That part of the applied stress which is associated with a volume change affects the tunnel currents primarily through E_g and m^*, which appear in the exponents of Eqs. (1) and (2). The variations of these quantities with stress can be estimated from the known pressure coefficients of the band gaps.

The pure shear part of the stress causes the conduction band valleys to shift in energy with respect to one another in such a way that their average energy is unchanged. Therefore, for the shifts in valley energies to produce a current change which is linear in stress, it is necessary (a) that the degeneracy of the valleys be removed by shear, and (b) that the current contributions of the valleys which are raised in energy be unequal to the contributions from those which are lowered.

If the electric field is in a [100] direction, all (111) valleys have the same effective-mass component in the field direction. For such a diode an energy shift of the valleys should not produce a current change which is linear in shear stress.[11] If the electric field is in the [110] direction, however, two valleys (those along $[1\bar{1}1]$ and $[1\bar{1}\bar{1}]$) have reduced effective masses along the field direction $m_1^*=m_2^*=(1/m_{te}+1/m_h)^{-1}=0.027$ m_0; while the two other valleys (along [111] and $[11\bar{1}]$) have reduced effective masses $m_3^*=m_4^*=(1/3m_{te}+2/3m_{le}+1/m_h)^{-1}=0.034$ m_0, where m_{te}, m_{le}, and m_h are the principal electron masses and the light-hole mass, respectively. Even though these effective masses differ by only about 25%, the currents themselves will differ by a large factor because of the exponential dependence. In our samples, for example, the exponent is about equal to 17. This leads to a factor of 6 difference in the currents. Such a diode will exhibit a first-order stress coefficient for a shear which causes the similar valleys to move in the same direction. (On the other hand, a shear which raises one valley of each pair while lowering the other valley will have no first-order shear dependence.)

III. EXPERIMENTAL

Our experimental diodes were chosen so that they are as identical as possible except that one sample has the electric field along the [001] axis and the other along [110]. For both samples the uniaxial stress direction was $[1\bar{1}0]$. The samples were in the form of rectangular bars with the long dimension along $[1\bar{1}0]$ and the short dimensions along [110] and [001]. Two diodes were alloyed near the center of each bar on opposite faces. It was found to be necessary to do this because it was impossible to avoid flexing the bars slightly. Since flexure causes equal and opposite stresses on opposite faces, the average of the results obtained from these diodes is independent of flexure.

The starting material was pulled along the [110] axis from a melt containing 6% Sb by weight. After orientation by x rays, the crystal was cut into wafers. These wafers were reoriented and cut into bars with the long dimension along $[1\bar{1}0]$ and the short dimensions along [110] and [001]. From resistivity and Hall effect measurements, the Fermi level penetration of our samples was calculated to be $\zeta_n=0.020\pm0.002$ V. The diodes were formed by alloying indium dots doped with 3/8% gallium on the appropriate faces. Double contact wires were attached to the dots and the samples were etched to remove the perimeter of the junctions. (This was done because the perimeter has the wrong orientation.) The diameter of a typical diode dot was about 0.05 cm.

The Fermi level on the p-type side was estimated to be approximately 0.140 ± 0.020 eV. No direct measurements were made to confirm this estimate, but since none of our conclusions is sensitive to the choice of ζ_p, as long as $\zeta_p>\zeta_n$, the accuracy of the estimate is unimportant.

Uniaxial compressional stresses X varying between 5×10^7 and 5×10^8 dyn/cm^2 were applied parallel to the $[1\bar{1}0]$ direction at temperatures between 1.5 and 4.2°K. The stress tunneling coefficient defined as $\Pi=\Delta I/IX$ averaged over the two opposed diodes was found to be independent of stress and of temperature within these ranges. The stress tunneling coefficients were measured at fixed bias voltages. In order to minimize the effect of series resistances due to the leads and the sample, the bias was measured potentiometrically using one pair of the double contact wires attached to the diode and to an Ohmic contact in close proximity of the diodes while the current was passed through the other pair of contact wires. Liquid helium was used as the pressure transmitting fluid for the hydrostatic pressure measurements. These were extended up to $p=10^3$ psi.

Figure 1 shows the stress tunneling coefficient as a

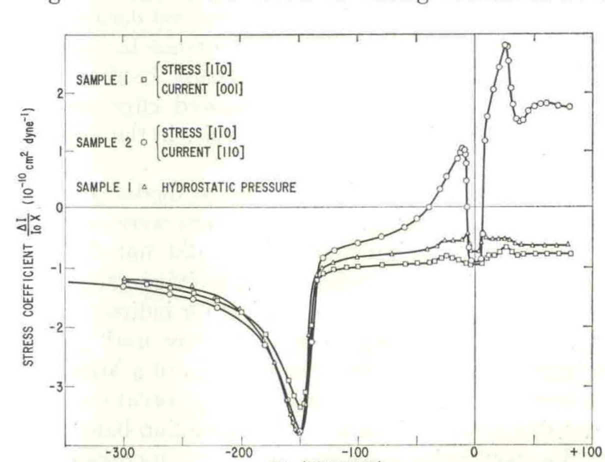

FIG. 1. Stress coefficients for uniaxial $[1\bar{1}0]$ compression and hydrostatic pressure as a function of bias voltage at 4.2°K.

[11] There is another mechanism by which shear can produce a first-order effect. In addition to a change in the valley energy, shear causes a deformation of the effective mass ellipsoids. Since tunneling depends only on the projection of the effective mass along the direction of tunneling, rather than an average over all directions, a linear effect occurs. This effect operates even when the valley in question is at a point of symmetry such that the valley energy cannot depend on shear.

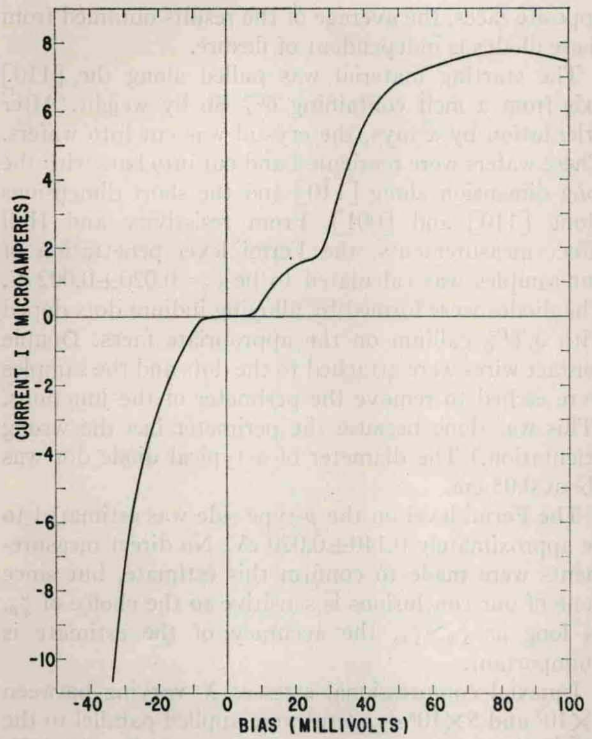

FIG. 2. Current-voltage characteristic of one diode of sample 2 at 4.2°K. Note the onsets of the *TA* and *LA* phonon contributions near the bias voltages ±8 and ±28 mV, respectively.

function of bias for the two samples. In sample 1 the diodes are on the (001) faces. This sample should, therefore, not respond to the shear induced shifts of the conduction band valleys. In sample 2 the diodes are on the (110) faces. The difference between these two curves is due mainly to the nonequivalence of the two pairs of valleys for tunneling in the [110] direction and the fact that the shear part of the applied stress causes these pairs to move in opposite directions.

The same figure shows the hydrostatic pressure coefficient of sample 1 at 4.2°K. In order to make a direct comparison with the uniaxial compression data possible $\Pi_p = \Delta I/I3p$ was plotted. The difference between the uniaxial and the hydrostatic pressure coefficients of sample 1 is due to the shear-induced effective mass changes of the electrons and light holes in the tunneling direction.

The *I-V* characteristic of one of the diodes of sample 2 is plotted on Fig. 2. The two diodes were so closely matched that their characteristics did not differ by more than 10% over the whole voltage range. The characteristic has the shape typical for indirect tunneling.[5] Only a very small current can flow until the bias is large enough to permit the emission of a low-energy phonon needed for wave number conservation in the tunneling process from a (111) conduction band valley to the (000) valence band. The current increases again when a higher energy phonon of the same wave number can be emitted. The phonons have been identified previously[5] as the *TA* and *LA* [111] phonons which have the energies 0.0076 and 0.028 eV, respectively.[12]

The *I-V* characteristic of the same diode is plotted on a different scale in Fig. 3 in order to show the rapid increase of the reverse current at a bias voltage of about -140 mV. This so-called Kane kink occurs[6] when the back bias is large enough to move the higher lying conduction band edge at $k=0$ on the *n*-type side below the Fermi level in the valence band on the *p*-type side, and thus, to allow a large direct tunneling current to flow. The relative position of the bands is shown schematically in Fig. 4 for a reverse bias beyond the Kane kink.

IV. INTERPRETATION

Comparing Figs. 1 and 2 one sees that the stress coefficients Π of the two samples differ greatly in the bias range of indirect tunneling, i.e., for $-135 < V < -8$ mV and $V > 8$ mV. We shall interpret this difference as being due to the shear induced shifts of the (111) valleys and the nonequivalence of the two pairs of valleys for tunneling in the [110] direction. In the small bias range $-8 \text{ mV} < V < +8$ mV a very small current flows. This must be due to a direct tunneling process since the energy difference between the Fermi levels on the *n*-type and *p*-type sides is too small for the emission of a phonon. Although the detailed nature of this direct tunnel current is not known, the relative magnitude of this component in Sb-, P-, and As-doped germanium tunnel diodes indicates[6] that the origin of this direct process is related to the impurity cell potentials of the *n*-type impurities.[13] The fact that the stress coefficients of the two samples are practically identical in this range indicates furthermore that this direct tunneling process cannot be associated with the density of states and the band edge energies of the individual (111) valleys.

As can be seen from Fig. 1, both samples exhibit a sharp rise in the stress coefficient at about 140-mV reverse bias. This effect is obviously associated with the onset of direct tunneling into the (000) conduction band. All three curves are nearly the same beyond the Kane kink. This one expects since the (111) valley contribution to the current is negligible in this range.

In the following we shall attempt a quantiative comparison between the experiments and Kane's theory.

[12] There is additional structure due to the optical phonons. Since this structure is small, we have treated the contribution of these phonons together with that of the higher energy acoustic phonon.

[13] The impurity cell potentials give rise to an admixture of (111) and (000) conduction band states to the wave function of a given electron and hence permit a fraction of the current to flow without phonon participation. Since these impurity cell potentials give rise also to the valley-orbit splittings of the 1*s*-like states of isolated Group V donor impurities one expects the relative strength of this phonon unassisted current for the different donor elements to correlate with the magnitude of this splitting. It may be misleading to refer to this process as direct tunneling since one is not dealing with an electron wave function characterized by the wave number $k=0$. We use the term only to denote that no phonons participate in the process.