# Gap enhancement in phonon-irradiated superconducting tin films

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We have measured the current-voltage ($I$-$V$) characteristics of tin-tin tunnel junctions driven out of equilibrium by a flux of near-thermal phonons from a heater. The reduced ambient temperature was $T/T_c = 0.41$. The nonequilibrium $I$-$V$ curves are compared to equilibrium thermal $I$-$V$ curves at an elevated temperature chosen to match the total number of quasiparticles. The nonequilibrium curves show a smaller current near zero bias and a larger gap than the thermal curves. This is the first experimental evidence of phonon-induced gap enhancement far below $T_c$. The results are discussed in terms of the coupled kinetic equations of Chang and Scalapino.

Enhanced superconductivity as determined by measurements of the critical current, transition temperature, or energy gap has received a great deal of attention.[1] Enhancement due to microwaves with frequencies $\hbar\omega < 2\Delta$ have been extensively studied. The results are apparently contradictory. The original experiment of Kommers and Clarke[2] for aluminum near the transition temperature $T_c$ shows an enhanced gap and enhanced $T_c$. Many experiments[3–6] show enhanced critical current $I_c$. An attempt to measure both gap and $I_c$ enhancement was made by Dahlberg, Orbach, and Schuller.[6] They observed large $I_c$ enhancement but no gap enhancement. Subsequently, gap enhancement has been seen by several workers.[7–10] Horstman and Wolter[9] suggest that the apparent conflict between gap and $I_c$ measurements may be due to inhomogeneous excitation of samples with cross-sectional areas larger than the square of the penetration depth.

Phonons present the possibility of uniformly perturbing a superconductor with low-energy radiation. Recently, Seligson and Clarke[11] reported gap enhancement and $I_c$ enhancement in Al near $T_c$ driven by 9-GHz ultrasound. Critical current[12] and indirect evidence for gap enhancement[13] have been seen in earlier experiments.

In our experiment, tin-tin tunnel junctions were irradiated with phonons from a heater. A cross stripe junction was formed by two 150-$\mu$m-wide by 150-nm-thick tin films on one face of a 0.25-mm-thick $c$-axis-cut sapphire substrate. The junction was centered over a 2.5-mm-square nichrome or gold resistive heater. It is crucial to use junctions with high resistance and low leakage to avoid Josephson effects that would mask small changes in the quasiparticle current near zero bias. The samples were immersed in superfluid $^4$He at a temperature of 1.52 K, well below $T_c$.

Two $I$-$V$ curves of a 14.5-$\Omega$ junction biased at voltages below $2\Delta/e$ are shown in Fig. 1. To set the scale, the current in the flat portions is about $\frac{1}{40}$ of the current at the top of the $2\Delta$ rise. In the flat region the currents in the two curves are matched to about 0.25%. This matches the quasiparticle density to the same precision. For biases $|V| \lesssim 0.2$ mV, the magnitude of the currents are different. The curve with the larger $|I|$ is a thermal $I$-$V$ curve at 1.77 K. The lower curve is a nonequilibrium $I$-$V$ curve of the same junction with the bath at 1.52 K and 79 mW dissipated in the heater. The difference in the $I$-$V$ curves near zero bias is plotted as open circles in Fig. 2. We also biased the junction 20 and 80% up the $2\Delta$ rise and measured the change in the gap. The nonequilibrium curve has a gap $\Delta$ that is $120 \pm 60$ nV larger than the equilibrium gap. The current rise at $2\Delta$ onsets at $V \approx 1.08$ mV for both curves. The large error bars on the difference of the gap reflect errors in matching the current at $V = 0.62$ mV. However, even when the thermal $I$-$V$ curve is measured at a lower bath temperature so that the thermal current is resolvably smaller than the nonequilibrium current, the nonequilibrium gap is still larger. Ex-

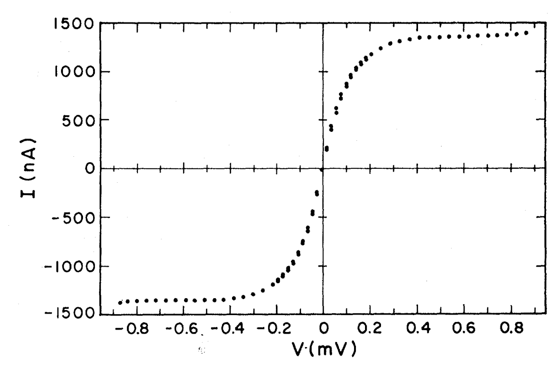


FIG. 1. Two current-voltage characteristics of the junction. For $|V| \gtrsim 0.2$ mV, the two curves are identical. For small $|V|$ the curve with larger $|I|$ is a thermal curve at $T = 1.77$ K; the other curve is a nonequilibrium curve with the bath held at 1.52 K and phonons from a heater irradiating the junction. The current rise at $V = 2\Delta e$ is not shown.

 

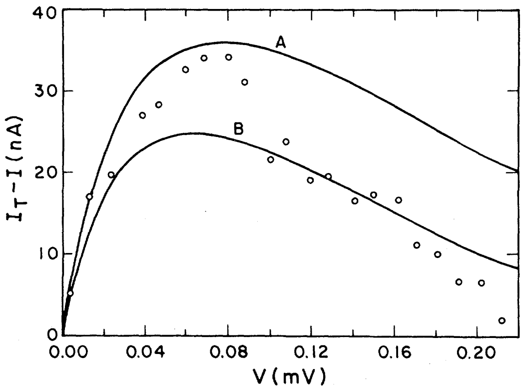


FIG. 2. Difference between the thermal and nonequilibrium $I$-$V$ curves. The open circles are the data. Curves A and B are calculated from the kinetic equations and tunneling integral. Curve A assumes

$$\tau_{esc}(\Omega > 2\Delta) = 0.32\tau_{esc}(\Omega < 2\Delta) \ .$$

Curve B assumes

$$\tau_{esc}(\Omega > 2\Delta) = 0.40\tau_{esc}(\Omega < 2\Delta) \ .$$

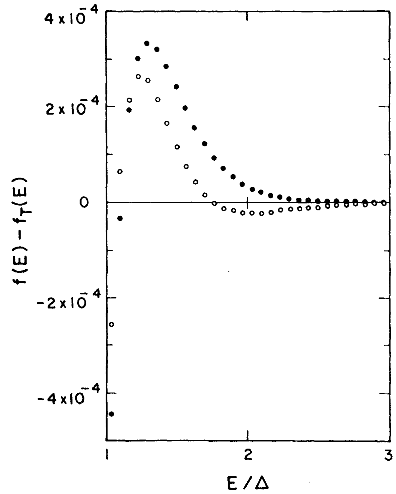


FIG. 3. Difference between the nonequilibrium quasiparticle distribution and a Fermi-Dirac distribution at 1.77 K. The solid circles correspond to curve A in Fig. 2, the open circles correspond to curve B.

pressing the gap difference as an equivalent cooling gives 1.4 ±0.7 mK.

These experiments are the first direct, experimental evidence for phonon-induced gap enhancement far below $T_c$. We have made measurements on seven samples ranging in resistance from 2 to 14.5 Ω and at several bath temperatures between 1.2 and 2.0 K. All of the samples showed the reduced current near zero bias. We only measured the energy gap in three of the samples, and all three showed larger than thermal gaps when irradiated by phonons.

A mechanism first suggested by Eliashberg[14] to explain microwave enhanced superconductivity can at least qualitatively explain the gap enhancement and reduced current in our experiment. The effect of low-energy radiation is to scatter quasiparticles away from the gap edge. Because quasiparticles at the gap edge reduce the gap more effectively than higher-energy quasiparticles, gap enhancement results. Figure 3 shows the difference between two such nonequilibrium distributions and the thermal, Fermi-Dirac, distribution at 1.77 K. The origin of these distributions will be discussed below. Both nonequilibrium distributions give the same current at $V = 0.62$ mV as does the thermal distribution. The difference between the thermal gap at 1.77 K and the nonequilibrium gap that arises from the difference between the quasiparticle distributions in Fig. 3 can be calculated from[15]

$$\delta(\Delta) = -\Delta \frac{\displaystyle\int_\Delta^\infty dE \frac{2[f(E) - f_T(E)]}{(E^2 - \Delta^2)^{1/2}}}{\displaystyle 1 + 2\int_\Delta^\infty dE \frac{E}{(E^2 - \Delta^2)^{1/2}} \frac{\partial f_T(E)}{\partial(E)}} \ , \tag{1}$$

where $f(E) - f_T(E)$ is the difference between the nonequilibrium and thermal quasiparticle distributions and $\Delta$ is the thermal gap. When this is done, the difference plotted as closed circles in Fig. 3 gives $\delta(\Delta) = 62.7$ nV, and the open circles give $\delta(\Delta) = 32.8$ nV. The sign of the change is positive in both cases, indicating gap enhancement, and the magnitude of this enhancement is roughly the same as the measured enhancement. The $I$-$V$ curves calculated with the nonequilibrium distributions substituted for the Fermi-Dirac functions in the usual tunneling integral[16] show the depressed current near zero bias and give the same current that results from a 1.77-K thermal distribution at 0.62 mV. The difference between the calculated thermal $I$-$V$ curve at 1.77 K and the nonequilibrium distributions that give the curves in Fig. 3 are shown as solid lines in Fig. 2. Curve A results from the distribution corresponding to the closed circles in Fig. 3 and curve B corresponds to the open circles. In both cases, the calculated nonequilibrium $I$-$V$ curves fail to return to the calculated thermal equilibrium $I$-$V$ curve at as small a bias as the measured nonequilibrium curve returns to the measured thermal curve. Nevertheless, these calculations show that Eliashberg's mechanism can explain the magnitude of both the gap enhancement and the depressed current near zero bias.

The nonequilibrium distribution functions discussed above were calculated from the coupled kinetic equations of Chang and Scalapino.[15,17] One assumes that the effect of the heater is to inject phonons into a state in the junction at a rate

$$I_{ph}^{a}(\Omega) = A[n(\Omega, T_H) - n(\Omega, T)] \ . \tag{2}$$

In Eq. (2), $A$ is a constant, $\Omega$ is the phonon frequency, $T_H$ is the heater temperature, $T$ is the bath temperature, and $n(\Omega, T)$ is the Bose-Einstein occupation function. The injected phonons alter the quasiparticle occupation through electron-phonon scattering in the superconductor. An important parameter in the model is $\tau_{esc}$, the escape lifetime for a phonon. In Ref. 15, $\tau_{esc}$ is taken to be independent of frequency and is measured in units of $\tau_B(\Omega = 2\Delta)$, the mean time for a phonon of energy $2\Delta$ to break a pair. In tin, this time is $1.1 \times 10^{-10}$ sec.[18]

To produce the distributions shown in Fig. 3, we assumed a value of $\tau_{esc}$ and a value of $T_H$ and calculated $\delta f(E)/A$, the change in the quasiparticle occupation from the thermal occupation at the bath temperature. The tunneling current was calculated and $A$ used to match the 1.77-K thermal current at 0.62 mV. We found that the calculated $I$-$V$ curve was relatively insensitive to $T_H$ and the magnitude of $\tau_{esc}$ because changes in these parameters could be compensated by changes in $A$. We used values of $T_H$ between 1.8 and 2.1 K, a range estimated from the heater power and values of the Kapitza resistance.[19] The $I$-$V$ curves that resulted from these calculations all showed reduced current at small bias and gap enhancement relative to a 1.77-K thermal $I$-$V$ curve. But the calculated current remained below the thermal curve to bias voltages of about 0.5 mV, whereas the measured $I$-$V$ curves are identical above 0.25 mV. We found that we could make the calculated nonthermal $I$-$V$ curve return to the calculated 1.77-K thermal $I$-$V$ curve at smaller biases by giving $A$ or $\tau_{esc}$ a frequency dependence. The curves shown in Fig. 3 resulted from assuming

$$\tau_{esc}(\Omega > 2\Delta)/\tau_{esc}(\Omega < 2\Delta) = 0.32$$

for the closed circles and 0.40 for the open circles. Assuming $A(\Omega > 2\Delta)/A(\Omega < 2\Delta) \approx 0.25$ resulted in $I$-$V$ curves that fell between the calculated curves in Fig. 3. A frequency dependence for $\tau_{esc}$ or $A$ can be expected from the frequency dependence of the transmission coefficient for phonons from a solid into liquid $^4$He. The ratio of the transmission coefficient for a $2\Delta$ phonon to a 1-K phonon is about 10.[20] High-energy phonons may escape into the helium more readily than low-energy phonons in either the heater or superconductor.

One might hope to improve the calculation by using a more realistic frequency dependence for $A$ or $\tau_{esc}$ than the step function used here. Part of the disagreement may result from the size of the perturbation used. Although the change in the gap from the ambient 1.52-K value to the nonequilibrium value is only 3%, the total quasiparticle population has changed more than a factor of 2. The linearized kinetic equations may be a poor approximation for so large a change. We are currently attempting to remedy these flaws by using a model for the phonon injection term that takes the frequency dependence of the solid $^4$He phonon transmission into account and to compare to our data for lower heater powers.

## ACKNOWLEDGMENTS

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