Title
DIRECT MEASUREMENT OF MICROWAVE ENHANCED ENERGY GAP IN SUPERCONDUCTING ALUMINUM

Permalink
https://escholarship.org/uc/item/5c068246

Author
Kommers, Tom

Publication Date
1977-02-01
DIRECT MEASUREMENT OF MICROWAVE ENHANCED ENERGY GAP IN SUPERCONDUCTING ALUMINUM

Tom Kommers and John Clarke

February 1977

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
DIRECT MEASUREMENT OF MICROWAVE ENHANCED
ENERGY GAP IN SUPERCONDUCTING ALUMINUM*

Tom Kromers and John Clarke

Department of Physics
University of California

and

Materials and Molecular Research Division
Lawrence Berkeley Laboratory
Berkeley, California 94720

ABSTRACT

Al-Al₂O₃-Al quasiparticle tunnel junctions were used to measure
directly large increases in the energy gap of superconducting aluminium
films in the presence of 10 GHz microwave radiation. When the microwave
power was increased at constant temperature, enhancement occurred only
for temperatures at which twice the equilibrium energy gap exceeded the
photon energy. When the temperature was increased at constant microwave
power, enhancement was observed at higher temperatures.
Eliashberg and coworkers\textsuperscript{1} have predicted that the energy gap, $\Delta$, of a superconducting thin film may be enhanced by microwave irradiation. In their model, photons of frequency $\nu < 2\Delta/h$ excite quasiparticles from states near the bottom of the excitation spectrum to states of higher energy. Thus, additional pair states near the Fermi wavevector, $k_F$, become available for occupancy. Since the pair states near $k_F$ contribute most strongly to the pairing interaction, this redistribution of pair state occupancy increases the condensation energy, and leads to an increase in $\Delta$. Eliashberg et al.\textsuperscript{1} have suggested that this increase would account for the microwave enhancement of the critical current of superconducting microbridges\textsuperscript{2}. Subsequently, several experiments have supported the concept of gap enhancement: Phonon induced enhancement of the critical current of superconducting microbridges and point contacts\textsuperscript{3}, microwave induced enhancement of the critical currents and transition temperatures of aluminum strips\textsuperscript{4}, and microwave induced enhancement of the voltage at which gap structure occurs in superconducting point contacts\textsuperscript{5}. Recently, Chang and Scalapino\textsuperscript{6} have performed detailed computer calculations of gap enhancement in which the energy dependence of the quasiparticle recombination time, and the effects of the non-equilibrium phonon distribution are included.

We have used Al-Al$_2$O$_3$-Al quasiparticle tunnel junctions to measure directly large increases in the energy gap of superconducting aluminum films in the presence of X-band radiation. We define $\langle \Delta \rangle_e$ as the average equilibrium gap for the two films of a given junction, and $T_\nu$ as the temperature at which $h\nu = 2\langle \Delta \rangle_e$. When the microwave power was increased from zero with the junction at fixed temperature, $T$, $\langle \Delta \rangle$ increased for
T < T_v, and decreased for T ≥ T_v. Alternatively, when we maintained constant microwave power and increased the temperature from below T_v, gap enhancement was observed to a temperature T↑, where T↑ > T_v. T↑ increased with microwave power. When the temperature was subsequently lowered at constant microwave power, the gap abruptly reappeared at a temperature significantly lower than T↓.

The Al-Al_{2}O_{3}-Al junctions were fabricated in a cross-film geometry with a film width of about 300 μm, and film thicknesses in the range 80 to 300 nm. Normal state resistances ranged from 1 to 10 Ω. The transition temperatures of the films were from 1.20 to 1.26 K. The substrate was usually BaF_{2}, which has good acoustical matching to aluminum, and a low absorption at microwave frequencies. Each substrate was mounted in an X-band waveguide near an adjustable short circuit plunger, with the plane of the films parallel to the axis of the waveguide. The junction and waveguide were immersed in a temperature-regulated helium bath. The temperature of the helium was measured to a relative accuracy of 0.3 mK with an Allen-Bradley carbon resistor that was carefully shielded to eliminate any discernible interaction with the microwaves. Two concentric mu-metal cans around the cryostat reduced the ambient field to below 10^{-6} T.

The differential resistance, dV/dI, of the junctions was measured using a standard technique. The upper curve in Fig. 1 shows dV/dI vs. voltage, V, for a representative junction on a BaF_{2} substrate in the absence of microwave power. The thickness of each Al film was about 300 nm. There are two sharp minima in dV/dI, a and b, that we assume occur at voltages (Δ_> + Δ_<)/e and (Δ_> - Δ_<)/e, where Δ_> and Δ_< are the larger and smaller energy gaps.
of the two films. Each gap was in good agreement with the BCS prediction over the temperature range studied. $T_{C>}$ and $T_{C<}$ were the temperatures at which $\Delta_>$ and $\Delta_<$ extrapolated to zero. We use the higher transition temperature, $T_{C>}$, in the definition of the reduced temperature, $t$. The remaining curves in Fig. 1 show the additional structure that was induced as the 10 GHz (41.4 $\mu$V) microwave power was increased. The power levels shown in the figure refer to the power delivered to the waveguide. At a reduced temperature of 0.99, $h\nu/2\Delta_<$ was equal to 0.83 for this junction. Part of the structure arose from photon assisted tunneling. The minima $c$, $d$, $e$, and $f$ occurred at voltages $(\Delta_> + \Delta_< + h\nu)/e$, $(\Delta_> + \Delta_< - h\nu)/e$, $(\Delta_> - \Delta_< + h\nu)/e$, and $(-[\Delta_> - \Delta_<] + h\nu)/e$ respectively. As the microwave power was increased from zero, the minimum at $a$ $(\Delta_> + \Delta_<)$ moved to higher voltages. At each power level, the photon assisted tunneling minima $c$ and $d$ $(\Delta_> + \Delta_< \pm h\nu)$ moved by the same voltage as the minimum at $a$, so that $c$ and $d$ were separated from $a$ by a constant voltage $\pm h\nu/e$. Thus, the average gap, $<\Delta> = (\Delta_> + \Delta_<)/2$, was enhanced by the microwaves. The voltage at which $b$ $(\Delta_> - \Delta_<)$ occurred was relatively independent of microwave power, as were the photon assisted tunneling minima $e$ and $f$ $(\pm[\Delta_> - \Delta_<] + h\nu)$. Additional structure indicated by arrows at the bottom of the figure was due to Josephson microwave-induced current steps at voltages $n(h\nu/2e = n(20.7 \mu V) (n = 0, \pm 1, \pm 2, ...)$. The voltages at which these steps occurred were independent of power. To within the experimental accuracy ($\pm 1 \mu V$), each type of structure occurred at the same voltage for positive and negative polarities. The amplitude of both the photon assisted tunneling minima and the Josephson minima oscillated as the power was increased to 20 mW.

In Fig. 2 we plot values of $2\Delta_>$, $2\Delta_<$, and $2<\Delta>$ vs. microwave power at $t \approx 0.99$ for the junction referred to in Fig. 1. As the power was in-
creased from 0 to 20 mW, $\Delta_\gamma$, $\Delta_c$, and $2\langle \Delta \rangle$ increased by about 80%, while
$(\Delta_\gamma - \Delta_c)/e$ varied by no more than about 3 $\mu$V. The variation of $\langle \Delta \rangle$
with microwave power qualitatively resembled the behavior predicted by
Chang and Scalapino\textsuperscript{6}. At the higher power levels, the enhancement began
to saturate, but, at this temperature, did not begin to decrease again
at the highest power available.

Figure 3 shows the temperature dependence of $2\langle \Delta \rangle$ for several power
levels for the junction on BaF$_2$ referred to in Figs. 1 and 2. These
curves were obtained using two different methods.

\textbf{Method 1.} The temperature was incrementally varied from the lowest
temperature shown, keeping the microwave power constant. In the case of
the 1 mW curve, at the highest temperature indicated, the structure in
dV/dI began to smear out; at higher temperatures, the structure became
so heavily smeared that we were unable to obtain a value for $\Delta_\gamma + \Delta_c$.
Similar behavior was observed at 2 mW. At the higher
power levels, however, the structure in dV/dI \textit{abruptly} disappeared when
we exceeded the temperature $T_\downarrow$. $T_\downarrow$ was substantially higher than $T_\uparrow$,
and increased with increasing microwave power. The curve labeled 18 mW
gave a $T_\downarrow \approx T_c$ within experimental error. Further increases in power
did not result in any further increase in $T_\downarrow$. When the temperature was
reduced (keeping the power constant) there was no structure in dV/dI
until we reached a temperature $T_\uparrow$, where the gap abruptly reappeared.$T_\uparrow$ decreased with increasing power. Thus, as the temperature was increased
at constant power ($\geq 3$ mW), $2\langle \Delta \rangle$ was maintained at a value greater than
$\hbar\nu$ until an instability occurred at $T_\uparrow$, and there was a first order tran-
sition to zero gap.
**Method 2.** We increased the microwave power from zero, keeping the temperature constant. At temperatures below $T_D$, marked (D) in Fig. 3, we obtained the same enhanced values of the gap as in Method 1, whereas, at temperatures $T_D$ and above, the behavior was markedly different. At $T_D$, there was a small enhancement at low power levels, but, as the power was increased above 3 mW, the structure in $dV/dI$ disappeared. At higher temperatures, no enhancement at all was observed; rather the gap became zero as the power was increased. For the junction represented in Fig. 3, $T_D$ was roughly 1 mK above $T_V$, the temperature at which $\nu = 2\langle \Delta \rangle$. Evidently, when the temperature was raised to $T_D$, the pair breaking effects of the microwaves and of the phonons emitted by quasiparticle relaxation began to reduce the enhancement; as the temperature was increased further, no enhancement of the gap was possible by Method 2. The frequency dependence of this effect is shown in the inset of Fig. 3, where the change in $2\langle \Delta \rangle$, $\delta(\Delta_+ + \Delta_-)$, is plotted vs. temperature for a junction on a glass substrate. This data was taken in the low power regime where Methods 1 and 2 were indistinguishable. At each of the two frequencies, (9.9 GHz and 11.9 GHz), there was an enhancement for $T \leq T_V$, while $\langle \Delta \rangle$ was depressed for $T \geq T_V$. This result is consistent with the observation by Tredwell and Jacobsen \(^3\) that the critical current of aluminum microbridges was enhanced by 10 GHz phonons only when $\nu < 2\Delta_e$. The depression of $\langle \Delta \rangle$ for $T \geq T_V$ suggests that 10 GHz microwaves do not enhance the transition temperature of aluminum by Method 2. Since Klapwijk et al. \(^4\) found that $T_c$ was enhanced by 3 GHz microwaves, the degree of enhancement is evidently strongly frequency dependent.

Further work is in progress to investigate the frequency dependence
of gap enhancement and the effect of changing the phonon coupling between film and substrate. We also intend to compare nonequilibrium values of $\Delta$ measured by tunneling with values inferred from critical current measurements.

We are grateful to Drs. J. J. Chang, C. C. Chi, J. E. Mooij, P. E. Lindelof, and D. J. Scalapino for helpful discussions, and to Drs. Mooij, Lindelof, and Scalapino for prepublication copies of their work.
References

*This work was supported by the USERDA.

   G. M. Eliashberg, Zh. Eksp. Teor. Fiz. 61, 1254 (1971) [Sov. Phys. -
   JETP 34, 668 (1972)]; B. I. Ivlev, S. G. Lisitsyn, and G. M. Eliashberg,

   Rev. 155, 419 (1967).

3. T. J. Tredwell and E. H. Jacobsen, Phys. Rev. Lett. 35, 244 (1975);

4. T. M. Klapwijk and J. E. Mooij, Physica 81B, 132 (1976); T. M. Klapwijk,
   J. N. van den Bergh, and J. E. Mooij, to be published.

5. B. R. Fjordbøge, T. D. Clark, and P. E. Lindelof, Phys. Rev. Lett. 37,
   1302 (1976).

   (following letter).

7. C. C. Chi and D. N. Langenberg, Bull. Am. Phys. Soc. 21, 403 (1976);
   C. C. Chi, private communication.

8. W. L. McMillan, and J. M. Rowell in Superconductivity (Dekker, New York,


Figure Captions

1. $dV/dI$ vs. voltage for Al-Al$_2$O$_3$-Al tunnel junction on BaF$_2$ substrate.

2. $2\Delta_>, \Delta_> + \Delta_<, \text{ and } 2\Delta_<$ vs. microwave power for Al-Al$_2$O$_3$-Al junction.

3. $\Delta_> + \Delta_<$ vs. reduced temperature at several levels of microwave power for Al-Al$_2$O$_3$-Al junction on BaF$_2$ substrate. Inset shows gap enhancement, $\delta(\Delta_> + \Delta_<)$, vs. temperature for Al-Al$_2$O$_3$-Al junction on a glass substrate at (a) 9.9 GHz and (b) 11.9 GHz. The appropriate values of $T_\nu$ are indicated.
$2\Delta$ vs. POWER (mW) for BaF$_2$ at 10.0 GHz, with $t \approx 0.99$. The graph shows $2\Delta$, $\Delta_>+\Delta<$, and $2\Delta<$. The power range is from 0 to 20 mW.
This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.