of the present method as compared to previous ones[8,17] which could not even give the correct order of magnitude.

The present theory can be improved by taking into account interaction among discrete levels and in this way it will hopefully be possible to explain the puzzling spectra of other systems. Work on $MgO:Cr^{3+}$ and $Cs_2SiF_6:Mn^{4+}$ is in progress.[20,21]

The authors wish to thank R. Englman, J. Jortner, E. Sigmund, N. Terzi, and M. Wagner for useful discussions.

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Microwave Enhancement of Superconductivity in Aluminum Tunnel Junctions

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(Received 28 July 1980)

Microwave radiation (0.1 to 12 GHz) was propagated in a microstrip transmission line formed by a superconducting Al film on a BaF_2 substrate. Cross strips formed Al–Al oxide–Al tunnel junctions that were used to study the effect of microwaves on the superconducting properties of the Al films. Large increases in the energy gap and transition temperature were observed for frequencies near 3.7 GHz. The enhancements were negligible below 1 GHz. Anomalous behavior of the features in the tunneling characteristics was observed above 5 GHz.

PACS numbers: 74.30.Gn, 73.60.Ka, 74.50.+r

The effect of microwave radiation on superconductivity has been of considerable experimental and theoretical interest, and also of some controversy, in recent years. Microwave enhancement of superconductivity has been reported in several manifestations: critical-current (I_c) and transition-temperature (T_c) enhancement in Al microbridges, point contacts, and narrow strips[1-3]; order-parameter enhancement in Al cylinders,[4] and energy-gap (Δ) enhancement in Al tunnel junctions.[5] Existing theories predict such enhancements as a consequence of a redistribution of quasiparticles away from the gap edge[6,7] and a reduction in the number of quasiparticles[7] in a superconductor irradiated with microwaves. Theoretical explanations of I_c enhancement without gap enhancement have also been proposed.[8-10] The quasiparticle redistribution theories[6,7] receive strong experimental support from the direct observation of gap enhancement via tunneling and from T_c enhancement in strips.[10] However, it was suggested in a recent communication that observations interpreted as T_c enhancement should instead be interpreted as I_c enhancement.[11]

Moreover, in recent experiments that culminated in consecutive measurements of I_c and Δ of two Al films that formed a tunnel junction, I_c enhancement was observed but gap enhancement was not.[12] Indeed, no confirmation of the direct observation of gap enhancement[5] has been published.

In this Letter we report enhancement of both Δ and T_c, as measured by tunneling, in Al films irradiated with microwaves. We also observed I_c enhancement in one junction electrode. In the frequency range 2–4 GHz, we observed large ($\approx 100\%$) increases in the energy gap. We also observed gap structure in the dV/dI vs V curves 16 mK above the temperature at which both films were normal (i.e., no structure in the dV/dI vs V curve) in the absence of microwaves. Finally, we observed new and unexpected behavior above 5 GHz.

Our Al–Al oxide–Al junctions (four per substrate) were fabricated in a cross-film geometry on single-crystal BaF_2 substrates,[13] which have a good acoustical matching to Al.[14] A 200-nm-thick, 1.47-nm-wide base electrode was common to all four junctions; the four contour electrodes were 200 nm thick and 140 μm wide. With a ground plane beneath the substrate, the base electrode formed a 50-Ω microstrip transmission line, enabling broadband (dc–18 GHz) coupling to the junctions.

A carbon resistance thermometer, a feedback circuit, and a heater provided temperature control of our pumped helium bath to better than ± 0.3 mK. Because microwave heating of a thermometer in a feedback circuit results in a lower bath temperature (and hence in a larger gap for Al films in the bath), careful shielding of the thermometer is essential. The effectiveness of our shielding was established as follows: A National Bureau of Standards SRM-767 device,[15] which includes a bulk sample of high-purity Al ($T_{cB} = 1.180 \pm 0.001$ K), was mounted near the junction. As the microwave power to the junction was slowly increased to maximum with the thermometer reading stabilized at T_{cB} by the feedback loop, the bulk Al sample remained at the midpoint of its transition, thereby demonstrating that the temperature had changed by < 0.2 mK. In addition, the gap voltage of a shielded control junction did not change when the microwave power was increased at constant thermometer reading at temperatures below T_{cB}.

We have observed gap enhancement in junctions on two BaF substrates. We present data from a single junction (a second junction on the same substrate also showed Δ and T_c enhancement; the other two junctions were shorted). The normal resistance of this junction was 3.5 Ω. A fit of the BCS temperature dependence near T_c to the experimental gaps of the two films in the temperature range 1.158 to 1.167 K yielded the values $T_{c1} = 1.170$ K and $T_{c2} = 1.168$ K.

Figure 1 shows the effect of increasing microwave power at $\nu = 3.72$ GHz on dV/dI of this junction at $t = T/T_{c1} = 0.996$; dV/dI traces for the control junction are also shown. In the absence of microwaves (upper curve), there is a sharp minimum at $(\Delta_1 + \Delta_2)/e = V_g$, and there is a much smaller minimum near $V = 0$ at $(\Delta_1 - \Delta_2)/e$. The remaining curves show additional minima, due to photon-assisted tunneling (PAT),[16] at voltages $\pm V_g \pm nh\nu/e$. The deepest minimum in dV/dI occurs at V_g in this particular set of curves. As the microwave power increases, V_g moves to higher voltages as do the PAT minima. The minimum at $(\Delta_1 - \Delta_2)/e$ is obscured by PAT structure at high power, so the relative enhancements of the gaps cannot easily be determined. However, the data clearly establish that the energy gap of at least one of the films was enhanced by the microwaves.

We determined the temperature and power dependence of the enhancement of V_g from dV/dI curves that were taken at fixed temperatures for several power levels. For frequencies near 3.7 GHz, our results for the temperature and power dependence[13] are quite similar to the results of Kommers and Clarke at 10 GHz (Figs. 2 and 3 of Ref. 5) and at 3.7 GHz.[17] Our results are also in qualitative agreement with theoretical curves derived from recent tunneling calculations based on Eliashberg's theory.[18]

We measured the highest temperature at which superconductivity occurred as a function of power. As the temperature was increased at constant power, the PAT structure in dV/dI disappeared abruptly at a temperature $T_{c\downarrow}$, and abruptly reappeared at a temperature $T_{c\uparrow}$ as the temperature was decreased. Figure 2 shows our experimental values of $T_{c\downarrow}$ and $T_{c\uparrow}$ as a function of the transmitted power P. Both $T_{c\downarrow}$ and $T_{c\uparrow}$ increase with increasing power up to $P \approx 90$ μW. Within experimental error, $T_{c\downarrow} = T_{c\uparrow}$ up to $P \approx 20$ μW, where the enhanced transition temperature is approximately 3 mK above T_{c1}. For $P > 20$ μW we observe hysteresis. The largest experimental value for $T_{c\uparrow}$ was 1.177 K (7 mK above T_{c1}) at $P = 90$ μW; the largest value for $T_{c\downarrow}$ was 1.186 K (16 mK above T_{c1} and 6 mK above T_{cB}) at $P = 160$

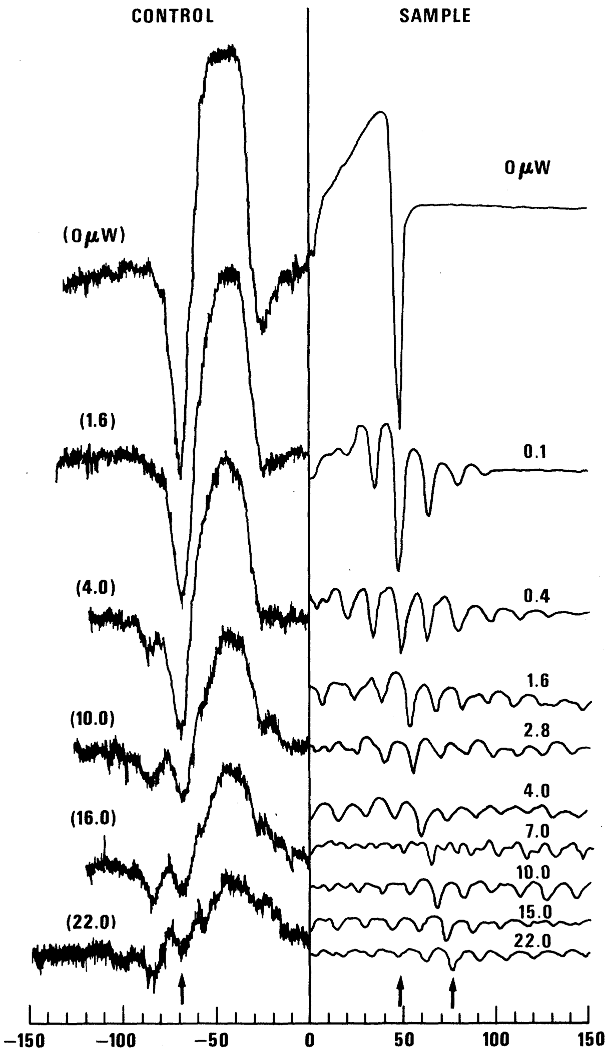

FIG. 1. dV/dI vs V for the sample ($V>0$) and the control ($V<0$) as a function of the microwave power P transmitted through the sample at 3.72 GHz. $V_g=(\Delta_1+\Delta_2)/e$ of the sample increased from 48 to 76 μV (see arrows) as P increased from 0 to 22 μW. The additional minima are due to photon-assisted tunneling. V_g of the control remained at 70 μV, indicating the bath temperature ($T=1.161$ K) remained constant (± 0.3 mK) as the power applied to the sample (in parentheses) increased to 22 μW. A fraction of the microwave power applied to the sample leaked to the control via dc leads. The temperature sensitivity of the control junction was $-3.0\ \mu$V/mK vs $-3.4\ \mu$V/mK for the sample.

μW. (The highest value reported by Kommers and Clarke for $T_{c\downarrow}$ at 10 GHz was the higher transition temperature of their films[5]; however, they observed enhancement of both $T_{c\uparrow}$ and $T_{c\downarrow}$ at 3.7 GHz.[17]) Thus we have observed T_c enhancement

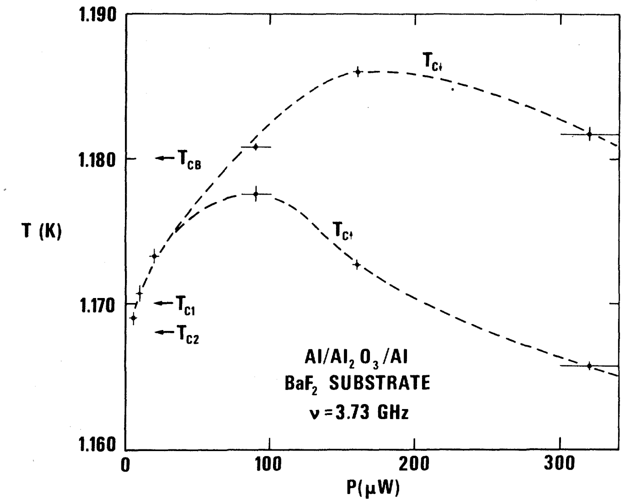

FIG. 2. T_c enhancement as a function of power. $T_{c\downarrow}$ is the T at which superconductivity (structure in dV/dI) abruptly disappeared as T was increased; $T_{c\uparrow}$ is the T at which superconductivity abruptly reappeared as T was decreased. The data points have been connected with smooth curves.

by a method that is different from the method criticized in Ref. 11 and that is not subject to the same criticism.

We have studied the frequency dependence of the enhancement of Δ and T_c.[13] Both effects were largest for frequencies near 3.7 GHz and were not observed for frequencies below 1 GHz. The maximum value of $T_{c\downarrow}$ exceeded T_{c1} by at least 1 mK for frequencies up to about 8 GHz. V_g did not increase significantly for frequencies above 5 GHz. We also measured I_c for the microstrip transmission line and observed enhancement over the same frequency range as T_c enhancement.

Figure 3 shows dV/dI curves at $t=0.992$ and $\nu=10.8$ GHz that illustrate the anomalous behavior that we observe at higher frequencies. Depending on t and ν, V_g may increase slightly (a few percent at most) but usually remains constant (as in Fig. 3) or decreases as the microwave power is increased to intermediate levels. The first PAT minimum appeared for $P\approx 0.5\ \mu$W (curve not shown) at the correct voltage spacing, $h\nu/e$, relative to V_g, but moved to higher voltages as the power was increased; at $P\approx 25\ \mu$W, a second PAT minimum appeared at a voltage spacing $h\nu/e$ above the first. Both minima moved to higher voltages and the spacing between them increased with increasing power. This behavior was repeated by successive minima. In the second

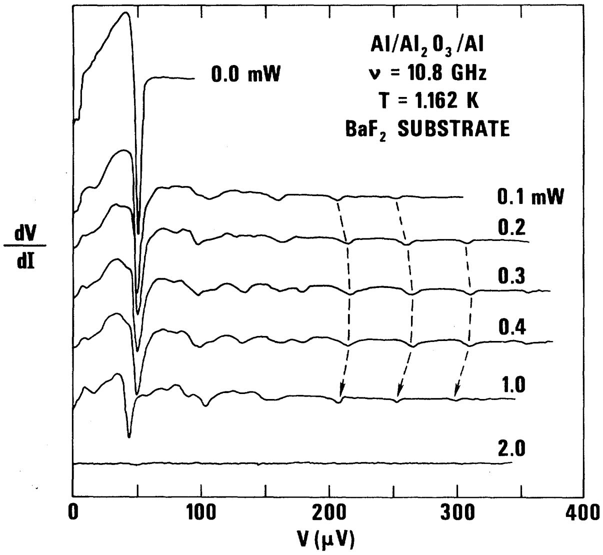

FIG. 3. Anomalous behavior of dV/dI as a function of power at high frequencies. Dashed lines connect associated minima, which show a change in spacing relative to V_g as the power changes.

curve of Fig. 3 ($P = 0.1$ mW), there are four such minima, and PAT structure relative to $-V_g$ occurs above V_g. At high power levels (1 mW in Fig. 3), V_g begins to decrease with increasing power, and the PAT minima begin to move toward lower voltages. This behavior continues until $V_g < h\nu/e$, when the structure in dV/dI disappears abruptly with a further increase in power (bottom curve in Fig. 3). (At $t = 0.85$, the gap did not shrink, and all PAT minima appeared and remained at the theoretically expected voltages $\pm V_g \pm nh\nu/e$.)

The nature and magnitude of the shifts of the PAT minima relative to V_g at high frequencies cannot readily be explained in terms of simple heating. In early theoretical descriptions of PAT, all the minima resulted from the nonequilibrium density of states.[16] The tunneling calculations of Entin-Wohlman[18] show that near T_c the minimum in dV/dI at V_g arises as usual from the nonequilibrium density of states, but the PAT minima arise from the quasiparticle distribution function. Chang and Scalapino show that the time required for a phonon to escape from the sample plays an important role in determining the nonequilibrium quasiparticle distribution function.[7] A combination of these concepts might explain our experimental observations at high frequencies. At low frequencies, our experimental results are in general agreement with the theories of Chang and Scalapino[7] and Eliashberg and co-workers.[6]

We acknowledge with appreciation valuable discussions with J. J. Chang, J. Clarke, E. D. Dahlberg, R. R. Lee, T. R. Lemberger, R. L. Orbach, I. K. Schuller, and B. N. Taylor. This work was supported in part by NASA through government order No. H-27908B. One of us (J.T.H.) is a National Research Council Research Associate.

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