacts. A more detailed description is given in Ref. 18. This layer allowed us to obtain very rapid temperature variations of the aluminum strip without changing the helium bath temperature by passing a current through it. The dissipation in the resistive layer heats the aluminum strip above the helium bath temperature. Usually the samples, mounted in an open nonmagnetic transistor header, were immersed in a temperature-regulated helium bath with the strip in direct contact with the liquid helium. In order to investigate the influence of heat resistance from the strip to the helium bath on the enhancement effects, we also had the possibility to mount the silicon chip on a copper heat sink in a vacuum chamber.

The influence of microwave irradiation on the superconducting properties of the aluminum strips was investigated by measuring the *I*-*V* characteristics of the strips. The *I*-*V* characteristic of a strip was determined by passing through the sample a current of triangular wave form as a function of time with a repetition rate of 200 Hz. The resulting voltage along the sample was measured with the help of separate voltage leads. Current and voltage signals were applied to the *X* and *Y* deflection plates of an oscilloscope; a typical resulting characteristic is sketched in Fig. 1. For increasing current the strip switches at the critical current I_c from the superconducting to the normal state. For decreasing current the strip

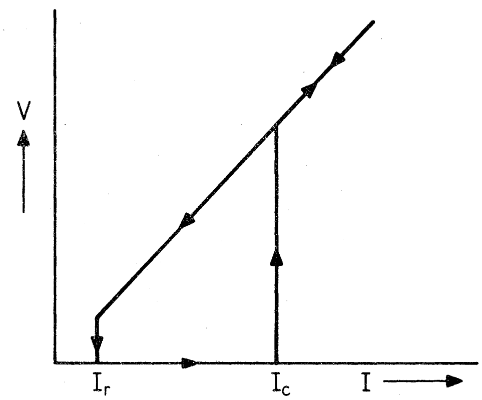

FIG. 1. Measured *I*-*V* characteristic of an aluminum strip below T_c. I_c is the critical current, I_r is the current at which the strip returns to its superconducting state when the current through the strip is decreasing.

switches back to the superconducting state at a much lower current value I_r. This hysteresis is caused by heat dissipation in the normal state, which keeps the temperature of the strip above the critical temperature as long as the dissipation exceeds a critical value. At I_r this value is reached and the superconducting state is restored. In the current region between I_r and I_c the strip can therefore be either in the normal or in the superconducting state. The measurement of the *I*-*V* characteristic is therefore very sensitive to external disturbances in this region. Any cause of switching to the normal state results in the strip staying in the normal state as long as *I* is greater than I_r, due to the immediately occurring dissipation. Therefore precautions have to be taken to keep the disturbance level sufficiently low in order to be able to reach I_c during the increasing part of the current cycle without premature switching to the normal state. For a repetition rate of 200 Hz a reliable determination of I_c turns out to be a realizable in practice without too much effort, whereas determination of the *I*-*V* curve with a recorder at a much lower speed is evidently more difficult. The value of the critical current I_c was determined either by directly reading its magnitude on the oscilloscope or more accurately by electronically measuring its value with a sample and hold circuit, triggered by the voltage step occurring at I_c.

Microwave energy could be coupled into the aluminum strip for frequencies up to 18 GHz by mounting the strip as a short circuit at the end of a coaxial cable from the generator into the helium Dewar. For the measurement at 36 GHz we used a different experimental set up. In this case the sample was placed in an 8 mm waveguide with a standing wave in it. The strip was mounted parallel to the electric field at a maximum of this field.

When microwave energy is coupled into the Al strip the I-V characteristic changes. At small microwave-power level the critical current I_c is found to increase. This is the enhancement effect we are interested in. The return current I_r, however, decreases due to the extra amount of heating in the strip caused by microwave absorption. At a certain microwave-power level this microwave heating in the normal state becomes so large, that once the strip is normal it remains normal due to the microwave heating alone. The return current I_r no longer exists in this circumstance. In order to be able to measure I_c at still higher microwave powers, it is then necessary to switch off the microwave energy during the time that the current through the strip is decreasing in order to allow the strip to switch back to its superconducting state. As soon as the strip has become superconducting the microwave power can be switched on again in order to re-establish the state of nonequilibrium superconductivity caused by microwave irradiation. The critical current of this state can then be determined during the period of time that the current through the strip is increasing. There are, however, circumstances where there exists a microwave-stimulated state of superconductivity but where the state without microwaves is normal. This is for instance the case at temperatures above the equilibrium critical temperature T_c or for high levels of injected electron current through the Schottky diode. In these cases it is not sufficient to switch off the microwaves during the time of the I-V characteristic determination with decreasing current in order to restore the superconducting state. It is then, obviously, also necessary, respectively,to lower the temperature below T_c or to switch off the injection current in order to allow the strip to become superconducting again. Once the strip has become superconducting the microwave power can be switched on again and the state of microwave-stimulated superconductivity will be restored. It is then possible, respectively, to bring the temperature of the strip above the equilibrium value of T_c or to switch on again the injection current. The critical current of the resulting state of the strip can then be determined during the time of increasing current through the strip. For measurements of stimulated superconductivity above T_c it is therefore necessary to be able to change the temperature of the strip with a repetition rate given by the recording rate of the I-V characteristic. It is not practical to change the helium bath temperature and this is the reason why sample structure B is made in which the temperature of the aluminum strip can be changed with a time constant lower than 10^{-4} sec.

III. MEASUREMENTS OF MICROWAVE-ENHANCED CRITICAL CURRENTS

We first report in Fig. 2 a measurement of the critical current I_c as a function of the power of 7 GHz irradiation on sample A, at various temperatures of the helium bath in which it is immersed.

For relatively low microwave power P the critical current is an increasing function of P and after having reached a maximum it decreases continuously to zero. The dashed line in Fig. 2 indicates the values of P where I_r becomes zero. At the right-hand side of this line it is therefore necessary to switch off the microwaves during the time that the current through the strip is decreasing in order to be able to measure I_c. The microwave energy is given in arbitrary units. An indication of the absolute power level can be obtained by equating the critical power level where I_r becomes zero to the dc power dissipation at the return current value I_r when no microwaves are present. On the assumption that the only effect of the microwaves on the sample in the normal state is heat dissipation, the absorbed microwave power in the normal strip is then obtained. It is indicated in Fig. 2 by a single absolute power level. The absorbed power in the superconducting state, however, will be

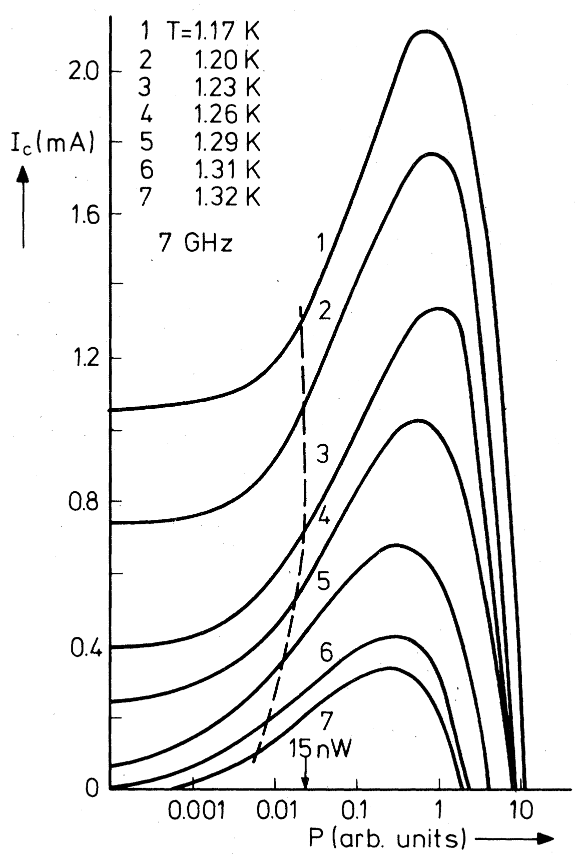

FIG. 2. Critical current I_c as a function of 7 GHz microwave power P with the temperature T of the helium bath as a parameter. The dashed line is the boundary where $I_r = 0$. The indicated absolute power level is the dissipated power in the strip in its normal state.

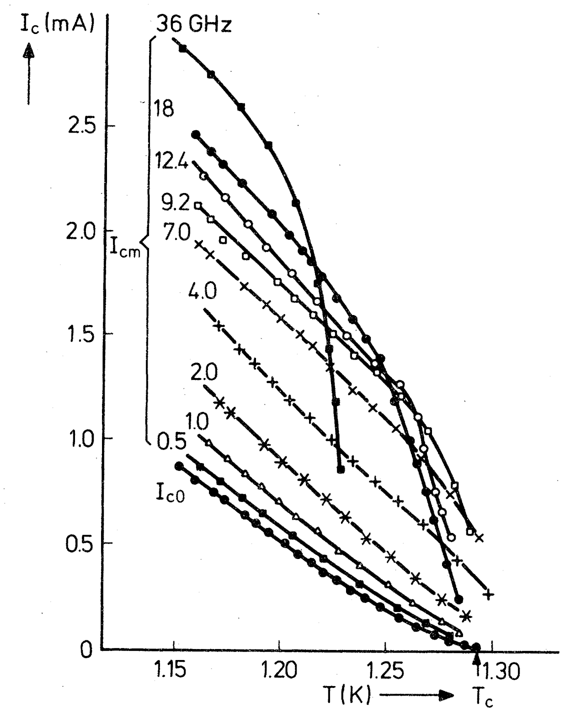

FIG. 3. Maximum stimulated critical current I_{cm} as a function of T for different microwave frequencies. The critical current I_{c0} without microwaves is also given.

smaller due to the difference in impedance between the two states. Such measurements were made for a number of different microwave frequencies ranging from 0.5–36 GHz. The maximum values I_{cm} of the

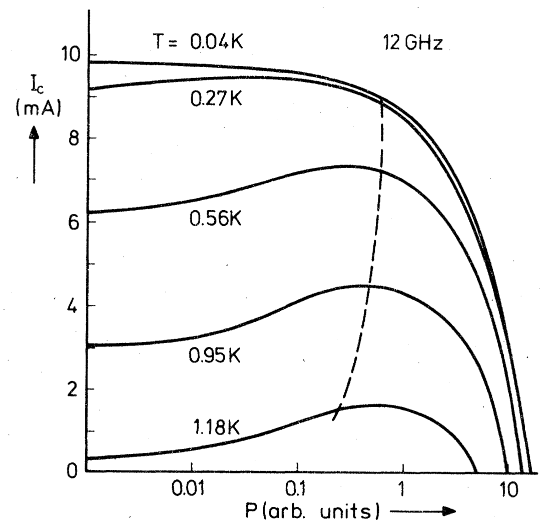

FIG. 4. Critical current I_c as a function of 12 GHz microwave power P for a sample in the mixing chamber of a dilution refrigerator. The dashed line is the boundary where $I_r = 0$.

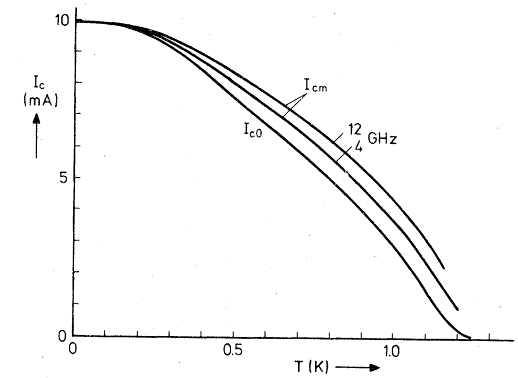

FIG. 5. Maximum stimulated critical current I_{cm} at 4 and 12 GHz irradiation and I_{c0} as a function of T for the sample in the mixing chamber.

critical current obtained as a function of temperature are given in Fig. 3. The critical current I_{c0} without microwaves is also displayed.

It is observed in Fig. 3 that at temperatures well below the equilibrium critical temperature T_c the enhancement effect increases with increasing frequency. At temperatures near T_c, however, the curves of I_{cm} for various frequencies cross each other. At or slightly above T_c the enhancement effect can no longer be observed without lowering the temperature of the strip below T_c during the time of decreasing current through the strip.

At the lowest temperatures reached in the measurements given in Fig. 3 there is still a large enhancement effect and it is interesting to know what happens at even lower temperatures. We therefore mounted the sample in the mixing chamber of a small dilution refrigerator and performed the same kind of measurements at lower temperatures. The resulting I_c as a function of microwave power at 12 GHz is given in Fig. 4 for various temperatures, and in Fig. 5 I_{c0} and I_{cm} are plotted as a function of temperature for 4 and 12 GHz radiation.

At temperatures, where $T/T_c \lesssim 0.1$, the values of I_{cm} are seen to saturate and they become equal to the critical current I_{c0} at $T \to 0$. Thus at very low temperatures any enhancement of the critical current is no longer observed; I_c only decreases with increasing microwave power. As soon as the temperature became so high that we were able to measure a value of I_{c0} smaller than the value at $T \to 0$ the enhancement effect was also observed. The enhanced critical current never exceeded the value of I_{c0} at $T \to 0$.

IV. ENHANCEMENT OF SUPERCONDUCTIVITY IN STRIPS WITH ELECTRON INJECTION

We have also investigated the combined influence of microwave radiation and local injection of electrons into the strip of sample A. By means of the Schottky barrier in the middle of the strip electrons can be injected into the strip with an energy of 0.6 eV, which turned out to be the barrier height at ~ 1 K. This current injection causes a weakening of superconductivity and the critical current of the strip decreases. Microwave enhancement of the critical current also occurs, as illustrated in Fig. 6, which gives I_c as a function of microwave power for various values of the injection current I_i. The ratio of maximum enhanced current I_{cm} and the critical current I_{c0} at $P=0$ is higher for a strip with injection of electrons than for a strip without injection, but at such a higher temperature that the I_{c0} values are the same in both cases. This can be seen by comparing Fig. 2 and Fig. 6. At the injection current $I_i = 125$ nA the critical current I_{c0} is found to become zero for the temperature at which the results of Fig. 6 are obtained.

At a somewhat higher value, $I_i = 145$ nA, superconductivity could be induced by the microwaves, but above 145 nA it turned out to be necessary to make

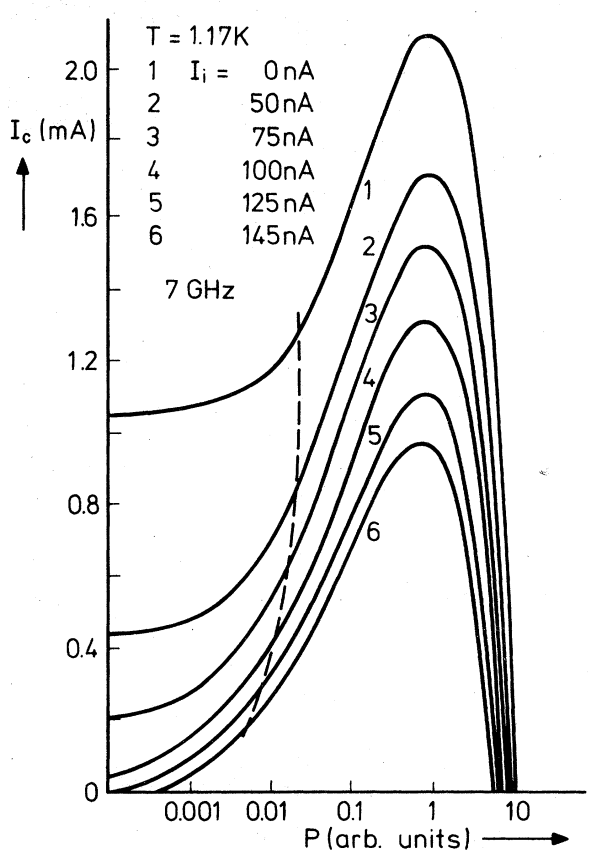

FIG. 6. Critical current I_c as a function of 7 GHz microwave power P at $T=1.166$ K with the injection current through the Schottky diode I_i as a parameter. The dashed line is the boundary where $I_r=0$.

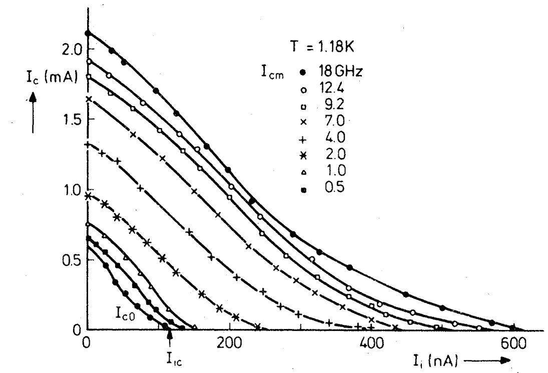

FIG. 7. Maximum stimulated critical current I_{cm} as a function of the injection current I_i at $T=1.18$ K for various microwave frequencies. The critical current without microwaves I_{c0} is also given.

$I_i = 0$ during the time of decreasing current through the strip, otherwise the strip did not return to its superconducting state. In this way we measured the results given in Fig. 7, in which I_{cm} for frequencies ranging from 0.5 to 18 GHz is plotted versus the injection current at a fixed helium bath temperature. The critical current I_{c0} without microwaves is also given. We observed that with 18 GHz irradiation superconductivity can be induced by the microwaves up to an injection current five times higher than the critical injection current I_{ic}, which makes I_{c0} equal to zero.

V. MICROWAVE-INDUCED SUPERCONDUCTIVITY ABOVE T_c

In the measurements reported in Sec. III a microwave-enhanced state of superconductivity was observed up to the equilibrium critical temperature T_c or even slightly above it. To observe microwave-induced superconductivity above T_c it is necessary to lower the temperature of the strip below T_c during the time of decreasing current through the strip in order to restore superconductivity as described in Sec. II. For measurements above T_c we used a heat pulse method with the help of the diffused resistance in the substrate of sample B. The resulting temperature of the aluminum strip as a function of the dissipated power in the heater was experimentaly determined.

For this purpose we first measured the critical current of the strip without microwaves I_{c0} and also the maximum stimulated critical current I_{cm} both as a function of the helium bath temperature with no dissipation in the heater. I_{c0} and I_{cm} were then measured at a fixed bath temperature below T_c as a function of the dissipated power in the heater. The temperature of the aluminum strip as a function of the heater power was found by equalizing it with the helium bath temperature, which resulted in the same value of I_{c0} and I_{cm} without dissipating in the heater. The resulting temperature T can very well be described by

$$T^4 - T_{\text{bath}}^4 = \alpha W \ , \qquad (1)$$

where T is the resulting temperature, when a heater power W is dissipated and the helium bath temperature is at T_{bath}. The value of the constant α depends on the heat resistance from the heater to the helium bath. This is illustrated in Fig. 8, where the resulting measured points are given for two cases. The silicon substrate is mounted on a copper heat sink which is at T_{bath} and the sample is either immersed in liquid helium or it is in vacuum. For the latter case, Eq. (1) is exactly followed within measuring accuracies; for the immersion in liquid helium a relatively small second-order correction term βW^2 has to be subtracted from the right-hand side of Eq. (1). This will be due to the effect that the transmission coefficient of phonons from the solid into the liquid helium is increasing with increasing temperature in the relevant temperature range.[19] The resulting temperature T will therefore be somewhat lower than given by Eq. (1). The relation (1) is found to be independent, whether it is determined with the help of I_{c0} or with I_{cm}. This gives confidence that the state of the aluminum strip can properly be described with a temperature T above T_{bath} when the heater power is on and that the heater power introduces no extra nonequilibrium effects in the strip. The described calibration of T as a function of W is only possible for $T < T_c$, otherwise I_{c0} does not exist. We, however, use Eq. (1) for $T > T_c$ by extrapolation. The fact that the constant α is found to be independent of T_{bath} for 0.8 $T_c < T_{\text{bath}} < T_c$ gives confidence that extrapolation of Eq. (1) to temperatures of about $1.1T_c$ is allowed. The time constant of the heating of the strip is of course dependent on the heat resistance.

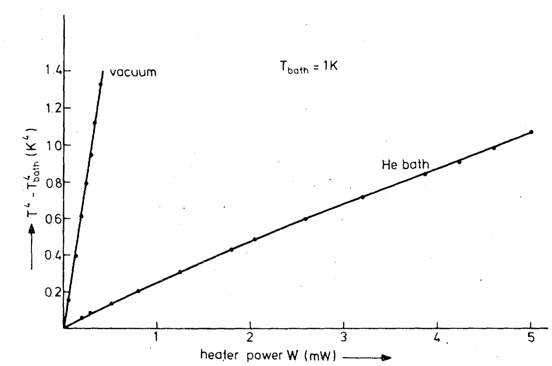

FIG. 8. $T^4 - T_{\text{bath}}^4$ as a function of the dissipated power in the heater for the sample surface exposed to vacuum or to liquid helium.

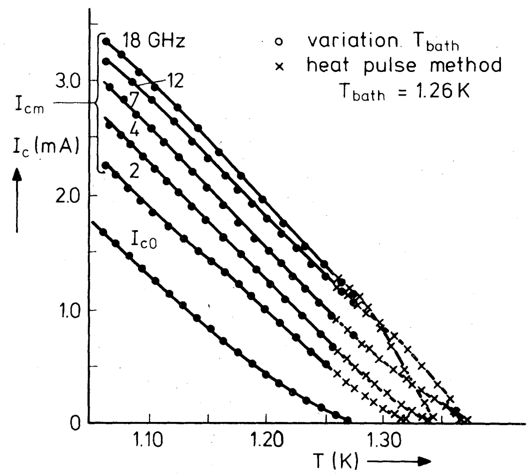

FIG. 9. Maximum stimulated critical current I_{cm} for various frequencies and I_{c0} as a function of T. Above T_c the heat pulse method has to be used.

In all our experiments it turned out to be smaller than 10^{-4} sec which is sufficiently low for our experiments where the I-V characteristics are measured with a repetition rate of 200 Hz.

The critical currents are measured with T_{bath} below T_c. Before the part of the I-V curve with increasing current is determined the microwave power and the heater power are subsequently switched on, so that the state of stimulated superconductivity is established at a temperature given by Eq. (1). During the determination of the part of the I-V curve with decreasing current the microwave power and heater power are switched off.

The results of the measured critical current values are given in Fig. 9, where I_{c0} and I_{cm} are plotted as a function of T. For $T > 1.26$ K we used the heat pulse method, with T_{bath} at 1.26 K. We also made the measurements with $T_{\text{bath}} = 1.05$ K and found points exactly on the same curves; for clarity, however, these points are not indicated in the figure. This again confirms that the heat pulse only increases the temperature of the strip and causes no measurable nonequilibrium effects. For a frequency of 7 GHz we found the state of stimulated superconductivity to extend to a temperature as high as 8% above the equilibrium critical temperature T_c.

VI. INFLUENCE OF HEAT RESISTANCE FROM SAMPLE TO HEAT SINK

In order to investigate the reason for the phenomenon that the critical current I_c decreases with increasing microwave-power level in the high-power region we varied the heat resistance from the sample to the helium bath. We again used sample B

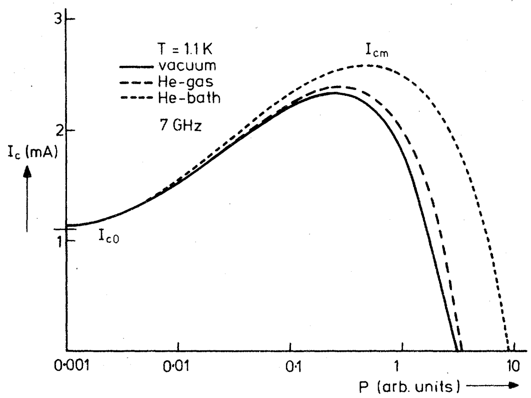

FIG. 10. Critical current I_c as a function of 7 GHz microwave power P for the sample surface exposed to vacuum, to helium gas or to liquid helium.

mounted on the copper heat sink. The resulting critical currents as a function of microwave power are given in Fig. 10 with the helium bath temperature at 1.10 K. The surface of the aluminum strip is either exposed to vacuum, to 0.1 Torr helium gas or to liquid helium. For low microwave powers the I_c values are found to be the same. For higher microwave powers the critical current is higher the better the contact of the sample with the heat sink. The maximum value of the critical current is reached at lower power levels for a larger heat resistance from the sample to the helium bath. The values of I_{cm} for the sample surface exposed to vacuum or to liquid helium are given in Fig. 11 as a function of temperature. The heat pulse method is used for two different values of T_{bath} and both are seen to give the

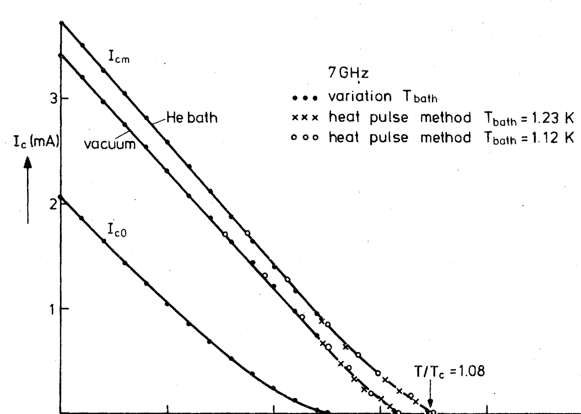

FIG. 11. Maximum enhanced critical current I_{cm} for the sample surface exposed to vacuum or to liquid helium and I_{c0} as a function of T. The heat pulse method is applied for two different temperatures of the helium bath.

same results. These measurements give a strong indication that the phenomenon of the maximum in I_c and the subsequent decrease is due to heating caused by microwave absorption in the sample. Similar measurements have been reported previously by Klapwijk *et al.*,[20] but they reported I_c curves as a function of microwave power which coincide in the high-power-level region and are different in the low-power-level regime, in contrast to our results as given in Fig. 10. As they also ascribe the difference in I_c for various heat resistances to heating in the sample, it is difficult to see why the I_c values should coincide in the high-power regime. The behavior as given in Fig. 10 is very reproducible with different samples too.

VII. HYSTERESIS IN THE CRITICAL TEMPERATURE OF THE STATE OF STIMULATED SUPERCONDUCTIVITY

Hysteresis has been reported in the transition temperature from the state of stimulated superconductivity to the normal state and vice versa.[7,8,13] In order to investigate whether this hysteresis is caused by an intrinsic first-order transition or by the difference in microwave heating in both states, we measured the transition temperatures as a function of microwave power. We made these experiments on sample B immersed in liquid helium. The temperature of the sample was varied by changing the dissipated power in the heater; the resulting temperature is given by Eq. (1). The transition between superconducting and normal states was determined by feeding a small dc current of 2 μA through the strip and measuring the resulting voltage along the strip as a function of the voltage across the heater. For this particular measurement we used a voltage across the heater with triangular wave form and a repetition rate of 4 Hz. The heater voltages at which the strip changes from the one state to the other can immediately be converted into transition temperatures.

In the inset of Fig. 12 we give a result of the voltage across the strip as a function of the temperature of the strip for two different values of the microwave power. For zero microwave power there is a finite but small transition region; for higher microwave power, where the hysteresis occurs, the transitions are sharp. By measuring these curves as a function of the microwave power we were able to determine the power dependence of the transition temperatures for increasing temperature T_{ci} and for decreasing temperature T_{cd}. A result is given in Fig. 12. As soon as T_{cd} has become equal to the helium bath temperature it can no longer be determined at higher microwave powers. It is then necessary to switch off the microwaves temporarily before the increasing voltage across the heater starts, otherwise the microwaves would keep the strip in its normal state.

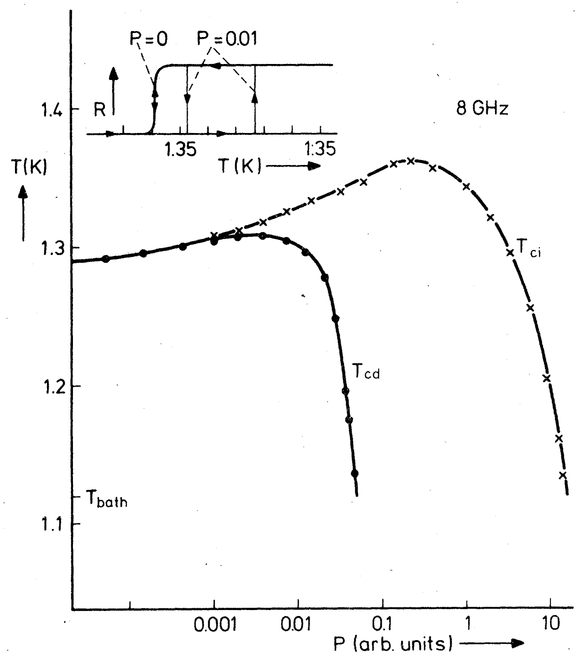

FIG. 12. Measured critical temperatures T_{ci} for increasing temperature and T_{cd} for decreasing temperature as a function of microwave power P. In the inset we have plotted the measured resistance of the strip as a function of T for microwave $P=0$ and $P=0.01$.

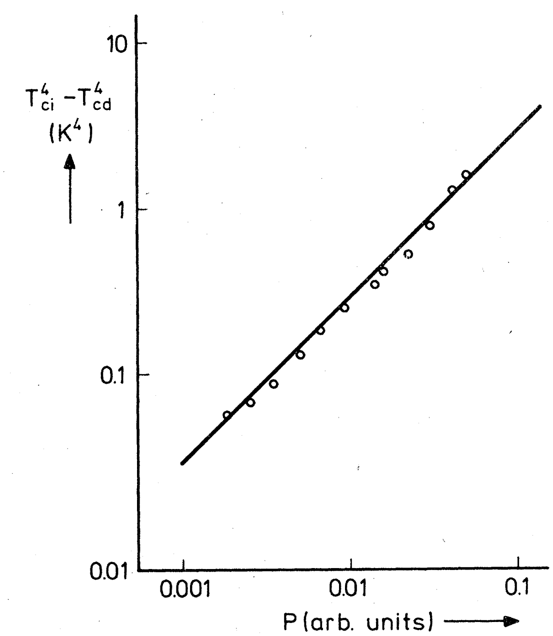

FIG. 13. $T_{ci}^4 - T_{cd}^4$ vs microwave power P.

At small microwave powers, when the critical temperature is already somewhat enhanced, we observe no measurable hysteresis. At higher microwave powers a hysteresis occurs which rapidly increases, and when T_{cd} has become equal to T_{bath} only the value of T_{ci} can be determined. In Fig. 13 we have plotted the value of $T_{ci}^4 - T_{cd}^4$ versus the microwave power P and we observe that both quantities are reasonably proportional to each other over more than an order of magnitude. If we suppose that the difference in microwave-power dissipation between normal and superconducting state in this temperature range is proportional to the microwave power, this dependence is what we would expect if the microwave heating is the cause of the hysteresis. This, together with the fact that no hysteresis is observed in the low-power region, gives reason to believe that the hysteresis is caused by heating effects.

VIII. DISCUSSION

The first microscopic explanation of microwave-enhanced superconductivity was given by Eliashberg.[15,16] In his model the microwave photons excite quasiparticles from the band gap to higher energies. These excited quasiparticles relax back to lower energies by electron-phonon interaction. In a stationary state the ensemble of quasiparticles is shifted on the average to higher energies. This causes an increase of the energy gap and correspondingly also of the critical current. In Eliashberg's model the phonons are assumed to keep their equilibrium distribution. In more recent numerical calculations reported by Chang and Scalapino[17] this assumption is no longer maintained. They solved a set of coupled kinetic equations for the quasiparticle and phonon distributions with a driving term given by the interaction of the microwave field with the quasiparticles. The mechanism which drives the distributions back to equilibrium is again the electron-phonon interaction for the quasiparticles and an interaction of the phonons with the heat sink described by a phonon escape time from the superconductor to the heat sink. They found not only that the redistribution of quasiparticles causes the gap enhancement, but also that a net decrease in the total number of quasiparticles plays an important role. The net decrease is caused by the increase of the recombination rate of quasiparticles into Cooper pairs when they are excited to higher energies.

Comparing the experimental results described in the previous sections with the microscopic models for the enhancement of superconductivity, we would like to make the following observations.

(a) At temperatures more than 0.2 K below T_c the enhancement effect is found to increase with increasing frequency up to the highest measured frequency of 36 GHz. The photon energy corresponding to this frequency is still below the energy gap at these temperatures and therefore the microwave photons cannot break up Cooper pairs. The increase of the enhancement with increasing frequency fits both microscopic models described above, for the quasiparticles will be excited to increasingly high energies where their depressing of the order parameter decreases and their recombination rate increases.

(b) Near T_c the curves of I_{cm} as a function of temperature for various frequencies cross each other, as can be seen in Figs. 3 and 9. In this temperature range the enhancement effect is therefore no longer a steadily increasing function of frequency. This cannot be ascribed to the breaking up of Cooper pairs, for the energy gap corresponding to the measured critical currents is still larger than the microwave photon energy. It is most probably due to a heating effect of the microwaves in the silicon substrate of the sample. An indication in support of this is the dependence of the crossing on the substrate material. For the measurements in Fig. 3 where sample A was used with a heavily doped n^{++} substrate, the crossings occur at lower temperatures compared to the measurements in Fig. 9 where sample B was used with a low doped substrate and a thin diffused n^{++} layer. The measured difference is to be expected if heating in the substrate is the reason for the crossing, because of the larger volume where dissipative currents are induced for sample A compared with sample B. It is also to be expected that with increasing frequency the heating will increase and therefore the I_{cm} curves at higher frequencies will tend to turn downwards more steeply, as can be seen to be the case in Figs. 3 and 9.

(c) The assumption used in Eliashberg's model that the phonon distribution remains in thermal equilibrium can only be correct at very low microwave-power levels. This is illustrated in Fig. 10. A change in the phonon coupling to the heat sink already causes a change in the enhancement effect at a relatively low power level. From this power level onwards Eliashberg's model therefore, cannot be used. In Eliashberg's model the occurrence of a maximum in the critical current as a function of the microwave power is also not expected. Chang and Scalapino's calculations, however, show the existence of a maximum in the enhancement effect followed by a subsequent decrease at still higher microwave powers. The position of the maximum with varying heat resistances in Fig. 10 is also in qualitative agreement with their calculations. They find a higher maximum positioned at a higher microwave-power level for a better coupling of the phonons to the heat sink, characterized by a shorter escape time for the phonons.

(d) In both microscopic models the enhancement effect is due to a change in the quasiparticle distribution, whether or not coupled with a decrease in the number of quasiparticles. The enhancement effect is therefore expected to disappear in the very low-temperature limit where the quasiparticle concentration tends to zero. This is in agreement with the low-temperature measurements reported in Sec. III.

(e) Whether the redistribution of quasiparticles is the cause of the enhancement effect, as in Eliashberg's model, or whether the increased recombination rate due to the redistribution plays the dominant role, as in Chang and Scalapino's calculation, cannot be concluded from the reported measurements. The physical parameters, for instance the microwave field strength in the superconductor, are not known accurately enough to allow a detailed comparison between experiment and theory. More numerical calculations would be necessary and also the relation between the enhanced energy gap and the enhanced critical current should be known. Recent measurements of characteristic times,[21] however, provide evidence showing the importance of the recombination and confirm Chang and Scalapino's numerical calculations.

(f) Schmid[22] has shown on the basis of Eliashberg's model that theoretically a first-order transition is expected to exist between the normal state and the state of stimulated superconductivity. The transition is expected to have a hysteretic behavior due to the existence of metastable states. In our measurements we found no experimental evidence of such a first-order transition. Within measuring accuracy we found the stimulated critical currents to decrease continuously to zero as a function of increasing temperature (Fig. 9) and no discontinuous drop to zero was observed. The hysteresis effect in the transition temperature as reported in Sec. VII can very well be explained by heating effects caused by the microwave radiation. The difference in microwave absorption between the two states is fundamentally unavoidable, and it is our opinion that the heating effect dominates the theoretically expected intrinsic hysteresis, which may also be present.

(g) Concerning the experiments with electron injection described in Sec. IV, we make the following remarks: The effect of electron injection through the Schottky diode cannot be described in terms of the model of Owen and Scalapino.[23] In this model the concentration of quasiparticles is above equilibrium with the energy distribution of the quasiparticles still described by the equilibrium temperature. With increasing injection this model predicts a discontinuous transition to the normal state, which we evidently do not observe. Neither is it possible to describe the effect of electron injection by an effective temperature increase of the film, as can be seen by comparing the effect of temperature increase and electron injection on the microwave-enhancement effect. It is remarkable that the microwave enhancement of the critical injection current, which makes the critical current through the strip zero, is very high, a factor of 5 for 18 GHz radiation.

Most likely the spatial dependence of the quasiparticle distribution from the injected region to the surrounding regions of the strip is important to understand the observed phenomena.

Another observation was that we never found any Josephson effect under the combined influence of electron injection and microwave irradiation. This is different from reported experiments[24] on 10-μm-wide tin strips where the superconductivity was locally weakened by quasiparticle injection through a tunnel junction from a 5-μm-wide lead overlay. The difference may be due to the much longer quasiparticle diffusion length in aluminum compared with tin. This causes the nonequilibrium region in aluminum to be larger resulting in a possible loss of phase coherence between the regions of the strip on both sides of the injection region.

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