EVIDENCE FOR HOLE-TO-PHONON INTERACTION FROM TUNNELING MEASUREMENTS IN GaAs-Pb JUNCTIONS

D. C. Tsui
Bell Telephone Laboratories, Murray Hill, New Jersey
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Structure in d^2I/dV^2 symmetrical about zero bias is observed in p-type GaAs-Pb junctions at bias energies equal to the transverse optical phonon energy of bulk GaAs. This is interpreted as due to hole–TO-phonon interaction through a deformation potential coupling in bulk GaAs.

Previous studies of metal-semiconductor tunnel junctions have shown that the interaction of tunneling carriers with longitudinal optical (LO) phonons in the bulk-semiconductor electrode gives rise to symmetrical structure in d^2I/dV^2 at bias energies equal to zone-center, LO-phonon energy ($eV \simeq \pm \hbar\omega_{LO}$).[1-4] Such structure was observed in p- and n-type GaAs[1] as well as p-type Si[2] and Ge.[4] In this Letter we report the first observation of additional but similar symmetrical d^2I/dV^2 structure in p-type degenerate GaAs-Pb junctions at bias energies equal to the transverse optical (TO) phonon energy of bulk GaAs. We interpret this as due to a deformation-potential interaction between the holes and TO-phonons in bulk p-type GaAs.

Single-crystal GaAs mechanically polished to an optical finish was first etched in a solution of 60% H_2SO_4, 20% H_2O_2, and 20% water by volume, and then insulated by collodion except for a narrow strip in the center of the sample. Cross strips of Pb about 2000 Å thick were evaporated on the sample in a vacuum of 2×10^{-6} mm Hg. First-derivative, second-derivative, and I-V curves were taken at liquid-He[4] temperatures using standard techniques.[5] Electron tunneling was assured by observing the superconducting characteristics of Pb.

In Fig. 1 the normalized conductance in the Pb phonon energy range of a typical junction at 1°K is compared with the normalized density of states in superconducting Pb determined from measurements with Pb-I-Pb junctions.[5] The structure due to Pb phonons in the data from GaAs-Pb junctions is not so sharp as that determined from the Pb-I-Pb junctions. However, the general agreement demonstrates that tunneling through a Schottky barrier can be used to probe fine structure in the density of states in superconductors. The normal metal-semiconductor tunneling characteristics were obtained by quenching the Pb superconductivity with a magnetic field of 5 kG. Our data on the background dynamical resistance (with Pb normal) are in qualitative agreement with those of Conley and Mahan on GaAs-Au junctions.[1] At zero bias, we observed a small resistance minimum of approximately 1-meV half-width superposed on the broad resistance maximum previously reported.[6,7] These zero-bias anomalies will be discussed elsewhere.

Figure 2 shows the d^2I/dV^2 signal from a p-type (Zn-doped) GaAs-Pb junction at 1°K with Pb superconducting. Two sets of strong symmetrical structure are seen: one set at the LO-phonon energy ($eV = 36.3$ meV) and the other set at the TO-phonon energy ($eV = 33.5$ meV).[8,9] The structure at LO-phonon energy has been seen in junctions made of both p- and n-type GaAs; the structure at TO-phonon energy has been seen only in p-type material. (The d^2I/dV^2 curve in n-type material is similar to that shown in Fig. 2 in all other respects.) The bias position of these peaks does not vary with carrier concentration over the range $5.0\times10^{18}/cm^3$ to $6.5\times10^{19}/cm^3$. The antisymmetrical structure below the sym-

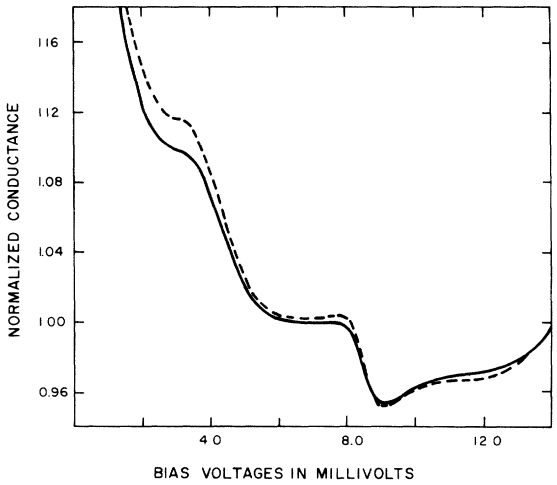

FIG. 1. Normalized conductance from a GaAs-Pb junction at 1°K versus bias energy measured from the Pb gap (solid curve). The dashed curve is the electronic density of states in superconducting Pb determined from tunneling measurements with Pb-I-Pb junctions taken from Ref. 5.

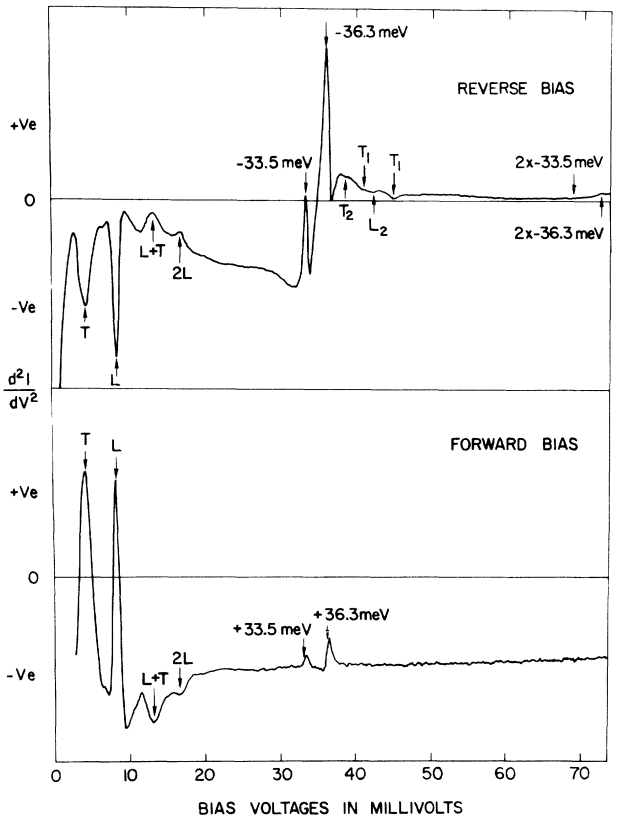

FIG. 2. d^2I/dV^2 signal from a p-type (Zn-doped) GaAs-Pb junction at 1°K. Bias energy is measured from the Pb gap. T and L indicate peaks due to the transverse and longitudinal structure in the superconducting density of states in Pb.

metrical peaks arises from the density of states of superconducting Pb.[10] When the Pb electrode is driven normal by a magnetic field, all of the antisymmetrical structure disappears and the symmetrical structure shifts its position in bias energy by the amount of the superconducting Pb gap. (The position of the symmetrical structure measured from the Pb gap remains unchanged.) We have not observed any other changes in these peaks with magnetic fields extending to 70 kG.

The main symmetrical peaks at $eV \simeq \pm \hbar\omega_{LO}$ were previously observed as abrupt changes in conductance in p-n junctions[8] and GaAs-Au contacts.[1] Conley and Mahan explained these peaks as resulting from electron–LO-phonon interactions through polar coupling.[1]

The second set of symmetrical peaks in Fig. 2, which are at the TO-phonon energy, results from the hole–TO-phonon interaction through a deformation-potential coupling in bulk GaAs. Further evidence supporting this explanation lies in the fact that these peaks are observed only in junctions made of p-type material. The absence of this structure in the d^2I/dV^2 curves from junctions made of n-type material indicates that this coupling is at least two orders of magnitude smaller in n-type than in p-type material. For a deformation-potential coupling, this selection rule is expected because of the different symmetry properties of the conduction-band wave function (s) from that of the valence-band wave function (p) near $k = 0$.[11,12] In the case of the carrier–LO-phonon interaction through polar coupling, which gives rise to the symmetrical structure at $eV \simeq \pm \hbar\omega_{LO}$ observed in both p- and n-type material, the symmetry properties of the carrier wave functions does not impose any selection rule.[13]

Recently, Davis and Duke[3] have calculated the influence of deformation-potential–coupled electron–optical-phonon interaction in one bulk electrode on the tunneling current in p-type silicon. The qualitative feature of their results, which are applicable to p-type GaAs, are in good agreement with our observation. In the weak-coupling limit, their results show symmetrical structure in d^2I/dV^2 at the optical-phonon energy. The slight asymmetry in energy positions in the two bias directions seen in Fig. 2 is also apparent in their results.

Additional weak structure above the strong symmetrical peaks is seen in reverse bias in Fig. 2. The peaks marked as T_1 and L_1 have been resolved in both bias directions. They are antisymmetrical about zero bias and disappear when the Pb electrode is in its normal state. The bias-energy positions of these peaks measured from the LO-phonon peaks are identical with those of the peaks from the transverse and longitudinal phonon structure in Pb measured from the Pb energy gap. They result from a reflection of the superconducting-Pb density of states at the main peak energies $eV \simeq \pm \hbar\omega_{LO}$.[14] The peaks marked by T_2 and L_2 are from the density of states of superconducting Pb reflected at $eV \simeq \hbar\omega_{TO}$. As far as we know, these results are the first observation of such an effect in tunneling spectroscopy. We also observed weak structure at twice the GaAs LO- and TO-phonon energies in the reverse-bias direction.

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DESTRUCTION OF SUPERCONDUCTIVITY BY A CURRENT

D. C. Baird
Department of Physics, Royal Military College, Kingston, Ontario, Canada

and

B. K. Mukherjee
Department of Physics, The University, St. Andrews, Fife, Scotland
(Received 19 August 1968)

We present a new model of the intermediate state in current-carrying superconductors. The model predicts a resistance transition which is in reasonable agreement with experimental values. An introductory treatment of secondary effects is also given.

When superconductivity in a wire is destroyed by a current, resistance returns in a manner different from that predicted by London,[1-4] and the consideration of secondary effects[5,6] does not account satisfactorily for the discrepancy. We present a treatment which gives the structure of the intermediate state, predicts a resistance transition in reasonable agreement with experimental observations, and enables the evaluation of secondary effects.

When the current in a superconducting wire reaches the value i_c at which the magnetic field at the surface has the critical value H_c, flux should start to penetrate the wire and create a series of normal regions along the wire. Throughout these regions the field must obviously be H_c or as close to H_c as possible. It follows that in the normal regions the variation of current density with radius r should ideally have the form

$$j(r) = (i_c/2\pi a)(l/r),$$

where a is the radius of the wire. However, it is not possible to find a finite structure which gives $H = H_c$ throughout the whole of the normal volumes, and the most important condition is obviously that $H = H_c$ at each normal-superconducting interface.

For a given boundary the potential distribution in one of the normal regions can be obtained by a numerical solution of Laplace's equation subject to the following boundary conditions: (i) V = constant on any s-n boundary and (ii) $\partial V/\partial r = 0$ at the surface of the wire. The current distribution, and hence the field distribution, can then be calculated from the potential distribution. Using trial and error methods, boundaries satisfying the field criterion mentioned above can be found for any given ratio of the wire radius a to the structure periodic length d, up to a limiting value $(a/d)_{\max} = 1.4$. The axial width of the normal regions at the center of the wire falls rapidly to zero as a/d approaches 1.4, thus making it impossible to find satisfactory boundaries for a/d larger than 1.4.

As has been pointed out by Shoenberg,[7] two mutually opposing criteria will determine the optimum value of a/d: (i) That throughout the normal region H be as close as possible to H_c. Quantitatively, this amounts to minimizing

$$e = \frac{H_c^2}{8\pi} V_n - \int_{V_n} \frac{H^2}{8\pi}\, dv$$