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Phonon-Induced Enhancement of the Superconducting Energy Gap*

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We have observed large increases of the critical current in Josephson junctions under 10-GHz phonon excitation. Eliashberg has predicted that absorption of microwaves in a superconducting film will increase the energy gap by creating a nonthermal quasiparticle distribution. By modifying this theory to account for phonon absorption we obtain a good agreement with our results on the phonon-induced enhancement of the critical current. We conclude that absorption of phonons of frequency $\omega < 2\Delta(T)/\hbar$ increases the superconducting energy gap.

In 1970 Eliashberg[1] suggested that absorption of microwave electromagnetic radiation in a superconducting film would increase the energy gap of the superconductor through the creation of a nonthermal quasiparticle distribution. Ivlev, Lisitysyn, and Eliashberg (ILE)[2,3] later derived expressions from which the microwave-induced increase of the energy gap could be calculated. The enhancement of the energy gap would be observed at temperatures such that the applied radiation does not break Cooper pairs, i.e., $\hbar\omega < 2\Delta(T)$. Eliashberg suggested that if a Josephson junction were used as a probe of this new state, the critical current of the junction would be increased.

A number of investigators[4-7] have reported small increases in the critical current of microbridge Josephson junctions under low-power microwave electromagnetic excitation. There is wide variation in the reported magnitudes and temperature dependences of this enhancement of the critical current. Several authors have suggested the ILE mechanism as the explanation for their results. However, no detailed comparison has been made between the observed enhancement of the critical current and the enhancement calculated on the basis of the ILE theory. Such a comparison would be of questionable value because of the presence in these experiments of other effects which significantly influence the critical current of a Josephson junction. These effects include the microwave-induced suppression of fluctuations,[8-10] which increases the measured critical current, and the direct effect of rf on the Josephson junction,[11] which decreases the critical current and also produces current steps in the I-V characteristics.

We have conducted a series of experiments in which the response of both point-contact and microbridge Josephson junctions to pulsed 10-GHz microwave *phonons* has been investigated.[12] We have observed large increases in the critical current of both types of junctions under phonon excitation. This is the first time that a *phonon*-induced enhancement of the critical current has been observed. Because of the absence of other effects which influence the critical current of the Josephson junction, such as those mentioned above in connection with microwave excitation, a direct comparison between the observed enhancement of the critical current and that predicted on the basis of the ILE theory is possible for phonon excitation.

The experimental arrangement comprised an X-cut quartz rod (3 cm length, 0.4 cm diameter), one end of which was inserted into a re-entrant microwave cavity[13]; the opposite end contained either a point-contact or weak-link–microbridge Josephson junction (see inset in Fig. 1). The point-contact junctions comprised aluminum films of thicknesses 1200 to 6400 Å ($\lambda_{\rm sound} = 6400$ Å) evaporated onto the end face of the quartz rod with an adjustable tin point mounted normal to the film. The weak-link bridges ($1\ \mu{\rm m} \times \frac{3}{4}\ \mu{\rm m}$) were fabricated from 1500–2000-Å aluminum films evaporated onto the rod end face by use of the technique of Gregers-Hansen and Levinsen.[5]

The response of the junctions to phonons was as follows. For $T - T_c < 0.005$°K the phonons caused the junctions to become normal. Abruptly at T/T_c

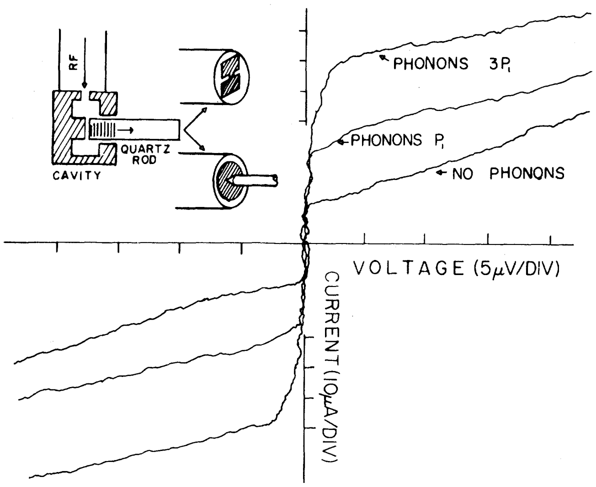

FIG. 1. *I-V* characteristics of a point-contact Josephson junction at $T = 0.97T_c$ for two phonon power levels, and without phonons. The rounding of the critical current is a result of variations in phonon power during the pulse. Inset shows experimental arrangement.

$= 0.996$ the critical current, instead of vanishing, was observed to increase greatly under phonon excitation. This phonon-induced enhancement of the critical current was observed to the lowest temperatures attainable in the present experiment (0.9°K).

Figure 1 shows typical *I-V* characteristics of a point-contact junction at $0.97T_c$ with and without phonon excitation. The data were obtained by monitoring the voltage across the junction with a video amplifier and boxcar integrator, with the gate of the boxcar integrator timed to coincide with the arrival of a phonon pulse. The enhancement of the critical current is about 450%; larger relative enhancements were observed at higher temperatures and higher phonon power levels. Microbridge Josephson junction displayed phonon-induced enhancements of the critical current of about the same magnitude.

In contrast to the very large enhancements of the critical current observed for both point-contact and microbridge junctions under *phonon* excitation, *microwave* excitation produced no enhancement of the critical current in point-contact junctions and only small enhancements in some microbridges. The maximum microwave-induced enhancement in the microbridge for $T/T_c = 0.97$ was 4%, as compared to over 400% observed for *phonon* excitation at the same temperature. The microwave-induced enhancement of

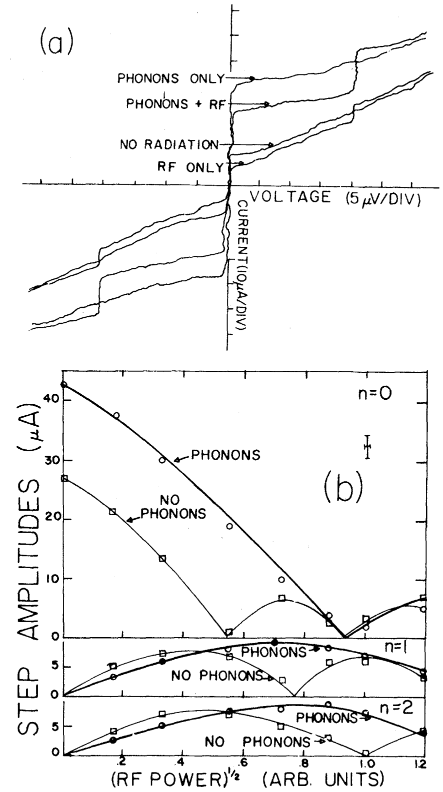

FIG. 2. (a) *I-V* characteristics of point-contact junction at $T = 0.97T_c$ under simultaneous phonon (pulsed) and microwave (continuous at low power) excitation. (b) Step amplitudes of the $n = 0$, 1, and 2 microwave-induced steps with and without phonon excitation for a point-contact junction at $T = 0.94T_c$. Solid lines are drawn for clarity.

the critical current in the microbridges was observed at low microwave power levels. At higher powers the critical current decreased and the *I-V* characteristics displayed the usual rf-induced steps which oscillated in rf power as described by previous investigators.[5] We would suggest that the decrease in the critical current due to the direct effect of microwaves on a Josephson junction occurs at much lower microwave power levels than the increase in the critical current caused by absorption of the microwaves predicted by the ILE theory, thereby rendering the latter effect difficult to observe. However, by using *phonons*, the enhancement of the critical current predicted by ILE becomes observable.

Data were also taken with simultaneous excitation by phonons (pulsed) and microwaves (continuous at low power). A typical *I-V* curve is shown in Fig. 2(a). Both the critical current and the microwave-induced current steps are enhanced by the phonons. Figure 2(b) shows the amplitudes of the $n=0$, 1, and 2 steps as a function of V_{rf}, the square root of the microwave power, for a point-contact junction with and without phonon excitation. The critical current is increased by the phonon excitation. In addition, the step amplitudes are increased and the zeros of the step amplitudes are moved farther out on the V_{rf} scale. These latter effects are a consequence of the increase in the critical current, as developed in the junction model of Fack and Kose[14] and Russer.[15]

We propose that the phonon-induced increase in the critical current of our junctions can be explained by the ILE theory. ILE have given expressions for the change in the energy gap due to microwave excitation of a thin superconducting film. We have modified these expressions[16] for phonon absorption by using the phonon coherence factor and transition rate to obtain the phonon-induced increase of the energy gap. Details of these calculations will be given in a later publication.

By using a Josephson junction as a probe of the film under phonon excitation, the increase of the energy gap is observed as an increase of the critical current. For many of our microbridges and point-contact junctions, the critical current was found to be linear in $1 - T/T_c$ at temperatures near T_c. For these junctions it can be shown that the critical current should increase with the energy gap as $I_0 \propto \Delta \tanh(\Delta/2k_B T) \approx \Delta^2$ at a given temperature. Figure 3(a) shows the relative increase in the critical current of an aluminum microbridge as a function of temperature along with the results calculated by use of the ILE theory modified for phonon excitation. The adjustable parameter is the absolute phonon power present. These data were taken at a relatively low phonon power level, where approximations in the ILE theory are expected to be valid. For $T/T_c > 0.996$ the junction is driven normal; this is due to the onset of pair breaking by the phonons and is predicted for phonon excitation by the calculations based on the ILE theory.

The decrease in the critical current for $\hbar\omega > 2\Delta(T)$ indicates that the increase of the energy gap would not be observed with the use of a thermal phonon source, such as a heat pulse. Such a source would contain a large number of phonons with frequency $\omega > 2\Delta(T)/\hbar$, which would break Cooper pairs and so tend to destroy the superconducting state.

Several of the microbridges displayed a critical current proportional to $(1 - T/T_c)^{3/2}$ for $T > 0.9T_c$. It can be shown that for this type of junction the critical current will increase as Δ^3 at a given temperature. Results for such a microbridge under phonon excitation are shown for two phonon power levels in Fig. 3(b) along with results of calculations based on the ILE theory.

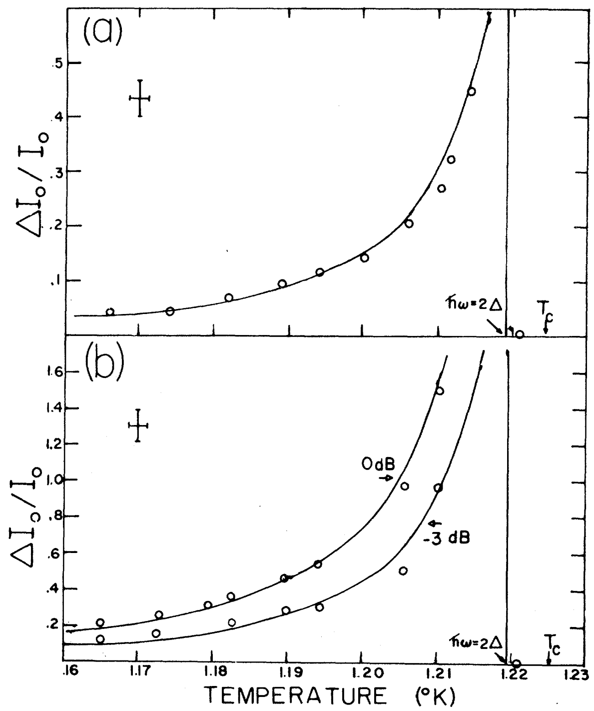

FIG. 3. (a) Relative increase in the critical current as a function of temperature for a microbridge with $I_0 \propto 1 - T/T_c$. Solid lines show prediction of ILE theory modified for phonon excitation. (b) Same as (a) for a microbridge with $I_0 \propto (1 - T/T_c)^{3/2}$ and two phonon power levels, where $P(0\text{ dB}) = 2P(-3\text{ dB})$.

The magnitude of the expected increase of the critical current was calculated by use of the estimated phonon power generated and the ultrasonic attenuation in aluminum measured by Fagan and Garfunkel.[17] The observed increase is within a factor of 4 of that predicted, well within the range of error of the estimates.

In summary, we have observed large increases in the critical current of point-contact and microbridge Josephson junctions under 10-GHz phonon excitation. The magnitude and temperature dependence of the enhancement of the critical current are fitted by predictions based on the ILE theory modified for phonon absorption. We conclude that the effect of phonons of frequency $\omega < 2\Delta(T)\hbar$ is to increase the superconducting energy gap.

We thank Professor Sidney Shapiro for many encouraging and illuminating discussions concerning experimental and theoretical aspects of Josephson junctions.

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[12]In a previously reported experiment [T. J. Tredwell and E. H. Jacobsen, Phys. Lett. 50A, 281 (1974)] we observed a decrease in critical current under phonon excitation of point-contact junctions formed between very thin ($< 500 \ll \lambda_s$) aluminum films and niobium points. We suggested that the coupling between sound wave and junction occurred via the modulation of the chemical potential of the film by the sound wave. In the present publication we present results for thicker films ($d \approx \lambda_s = 6400$ Å). In these thicker films the absorption of the sound wave is much greater and so dominates the modulation of the chemical potential, the latter tending to average to a very small value over the thick film. Thus we observe an increase in the critical current due to phonon absorption instead of a decrease of critical current, with the appearance of steps in the I-V characteristic, caused by modulation of the chemical potential. For much thicker films ($>20\,000$ Å) partial thermalization of the 10-GHz phonons occurs as a result of absorption of the relaxation phonons emitted by the excited quasiparticles. For film thicknesses reported here (~ 6400 Å) the relaxation phonons readily escape to the substrate and helium bath.

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Percolation Conductivity in W-Al_2O_3 Granular Metal Films

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The growth of W grains in sputtered W-Al_2O_3 films as a consequence of annealing results in a narrowing of the transition region from metallic to nonmetallic conductivity. The conductivity, σ, as a function of the volume fraction of the metal, x, exhibits a critical behavior given by $\sigma \sim (x - x_c)^p$, where the critical volume fraction of the metal $x_c = 0.47 \pm 0.05$ and the critical exponent $p = 1.9 \pm 0.2$. For $x < 0.47$ the temperature dependence of σ has the form $\ln\sigma \sim -1/\sqrt{T}$ which is characteristic of tunneling between isolated grains.

Granular metals (cermets) fall into the general category of metal-insulator mixtures in which the electrical conductivity is determined by percolation. The electrical properties of such mixtures are of general interest because of their application to problems of conductivity and metal-nonmetal transitions in disordered systems.[1,2] In this Letter we present results of the effect of grain size on the resistivity of granular metals in which the volume fraction of the metal, x, is varied over the range $0.1 < x \leq 1$. By cosputtering the metals W or Mo with the insulators Al_2O_3 or SiO_2, a very finely dispersed grain structure[3] results. With annealing, the size of the metal grains can be varied over a wide range. Unlike the case of Au and Ag cermets,[4,5] the W or Mo does not precipitate out with annealing but remains uniformly dispersed within the insulator.