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$$F_{\pm}(0)=\int N_{\pm}(\epsilon)\frac{\partial f_{\pm}}{\partial \epsilon}d\epsilon,$$

or, for the parabolic band

$$F_{\pm}(0)=N_{\pm}(0)\left[1-\frac{\pi^2}{12}\left(\frac{k_BT}{\epsilon_{F\pm}}\right)^2+\cdots\right].$$

[13]More precisely, $vF(0)_{T=T_c}=1$. This condition is not satisfied in pure Pd where $vN(0)\simeq 0.9$. In Ni and Fe, $vF(0)$ may be greater than 1 below the Curie temperature. As can be easily shown, these details do not affect the qualitative features of our problem.

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EVIDENCE OF HOLE-OPTICAL-PHONON INTERACTION IN DEGENERATE SILICON IN TUNNELING MEASUREMENTS†

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Tunneling from a metal into degenerate p-type silicon exhibits peaks in d^2i/dV^2 at biases $eV=\pm\hbar\omega_0$, where $\hbar\omega_0$ is the $k=0$ optical-phonon energy of the semiconductor. It is suggested that these peaks reflect modifications in the bulk semiconductor states at energies $\hbar\omega_0$ above and below the Fermi energy arising from hole–optical-phonon interaction. An additional peak near the optical-phonon frequency, but well resolved from it, is identified with vibrations of the boron acceptor impurity.

Interaction of holes with optical phonons in the covalent group-IV semiconductors was originally inferred from analysis of the temperature dependence of the hole mobility[1,2] and has recently been more directly verified by observations of oscillatory photoconductivity[3] in germanium[4] and silicon.[5] In the present measurements of d^2i/dV^2 characteristics of metal-insulator-semiconductor tunnel junctions, formed using indium on degenerate p-type silicon, the interaction of holes and optical phonons at small wave vector k is clearly indicated by peaks occurring at values of the applied bias voltage V such that $eV=\pm\hbar\omega_0$, where $\hbar\omega_0$ is the optical phonon energy at $k=0$. The absence of strong zone-boundary phonon effects[6] is consistent with a direct tunneling process from the metal Fermi surface to a small Fermi surface in the semiconductor valence band at $k\cong 0$. The behavior at positive bias $eV=+\hbar\omega_0$, corresponding to a positive step in conductance, resembles that observed in direct tunneling situations in III-V semiconductors.[7,8] This was originally described as a threshold effect.[7] The companion peak in d^2i/dV^2, which we show in detail at negative bias $eV=-\hbar\omega_0$, corresponds to a decrease in conductance and thus is of the wrong sign for a threshold effect. This leads us to suggest the possibility that both peaks should be interpreted in terms of modifications in the bulk semiconductor states at $E=\pm\hbar\omega_0$, resulting from phonon coupling.

Small-area indium-silicon junctions were formed on cleaved ⟨111⟩ faces of silicon single crystals containing 1.3×10^{20} cm^{-3} boron, corresponding to a free-carrier Fermi degeneracy μ of 160 meV, assuming a density-of-states mass of 0.58. Small bars ($2\times4\times10$ mm^3), having ⟨111⟩ axis, were completely nickel plated[9] and Ohmic return contacts and leads attached. The bars were then clamped, scribed with a diamond, and fractured by application of a sharp bending force. Inspection of the silicon faces showed that portions of each exposed the {111} cleavage plane.[10] Although such areas rarely exceeded 0.5 mm diam, this sufficed to locate the tunneling contact, 0.01 to 0.1 mm diam, formed by spring-loading against the cleaved face an indium wire freshly cut to a point using a cleaned razor blade mounted in a microtome. A force of 10 to 100 mg was applied to the point. These operations were performed in the air in about 10 min; absorption and/or oxidation on the surfaces are thought to produce a tunneling barrier of substantially lower transmission than the silicon depletion layer alone.[11] The extreme softness of the indium insures that local pressures under the contact do not appreciably exceed the average pressure of 0.1 to 1.0 kg/mm^2, and makes the assembled contact in its jig stable enough mechanically to permit mounting in an immersion Dewar system and cooling to 4.2°K or lower. The absence of heating or chemical treatment of the silicon surface in this scheme insures that the boron density is constant to within a few angstroms of the surface.

The tunneling configuration is taken such that at positive bias the metal Fermi level is raised relative to the semiconductor Fermi level. Electron energy in the semiconductor is measured from the Fermi level, so that the valence band edge occurs at $E=\mu=160$ meV. For positive bias V, final states for tunneling transitions from the metal lie in the valence band in the range $0<E\leq eV$. At negative bias, the

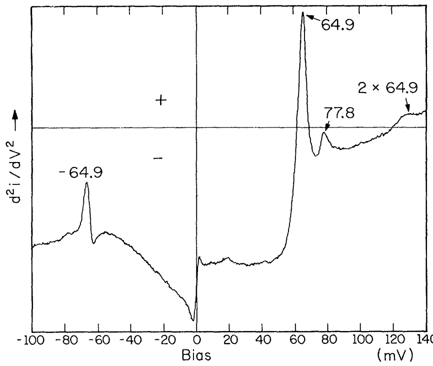

FIG. 1. d^2i/dV^2 spectrum for indium-p-type silicon (1.3×10^{20} cm^{-3} boron) tunnel junction at 4.2°K. Modulation level is 3 mV. Peaks (left to right) occur at −64.9(+), −60.7(−), −2(−), +2(+), +19.5(+), +64.9(+), +77.8(+), and +129(+), in millivolts.

process may be regarded as tunneling of holes into occupied ($E<0$) states in the valence band.

Second derivative spectra at 4.2 and 1.6°K are shown in Figs. 1 and 2, respectively. The main peaks occur at $V=\pm64.9\pm0.5$ mV, which is in excellent agreement with the value 64.8 mV obtained from Raman scattering[12] for the $k=0$ optical phonon in silicon. This structure has been observed in a sequence of five samples with reproducible energies and band shapes. Within an experimental accuracy of 0.1°K of the transition temperature of indium, 3.41°K, prominent superconducting structure appears in a millivolt range at $V=0$ (note reduced gain in Fig. 2 near $V=0$). In addition, structure clearly identifiable as (modulation-broadened)

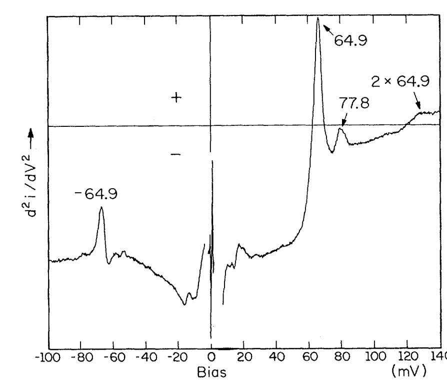

FIG. 2. d^2i/dV^2 spectrum for the sample of Fig. 1 as observed at 1.6°K. Modulation level is 4 mV peak-to-peak, except in center where it is 0.3 mV peak-to-peak. Differences between this curve and Fig. 1 in the range -20 mV $\leq V\leq 20$ mV are satisfactorily explained by the superconductivity of the indium, and are regarded as important justification for the techniques employed and for analysis of the spectra in terms of tunneling.

indium phonon structure[13] appears in Fig. 2 at approximately $V = \pm 15$ mV. These features are in reasonable agreement with published results for normal metal–superconducting-indium tunneling data and their appearance is taken as strong justification for the interpretation of the spectra shown in Figs. 1 and 2 in terms of tunneling.

The 77.8-mV peak present in both spectra agrees well in energy with the localized vibrational mode of boron in silicon, as observed in infrared absorption[14] in samples containing up to 1.3×10^{19} cm^{-3} boron. Since the strength of this peak relation to the 64.9-mV peak decreases rapidly as the boron concentration decreases, it seems clear that this peak is associated with the boron impurity. A corresponding peak at negative bias of -77.8 mV has not been seen. However, the signal-to-noise ratio was generally poorer at negative bias by virtue of a sharply rising conductance in this range. The zero-bias anomaly observed at 4.2°K corresponds to a minimum in conductance with full width of 4 mV between points of maximum slope. This structure is broader than the conductance maximum reported previously[15,16] in silicon p-n junctions at high doping, which we also observe at lower boron concentrations of 5×10^{19} cm^{-3} and 2×10^{19} cm^{-3}. The minimum shown in Fig. 1 is too narrow, on the other hand, to be explained as resulting from excitation of collective modes in the barrier.[16,17] Additional weak features in Fig. 1 are peaks at 19.5 and 128.6 mV identified as the transverse acoustic phonon at the zone boundary and twice the $k = 0$ phonon, respectively.

The prominent peak in d^2i/dV^2 at +64.9 mV corresponds to an increase (~10%) in conductance di/dV at this bias. Two possible lines of argument in explaining this are these: (a) 64.9 mV corresponds to the opening up, at a threshold for excitation of the barrier, of an additional channel for charge transfer.[18] (b) At the energy $E \cong \hbar\omega_0$, the tunneling current is altered as a result of the interaction of holes and optical phonons in the bulk. On the basis of the peak in d^2i/dV^2 at $+\hbar\omega_0$ alone, the data do not offer a means of discriminating between the two possibilities. However, the barrier threshold (a) as an explanation for the $eV = +\hbar\omega_0$ peak would imply also a threshold, and hence increase in conductance at negative bias $eV = -\hbar\omega_0$. This is contrary to what is observed, namely that the peak in d^2i/dV^2 at -64.9 mV is observed to be a decrease in conductance.

It is suggested that this may be explained by a deformation-potential–type interaction[1-5] of holes with the $k \cong 0$ optical phonon, resulting in a modification of the states in the bulk[19,8] at energies $E \cong \pm\hbar\omega_0$. The oscillatory photoconductivity experiments demonstrate that, as soon as a hole is energetically able to emit an optical phonon, it does so very rapidly.

The tunneling probability depends strongly on the wave vector k of the final state in the semiconductor, which in the absence of the phonon interaction is given by $E = \mu - \hbar^2k^2/2m$, with E positive in the forward direction, negative in the reverse. The conductance of the junction increases with increasing $|k|$ in the direction of reverse bias, and decreases as $|k|$ decreases in the direction of forward bias.[17] The effect of coupling with the optical phonons is indicated qualitatively in Fig. 3. Note that $|k|$ increases to the left. In the forward direction, k is decreased for E just below $\hbar\omega_0$ and increases for E just above $\hbar\omega_0$. Thus, there is a decrease in conductance as $eV = E$ approaches $\hbar\omega_0$ from below, followed by an increase for $eV > \hbar\omega_0$. In the reverse direction, the sharp decrease of $|k|$ for $|E|$ just greater than $\hbar\omega_0$ is associated with the decrease in conductance at $eV = -\hbar\omega_0$. Preliminary calculations by Duke and Davis[20] indicate that this model properly predicts the qualitative features of the data near $E = \pm\hbar\omega_0$.

The boron impurity peak probably results from a threshold effect associated with the barrier. The data do not rule out the possibility, however, of a bulk effect involving a phonon impurity band as has been reported for superconducting alloys.[21]

The author is indebted to John Bardeen, F. C. Brown, W. Dale Compton, and C. B. Duke for discussions of the experimental results and

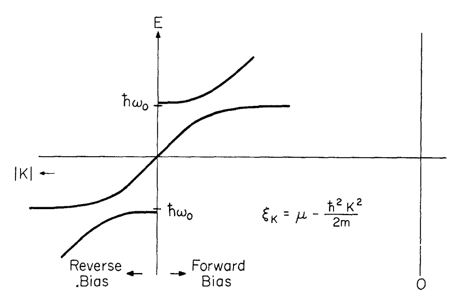

FIG. 3. Schematic representation of the electron-phonon dispersion relation indicating the effect of coupling at the longitudinal optical phonon energy $\pm\hbar\omega_0$.

for reading the manuscript; and in particular to Professor Bardeen and Professor Duke for extensive discussions of the interpretation of the results. It is a pleasure to thank Professor Compton, in addition, for his support, encouragement, and interest in all aspects of the work.

*Supported in part by the National Aeronautics and Space Administration under Grant No. NsG 228-62, and by the Joint Services Electronics Program, U. S. Army, Contract No. DAAB-07-67-C-0199.

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CIRCULARLY POLARIZED ULTRASONIC SHEAR WAVES IN METALS*

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Theoretical treatments[1,2] of the attenuation of ultrasonic shear waves propagating parallel to an external magnetic field in a pure metal usually assume propagation along a crystallographic axis of threefold or higher symmetry. Under this assumption, solutions of the equations of motion of the lattice are identifiable as right- and left-circularly polarized shear waves. This paper reports observation of the separate generation of these two modes.

Conventional ultrasonic techniques[3] employ piezoelectric transducers, which, being linearly polarized devices, produce equal mixtures of the two circular shear modes.[4] In propagating along a high-symmetry axis of a metal in the presence of a magnetic field, the right- and left-circularly polarized modes can suffer a relative phase shift as well as different attenuations (e.g., in the vicinity of a Kjeldaas absorbtion edge[5]) and recombine at the receiving transducer as an elliptical shear wave whose major axis has rotated from the plane of polarization of the generating transducer. Although the complications involved in attenuation measurements due to the presence of both modes have been studied to advantage by other workers,[6-8] attenuation measurements on a single circularly polarized wave generated by the technique described here should be more directly related to the theoretical results.

The generation technique used in this work utilizes the rf-ultrasonic coupling scheme which has been reported recently by Houck et al.[9] and Betjemann et al.,[10] and has also been discussed by Quinn.[11] Coupling takes place at the surface of a metal in the presence of an external magnetic field and is linearly proportional to the magnetic field strength.

In our experiment two identical pairs of Helm-