Energy-gap enhancement in superconducting tin by microwaves

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The energy gap in tin has been measured by observing the subharmonic gap structure in the current-voltage characteristics of a microbridge. The microbridge was irradiated with microwaves and the enhancement of the energy gap was compared to the predictions of the Eliashberg theory. At low power levels the agreement between theory and experiment is good but there is a large deviation at high power levels.

When a superconductor is irradiated with microwaves nonequilibrium quasiparticle states are induced which give rise to an enhancement in the critical current, energy gap, and critical temperature. The enhancement in the critical current and the energy gap is most prominent near the critical temperature. Eliashberg[1] has developed a theory that explains these enhancements. When a quasiparticle close to the gap edge is raised to a higher energy state by an applied microwave energy source, $\hbar\omega$, with $\hbar\omega < 2\Delta(T)$ so that pair breaking does not occur directly, then the population of quasiparticles at low energies will decrease. For this reason the energy gap will increase which causes the critical current and the critical temperature to increase in turn. The total number of quasiparticles remains constant. In order to maintain the nonequilibrium state the rate of transfer of quasiparticles to higher energy must be greater than $1.73/\tau_E$. τ_E is the inelastic scattering time.[2]

An extension to the theory of Eliashberg was made by Chang and Scalapino,[3] who included the effects of the interaction of the quasiparticles with the phonons. Their calculation used a set of two Boltzmann-type equations, one for the quasiparticles and one for the phonon distribution and they solved these equations together with the BCS gap equation selfconsistently. Because the strength of the electron-phonon interaction varies as ω^2 they found that an excited quasiparticle of energy $\Delta+\hbar\omega$ recombines more rapidly than one at the gap edge. Heating effects were also considered in this work. In order to compare experimental data to the theory of Chang and Scalapino it is necessary to know the magnitude of the microwave power at the microbridge. However, it is not possible to measure this quantity at the present time. Most experimental data is compared to the Eliashberg theory. The phonon escape time τ_γ plays an important part in the energy-gap enhancement. If τ_γ is short, the irradiated superconductor can have a lower density of quasiparticles than the nonirradiated one leading to an additional enhancement of the superconducting state parameters. The model of Chang and Scalapino includes the influence of the phonon escape time. There is a large amount of experimental data of the variation of the critical temperature with applied microwaves and this data qualitatively agrees with the Eliashberg[1] theory. However, there is a paucity of experimental measurements of the experimental enhancement of the energy gap with the applied microwaves. Measurements have been reported by Kommers and Clarke[4] and by Hall *et al.*[5] of the energy-gap enhancement by microwaves in aluminum.

The energy gap of a superconductor may be accurately determined from the current-voltage quasiparticle tunnel characteristic of a thin-film tunnel junction. Both Kommers and Clark and Hall *et al.* used this technique. However, it was necessary to take measurements close to T_c where the quasiparticle density is at its largest and produces the largest relative gap enhancement.

In this paper, a different technique for observing the enhancement of the energy gap by applied microwaves is described. Microwaves were applied to a superconducting microbridge. Quasiparticle tunneling does not occur in a microbridge and so the energy gap cannot be determined by this method. However, subharmonic gap structure is present in the current-voltage characteristic and the energy-gap enhancement may be determined from this. The microbridges of length 1000 and 3000 Å (Fig. 1) were prepared by a previously described technique.[6] The thickness of the banks was 6000 Å. These variable thickness microbridges have the advantage that they are able to sustain higher levels of heat dissipation than planar microbridges. The subharmonic gap structure is small close to T_c but becomes more prominent at low temperatures. The microbridge was mounted at the lower end of a glass

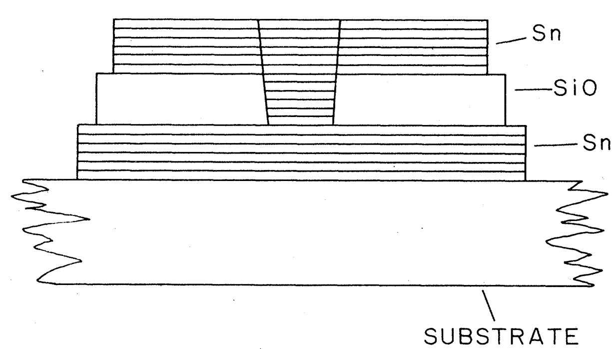

FIG. 1. Schematic outline of the microbridge.

Dewar which was surrounded by μ metal shielding. Ferrite beads were added to all leads to the microbridge in order to minimize external noise to the microbridge. The microbridge was irradiated with 23-GHz microwaves via a circular wave guide at the upper end of the dewar.

The subharmonic gap structure does not appear so clearly as the quasiparticle tunneling energy-gap structure in the current-voltage characteristic of a thin-film tunnel junction. In order to facilitate the location of the subharmonic gap structure in the current-voltage characteristic of a microbridge the differential resistance, dV/dI, of the current-voltage characteristic is obtained. The standard technique for obtaining dV/dI uses low-level ac modulation and a lock-in amplifier. This has the disadvantage that the amplifier filter parameters must be set at the time that the data is taken. In a second technique[7] the current-voltage characteristic is digitized and dV/dI is determined from this data at a later time by a combined differentiating and digital filtering routine. This latter procedure has the advantage that the filter parameters are set by the software after the data has been taken. It should be remembered that the purpose of a filter is to separate the desired information from unwanted noise and as the relative magnitudes and frequency spectrum of both the information and the noise are not completely known, a certain judgement must be made with regard to the filter parameters. It is easier to make these decisions after the data has been taken. Figures 2 and 3 show dV/dI versus voltage for two microbridges of different lengths and at different temperatures. In Fig. 2 the length is 1000 Å and in Fig. 3 the length is 3000 Å. The current-voltage data consisted of 4000–7000 data points. The filter parameters, as defined in Ref. 7, were $\lambda=80$ db, $\beta=0.003$, $\delta=0.0012$, and the combined filtering and differentiation summation was carried out over 400 pairs of data points. The steps that are induced by the microwaves at multiples of 47 μV are visible in Fig. 3. The experimental peaks corresponding to Δ in the absence of microwaves are at a higher value than the value of Δ calculated from BCS theory. The position of the calculated value of Δ is indicated by an arrow in Figs. 2 and 3. The enhancement in the energy gap in the absence of microwaves has not been explained although Gregers-Hansen *et al.*[8] also found that the experimental value of the energy gap in the absence of microwaves was higher than the value predicted by BCS theory. The energy-gap enhancement in the absence of microwaves may be due to the nonequilibrium states induced in the microbridge by the bias current.[9] The presence of these states is evidenced by the existence of dynamically enhanced critical current in the current-voltage characteristic at low potentials. However, Octavio[10] found that the experimental value of Δ in the absence of microwaves was lower than the theoretical BCS value but he attributed this depression of the energy gap to heating in the microbridge.

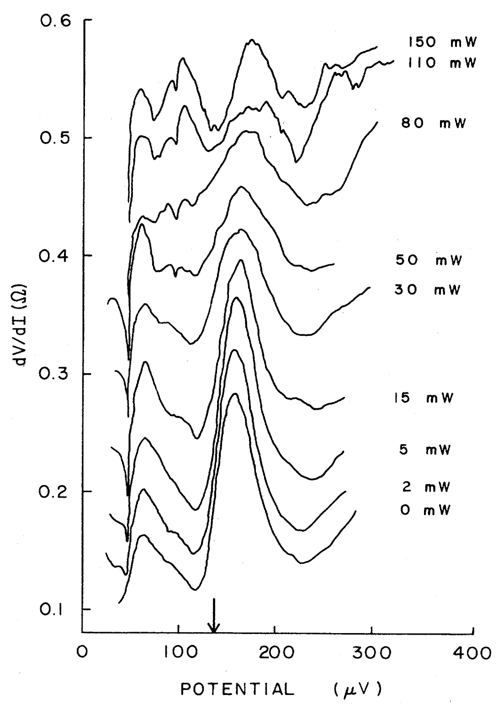

FIG. 2. dV/dI versus potential of the 1000-Å microbridge at 3.718 K for various microwave powers. The plots have been displaced vertically from each other for clarity. The arrow indicates the calculated BCS gap value at that temperature.

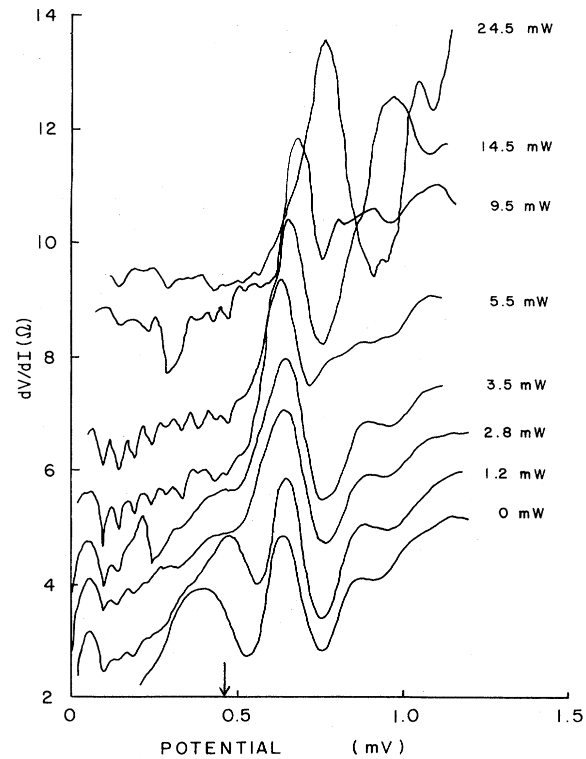

FIG. 3. dV/dI versus potential of the 3000-Å microbridge at 2.775 K for various microwave powers. The plots have been displaced vertically from each other for clarity. The arrow indicates the calculated BCS gap value at that temperature.

The Eliashberg theory predicts that an extra nonequilibrium term

$$\frac{1}{4}(\alpha_\omega/\gamma_r)(\hbar\omega/kT_c)G(\Delta/\hbar\omega) \quad (1)$$

must be added to the Ginzburg-Landau equation. Eckern *et al.*[11] calculated an additional term that should be included in the Ginzburg-Landau equation when nonlinear terms of the nonequilibrium Fermi distribution are taken into account. Mooij[2] modified this extra term to the following form:

$$-0.17(\alpha_\omega/\gamma_r)(\hbar\omega/kT_c)^2 \ . \quad (2)$$

When simple heating effects are included, a further term must be added:

$$-F_h(\alpha_\omega/\gamma_r)(\hbar\omega/kT_c)^2 \ . \quad (3)$$

Along the lines suggested by Mooij, the sum δ of the three terms due to the applied microwaves have been calculated. δ_{expt} which is proportional to the difference between the squares of the energy gap and the square of the energy gap of the unirradiated superconductor, is calculated from the experimental data. According to the theory δ and δ_{exp} should be equal. Unfortunately the magnitude of the coupling between the microwaves and the microbridge is not known. It was only possible to fit the theory δ and the experimental δ_{expt} curves at low power levels by adjusting (α_ω/γ_r). For both the 1000 and the 3000 Å microbridges there is divergence between the values of δ and δ_{expt} at higher microwave powers (Figs. 4 and 5). The works of Kommers and Clarke[4] and Holdeman *et al.*[12] found a similar behavior with their work on aluminum tunnel junctions. Agreement between theory and experiment exists only at low power levels. In Fig. 4 the divergence at higher power is increasing and, in fact, the experimental curvature is qualitatively reminiscent of the Chang-Scalapino theory. On the other hand Fig. 5 shows theoretical (solid line) and experimental data (circles) of a microbridge of length 3000 Å at $T=2.775$ K. Critical current was not observed in this bridge at temperatures above 2.90 K. However, the gap enhancement is very strong for high relative powers. At low power the behavior is qualitatively similar to that of Fig. 4. In this case the critical temperature of the banks is 3.790 K which is well above the measurement temperature so that the magnitude of the energy gap in the banks is relatively large. It was not possible to get the theory and experimental data to agree even when heating effects were included. In Fig. 5 heating effects have not been included. The factor (α_ω/γ_r) was set seven times greater than the factor (α_ω/γ_r) that was used to fit the data for the 1000-Å microbridge in Fig. 4. This gave the best agreement between the theory and experiment at low power levels. As there is considerable impedance mismatch between the microwave radiation and the microbridge, we would expect the radiation to appear as a current source to the microbridge. Thus the power transmitted to the microbridge would be proportional to the resistance of the microbridge. The 3000-Å-long microbridge had a resistance that was approximately seven times greater than the resistance of the 1000-Å-long microbridge. Thus we would expect the coupling factor (α_ω/γ_r) that was required to fit the experimental data for the 3000-Å-long microbridge to be seven times the coupling factor that was required for the 1000-Å-long microbridge. However, the enhancement in the energy gap that occurs at the higher power levels in the 3000-Å-long microbridge is much greater than that predicted by the Eliashberg theory. A last comment about Figs. 4 and 5 is that both figures shown a kind of transition between one behavior to another; in our experimental plots this threshold is at about 15 mW. The work of Seligson and Clarke[13] measured the enhancement of the energy gap of a superconductor when irradiated by low-energy phonons. At low power levels they found that they could fit their experimental data to the theory of Eckern *et al.*, while at high power levels there was considerable divergence. They could not explain this phenomena and it is interesting to note that our data show a simi-

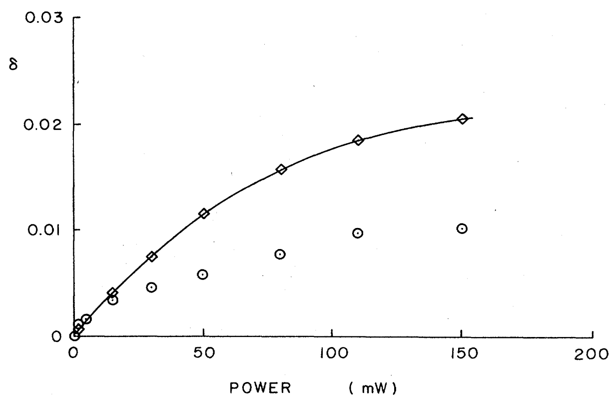

FIG. 4. Experimental and theoretical values of δ versus microwave power for the 1000-Å microbridge at 3.718 K. $R_N=0.2\ \Omega$; $\alpha_\omega/\gamma_r=0.03$; $F_h=2$. The circles represent the experimental data δ_{expt}. The continuous line with the squares represents the theoretical calculation.

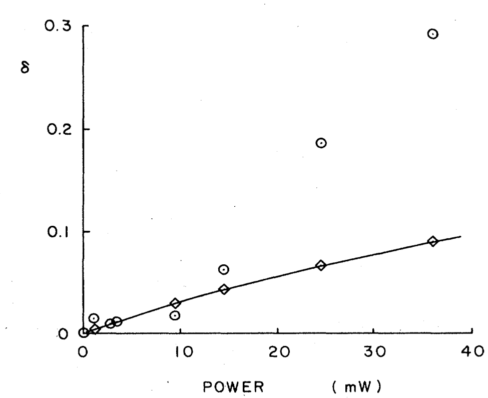

FIG. 5. Experimental and theoretical values of δ versus microwave power for the 3000-Å microbridge at 2.775 K. $R_N=1.4\ \Omega$; $\alpha_\omega/\gamma_r=0.2$; $F_h=0$. The circles represent the experimental data δ_{expt}. The continuous line with the squares represents the theoretical calculation.

lar divergence for the short microbridge. Prior to comparing the data of energy-gap enhancement due to phonons with the data of energy-gap enchancement due to microwaves in microbridges, a term should be included in the Eliashberg theory that takes account of the dynamic energy-gap enhancement due to the nonequilibrium effects caused by the bias current in the microbridge. This dynamic energy-gap enhancement due to nonequilibrium effects caused by the bias current has been discussed in detail by Schmid, Schön, and Tinkham.[9]

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[1]G. M. Eliashberg, in Pis'ma Zh. Eksp. Teor. Fiz. 11, 186 (1970) [JETP Lett. **11**, 114 (1970)]; B. I. Ivlev and G. M. Eliashberg, *ibid.* 13, 464 (1971) [*ibid.* **13**, 333 (1971)]. B. I. Ivlev, S. G. Lisitsyn, and G. M. Eliashberg, J. Low Temp. Phys. **10**, 449 (1973).

[2]J. J. Mooij, *Nonequilibrium Superconductivity, Phonons and Kapitza Boundaries,* edited by K. E. Gray (Plenum, New York 1981).

[3]J. J. Chang and D. J. Scalapino, J. Low Temp. Phys. **29**, 477 (1977).

[4]T. Kommers and J. Clarke, Phys. Rev. Lett. **38**, 1091 (1977).

[5]J. T. Hall, L. B. Holdeman, and R. J. Soulen Jr., Phys. Rev. Lett. **45**, 1011 (1980).

[6]R. Escudero and H. J. T. Smith, Phys. Rev. B **30**, 2527 (1984).

[7]H. J. T. Smith, Rev. Sci. Instrum. **52(3)**, 483 (1981).

[8]P. E. Gregers-Hansen, E. Hendricks, M. T. Levinsen, and G. R. Pickett, Phys. Rev. Lett. **31**, 524 (1973).

[9]A. Schmid, G. Schön, and M. Tinkham, Phys. Rev. B **21**, 5076 (1980).

[10]M. Octavio, Technical Report No. 13, Harvard University, 1978 (unpublished).

[11]U. Eckern, A. Schmid, M. Schmutz, and G. Schön, J. Low Temp. Phys. **36**, 643 (1979).

[12]L. B. Holdeman, J. T. Hall, D. Van Vechten, and R. J. Soulen Jr., Physica (Utrecht) **108B**, 827 (1981).

[13]D. Seligson and J. Clarke, Phys. Rev. B **28**, 6297 (1983).