studied the Mössbauer effect in K^{40} using the reaction $K^{39}(d,p)$ to populate the 29.4-keV level. Their measurements, made at 78°K, indicated no observable resonance with KBr and KOH targets. With metallic potassium they observed a resonance amplitude of about 1%, although in the latter measurement there is some uncertainty concerning the chemical form of the source. These authors have speculated that radiation-damage effects caused by the method of production are responsible for their failure to observe resonant absorption in insulators.

The isomer shifts for K, KCl, and KF (see Table I) are essentially zero. Assuming electronic configurations of $3s^2 3p^6 4s$ and $3s^2 3p^6$ for the metallic source and the KCl absorber, respectively, an upper limit can be established for the change in nuclear radius, $\Delta R/R = (R_{29.4} - R_{\text{gnd}})/R_{\text{gnd}}$, between the ground and first excited states of K^{40}. The error limit of ±0.4 mm/sec obtained for metallic potassium yields a value of $|\Delta R/R| < 0.004$. K^{40} consists of a $d_{3/2}$-proton hole and an $f_{7/2}$ neutron outside the doubly closed-shell Ca^{40} nucleus. According to Goldstein and Talmi[4] the odd nucleons couple together to form the 4^- ground state, a 3^- first excited state (29.4 keV), and two higher states with spins 2^- and 5^-. On the basis of this model one would expect no change in nuclear radius as these particles are recoupled. Our results for $\Delta R/R$ are consistent with this picture.

The authors wish to express appreciation to the members of groups CMF-9 and P-2 for making available much of the apparatus with which this experiment was performed. They are also grateful to S. L. Ruby and R. E. Holland for communicating their results prior to publication.

---

†Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]G. Lang, Nucl. Instr. Methods 24, 425 (1963).

[2]F. J. Lynch and R. E. Holland, Phys. Rev. 114, 825 (1959).

[3]S. L. Ruby and R. E. Holland, preceding Letter [Phys. Rev. Letters 14, 591 (1965)].

[4]S. Goldstein and I. Talmi, Phys. Rev. 105, 995 (1957).

MICROWAVE-PHONON-ASSISTED TUNNELING IN SUPERCONDUCTING DIODES

B. Abeles and Y. Goldstein

RCA Laboratories, Princeton, New Jersey

(Received 17 March 1965)

In this Letter we present data on tunneling between superconductors induced by transverse microwave phonons. The coherent sound waves give rise to an extra tunneling current, ΔI_S, which depends strongly on the voltage bias across the tunnel diode. The bias dependence for transverse phonons is remarkably different from that reported earlier[1] for longitudinal phonons. Similarly, the dependence of ΔI_S on the acoustic power is different for the two polarizations. To the best of our knowledge this is the first time that such a dependence on the phonon polarization was observed. Our results disagree with those published recently by Lax and Vernon.[2]

The measurements were performed on Al-Pb tunnel diodes deposited on one of the ends of optically polished single-crystal rods. The rods were 1 in. long with end faces parallel to better than 6 sec of an arc. Sound waves were excited in the rods using standard pulse-echo techniques. Power from a microwave transmitter, in the form of 1-μsec pulses, was fed into a re-entrant cavity[3] resonating at a frequency $\nu = 9.3 \times 10^9$ cps. The ends of the rods opposite the tunnel diode, $\frac{1}{8}$ in. in diameter, were inserted into the cavity. In the early measurements sound waves were generated by surface excitation[3] using X- and AC-cut quartz rods. To eliminate possible effects due to the piezoelectric field associated with the sound wave, measurements were also performed on tunnel diodes deposited on [100] germanium, and Z-cut quartz rods. In these cases the sound waves were generated by overtone resonant transducers bonded to the rods. The results obtained with the two techniques were in agreement.

The effect of the microwave excitation on the tunneling current was detected by a low-noise pulse amplifier. Coincident with the transmitter pulse a large pulse was observed in the tunneling current. This pulse is due to the direct interaction[4] of the tunnel diode with microwave radiation leaking out of the cavity. The first current pulse due to the sound pulse, ΔI_S, was delayed by the time of flight of sound through the crystal rod. Subsequent current pulses, due to the sound-pulse echoes, were observed separated in time by twice the time of flight. As many as 21 current pulses due to one microwave excitation pulse were detected. The amplitudes of the phonon-induced current pulses were at least one order of magnitude lower than the current pulse due to the leaked-out microwave radiation.

In Fig. 1 typical results of ΔI_S due to transverse and longitudinal phonons are plotted (on a relative scale) versus the voltage bias across the tunnel diode. The curve for the shear waves was obtained using an AC-cut quartz rod, while that for the compressional waves by using a Z-cut quartz rod with an X-cut quartz transducer. The shapes of these curves do not change appreciably with power at the power levels available. Also shown in the Figure are the derivatives dI/dV and d^2I/dV^2 of the current-voltage characteristics.[5] ΔI_S due to longitudinal phonons closely follows d^2I/dV^2 in all its fine structure.[6] ΔI_S due to transverse phonons, on the other hand, shows a totally different behavior. The dependence of ΔI_S on acoustic power is shown in Fig. 2. The data in Fig. 2 were taken at the bias of 1.6 mV, where ΔI_S is largest. The maximum acoustic power, corresponding to 0 dB in the figure, was 10 mW. ΔI_S was normalized with respect to I_0, the current jump occurring at the bias $qV=(\epsilon_1+\epsilon_2)$, where q is the charge of the electron and $2\epsilon_1, 2\epsilon_2$ are the energy gaps of the two superconductors. Measurements of $\Delta I_S/I_0$ made on diodes whose I_0 varied between 100 and 500 μA all agreed with the normalized curves shown in Fig. 2.

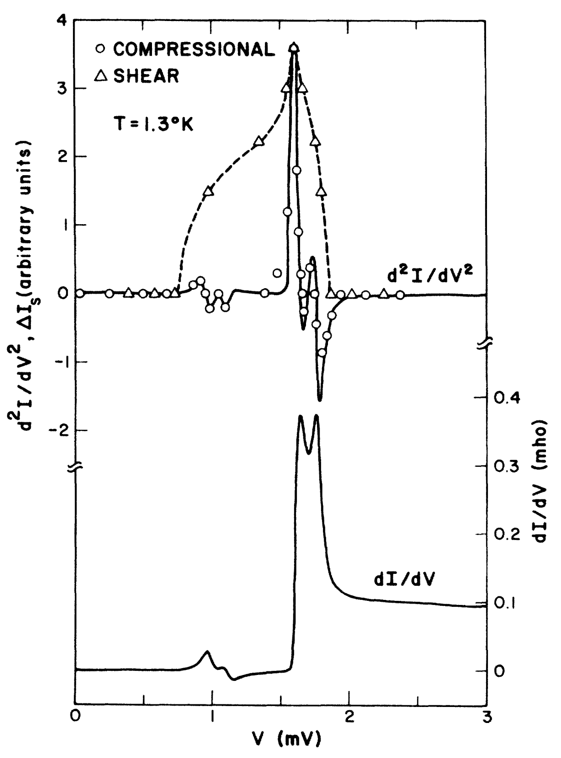

FIG. 1. Typical bias dependence of the current pulses, ΔI_S, due to compressional and shear sound waves, obtained with Al-Pb tunnel diodes.[5] The first and second derivatives of the current-voltage characteristics are also shown.

Since ΔI_S for longitudinal phonons is proportional to d^2I/dV^2, it is convenient to define the quantity

$$V_{eq}^{\ 2}=2\Delta I_S/(d^2I/dV^2). \qquad (1)$$

V_{eq} has the dimensions of voltage and can be thought of as an equivalent voltage across the diode due to sound absorption. Such an equivalent voltage can be derived using a simple model in which the tunnel diode acts as a quantum detector of sound. This interpretation is analogous to that of Dayem and Martin,[4] but using phonons rather than photons. The ab-

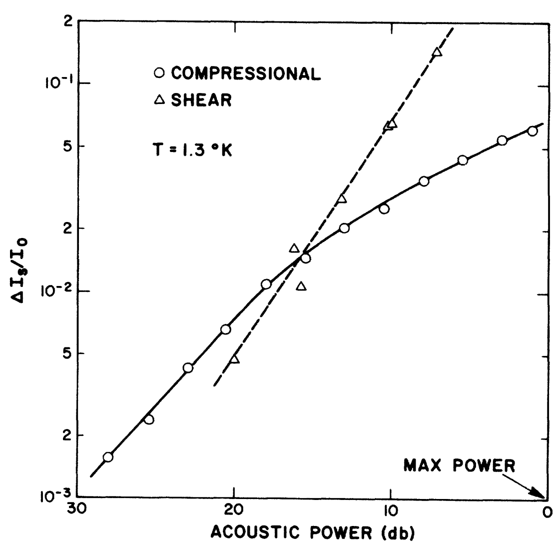

FIG. 2. The power dependence of $\Delta I_S/I_0$ for Al-Pb tunnel diodes.

sorption of phonons of energy $h\nu$ is expressed by an extra voltage, $h\nu/q$, across the tunnel diode acting on the excited electrons. This voltage gives rise to an extra current:

$$\Delta I_S = (\tfrac{1}{2})\beta^2(h\nu/q)^2(d^2I/dV^2), \qquad (2)$$

where β^2 is the fraction of the tunneling electrons excited by phonons. In Eq. (2) odd powers of $h\nu$ are assumed to cancel due to the presence of stimulated emission, and the remaining even powers are neglected. We also neglect multiple-phonon processes. Equation (2) explains the observed bias dependence of ΔI_S due to longitudinal phonons and yields for V_{eq}

$$V_{eq}^2 = \beta^2(h\nu/q)^2. \qquad (3)$$

V_{eq} attains its maximum value of $h\nu/q$ (38.5 μV at $\nu = 9.3\times10^9$ cps) at high acoustic powers when all the tunneling electrons are excited. The experimental value of V_{eq} obtained from Eq. (1) using the near-saturation value of $\Delta I_S/I_0$ measured at the highest powers is 38 μV in agreement with the model. At low powers the fraction β^2 of excited electrons is proportional to the acoustic power. Equation (3) thus predicts a linear dependence of V_{eq}^2 on acoustic power, which is in agreement with the experiment.

Also, the values of β^2 at these powers, estimated from the ultrasonic absorption coefficient and electronic relaxation time, are in reasonable agreement with β^2 determined from Eqs. (1) and (3).

To check the dependence of ΔI_S on phonon frequency, measurements were also performed at 3.3×10^9 cps. The bias dependence of ΔI_S due to longitudinal phonons was found to be the same as at 9.3×10^9 cps, but the values of V_{eq}^2 were down by approximately one order of magnitude. This again agrees with Eq. (3).

The experimental results for shear waves cannot be explained on the basis of the above simple model. It is thought that the different behavior due to transverse phonons arises from the magnetic field associated with the shear wave. According to the calculations of Cullen and Ferrell,[7] at microwave frequencies this magnetic field is not screened out effectively by the Meissner effect.

Lax and Vernon[2] performed measurements similar to ours using a microwave signal modulated at 10^3 cps. The value they report for V_{eq}^2 at an acoustic power level of 0.1 mW is 25×10^{-10} V^2. The value of V_{eq}^2 determined from our measurements, for the same acoustic power, is 1.6×10^{-10} V^2, more than one order of magnitude smaller. A likely explanation for this discrepancy lies in the fact that the measurements of the above authors were performed using essentially cw microwaves, and thus their observed ΔI_A may have been dominated by the microwave leakage effect[8] described previously. It seems reasonable that the microwave leakage effects were the same in both experiments since the experimental configuration used by Lax and Vernon[9] was very similar to ours. The bias dependence[1] of such a photon-assisted tunneling is the same as that of ΔI_S due to longitudinal phonons, namely, proportional to d^2I/dV^2. This would also explain the discrepancy in the bias dependence of ΔI_S due to transverse phonons. Whereas Lax and Vernon[2] report a proportionality to d^2I/dV^2 for both longitudinal and transverse phonons, the present results for transverse phonons are markedly different.

We express our thanks to K. R. Keller for making the ultrasonic bonds and for his help with the microwave equipment, and to G. Weisbarth for the preparation of the tunnel diodes.

[1]Y. Goldstein and B. Abeles, Phys. Letters 14, 78 (1965); B. Abeles and Y. Goldstein, postdeadline paper presented at the meeting of The American Physical Society, Berkeley, California, December 1964.

[2]E. Lax and F. L. Vernon, Jr., Phys. Rev. Letters 14, 256 (1965); Bull. Am. Phys. Soc. 9, 713 (1964).

[3]H. E. Bömmel and K. Dransfeld, Phys. Rev. Letters 1, 234 (1958); Phys. Rev. 117, 1245 (1960).

[4]A. H. Dayem and R. J. Martin, Phys. Rev. Letters 8, 246 (1962).

[5]The thicknesses of the aluminum films were 500-600 Å, sufficiently thin to be superconducting above the bulk T_c. This is essentially in agreement with D. H. Douglass, Jr., and R. Meservey [Phys. Rev. 135, A19 (1964)], even though our transition temperatures were somewhat higher.

[6]The complex structure in dI/dV and d^2I/dV^2 results from multiple peaks in the density of states of lead. Similar structures were observed by P. Townsend and J. Sutton [Phys. Rev. Letters 11, 154 (1963)], and G. I. Rochlin and D. H. Douglass, Jr. [Bull. Am. Phys. Soc. 10, 46 (1965)].

[7]J. R. Cullen and R. A. Ferrell, Bull. Am. Phys. Soc. 10, 318 (1965).

[8]Lax and Vernon state that the possibility that their measured results were caused by electromagnetic leakage was eliminated by careful shielding of the sample. They also performed measurements on a tunnel diode deposited on top of an 1.5μ-thick superconducting shield. However, we determined experimentally that the radiation leaks via the hole through which the excitation rod is inserted into the cavity, and cannot be blocked even by a thick (1-2 μ) superconducting shield.

[9]E. Lax and F. L. Vernon, Bull. Am. Phys. Soc. 9, 713 (1964).