Tunneling study of hole–TO-phonon interaction in GaAs and GaSb

D. C. Tsui
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 4 September 1973)

This paper describes an electron-tunneling experiment to study the nonpolar interaction of charged carriers with optical phonons in GaAs and GaSb. We have used GaAs-Pb and GaSb-Pb tunnel junctions and made direct observation of the selection rule, predicted by the deformation-potential theory, that only holes interact with TO phonons in these materials. The ratio of the strength of hole–optical-phonon interaction through the polar coupling to that through the nonpolar coupling is estimated to be approximately 7 for GaAs and 5 for GaSb, in samples having no free carriers to screen the polar interaction. The interaction of holes with two optical phonons has been observed in GaAs. Its strength is approximately 50 times less than that of the hole–optical-phonon interaction involving a single optical phonon.

I. INTRODUCTION

In a cubic semiconductor, the deformation-potential theory predicts selection rules for the nonpolar interaction of electrons or holes (carriers) with long-wavelength ($q \approx 0$) optical phonons.[1,2] In particular, this interaction vanishes for carriers whose energy band is s-like and has either an energy minimum at the center of the Brillouin zone, $k=0$, or siliconlike energy minima on the cubic axes. This symmetry requirement, which is satisfied by the conduction band of Si, is also satisfied by the conduction band of the direct-gap III-V compounds, e.g., GaAs, whose band minimum is at $k=0$. Although this theory of nonpolar optical-phonon scattering has been essential to our understanding of the temperature, as well as electric field, dependence of the mobility of carriers in Si and Ge, a direct experimental verification of this selection rule has not been possible from conventional transport measurements. Previously, we observed this selection rule in electron-tunneling measurements on GaAs-Pb junctions.[3] In this case, since the GaAs crystal is partially ionic, its optical phonons at $q \approx 0$ are split into a longitudinal-optical (LO) branch and a doubly degenerate transverse-optical (TO) branch, with the LO branch at the higher energy. The symmetry of the conduction band (s-like) and the valence band (p-like) of GaAs forbids the electrons to interact with either the LO or the TO phonons through nonpolar coupling. Only the interaction of holes with LO and TO phonons through nonpolar coupling is allowed. On the other hand, this symmetry of the energy bands imposes no selection rules for the polar coupling between both types of carriers and the LO phonons. Consequently, our observation of TO phonons in electron tunneling through p-type GaAs-Pb junctions, and not in the n-type GaAs-Pb junctions, constitutes a direct verification of the selection rule for nonpolar optical-phonon scattering predicted by the deformation-potential theory.

More recently, the importance of nonpolar scattering of carriers by optical phonons in III-V compounds has been reassessed as a result of two developments. First, it was often claimed that polar scattering by LO phonons is the dominant carrier scattering mechanism in determining the room-temperature carrier mobility of III-V compounds.[4] Wiley and DiDomenico[5] have pointed out that, while this is the case for electrons in direct-gap (at $k=0$) III-V compounds, this claim is not justified for electrons in indirect-gap materials and for holes. They demonstrated that the temperature dependence of the hole mobility of several III-V compounds can be explained by a combination of acoustical and nonpolar optical scattering alone, assuming no polar scattering, and concluded that the deformation-potential scattering by the acoustical and the optical phonons is the dominant scattering mechanism for holes in III-V compounds. Second, Kaplan, Ngai, and Henvis[6] have observed interactions of bound holes with TO as well as LO phonons in InSb in their magneto-optical measurements. Their experiment has led to studies of the deformation-potential theory of nonpolar optical-phonon scattering of carriers in the presence of an external magnetic field.

In this paper, we present a detailed account of our electron-tunneling data on GaAs-Pb junctions, which are pertinent to the nonpolar hole–optical-phonon interaction in III-V compounds. We also present similar results obtained from GaSb samples and include a brief discussion of an unsuccessful attempt on InSb samples. The experimental details are described in Sec. II and the results are discussed in Sec. III. Section IV gives a summary of this paper together with some concluding remarks.

II. EXPERIMENTAL DETAILS

The tunnel junctions are metal-semiconductor contacts made by evaporating Pb films on bulk single-crystal GaAs or GaSb samples. The sample is usually a $8 \times 5 \times 1$-mm platelet, with the flat surfaces parallel to a (111) or (100) crystallographic plane. The surface of the sample is prepared by first mechanically polishing it to an optical finish and then chemically etching it to remove mechanical damage. The etching removes approximately 100 μm of material and leaves a brightly polished surface, free of observable scratches. GaAs is etched in a freshly prepared solution of 1 part water, 1 part superoxol (30% hydrogen peroxide), and 3 parts concentrated sulfuric acid; GaSb is etched in a modified *CP*4 solution: 4 parts nitric acid, 2 parts acetic acid, and 1 part hydrofluoric acid. Immediately after etching, the sample is insulated by collodion, except for a strip in the center of the surface, and cross strips of Pb approximately 2000 Å thick and varying from 25 μm to 1 mm wide are evaporated on the sample in a vacuum of better than 2×10^{-6} Torr.

The measurements made on these junctions are their current-voltage (I-V), dV/dI-V, and d^2I/dV^2-V curves. The measuring method and the circuits used in this work have been described in detail by McMillan and Rowell[7] and by Thomas and Rowell.[8] We use the standard cross-strip configuration to facilitate four-terminal measurements and take special precautions to make sure that the contact resistance between the electrical leads and the electrodes of the junction is indeed negligible. A convenient method for making an Ohmic contact to a GaAs or GaSb sample, having carrier concentration n or $p > 10^{18}/\text{cm}^3$, is to solder indium to it with the aid of an ultrasonic vibrator. We also use indium to solder the electrical leads to the Pb films and to the Ohmic contacts on the semiconductor.

We utilize the well-known tunneling characteristics of superconducting Pb to evaluate the quality of these junctions[7] and adapt the following procedure for this purpose: Usually, we prepare five junctions on one sample. After the I-V characteristic of each junction is recorded at 300 and 78 °K, the sample is cooled to 4.2 °K and the junction I-V characteristic is examined again. If the superconducting energy gap of Pb is observed, the sample is cooled further to 1 °K and the current, at a bias much smaller than that corresponding to the Pb energy gap, $\Delta = 1.38$ meV, is measured. This excess current, which does not arise from electron tunneling, is compared to the current at the same bias when the Pb electrode is normal. Detailed measurements of dV/dI-V and d^2I/dV^2-V curves are made on those junctions whose excess current is approximately 0.05 to 1% of their normal-state current. All these junctions show the phonon-induced structure in the tunneling density of states of superconducting Pb, which agrees with that obtained from Pb-oxide–Pb junctions.[3] The data discussed in this paper are representative of these junctions. We note that all the GaAs-Pb junctions, which we have prepared following the procedure described above, show the superconducting Pb energy gap in their I-V curves and approximately half of them show $\lesssim 1\%$ excess current. In the case of GaSb-Pb junctions, however, only about 75% of all the junctions show the superconducting Pb energy gap at all, and approximately 20% of these junctions show $\lesssim 1\%$ excess current. It should also be noted that we have no direct information on the nature of the tunnel barrier of these junctions. From their fabrication procedure, it is reasonable to assume the barrier to be a thin layer of oxide and the surface-depletion layer of the semiconductor (Fig. 1). This assumption appears consistent with our having been able to detect reasonable resistance in junctions made on the most heavily doped samples ($p \sim 10^{20}/\text{cm}^3$) and with our observing only a weak temperature dependence in the resistance of these junctions despite the Schottky barriers being low for these p-type materials.[9]

III. RESULTS AND DISCUSSION

Before discussing results pertinent to the nonpolar optical-phonon interaction in GaAs and GaSb, we present in Fig. 2 the dV/dI-V curves of a p-GaAs–Pb junction (at 4.2 °K) and a p-GaSb–Pb junction (at 1 °K) to show some gross features of their tunneling characteristics. The I-V curves of the same p-GaSb–Pb junction at 1 °K is given in the insert to illustrate the superconducting energy gap of Pb and the excess current across the junction, which is approximately 0.5%. It is obvious that the dV/dI-V curve of either junction reaches a broad maximum in the Pb(−) bias. The carrier-concentration dependence of the bias position, V_m, of this maximum has been studied for

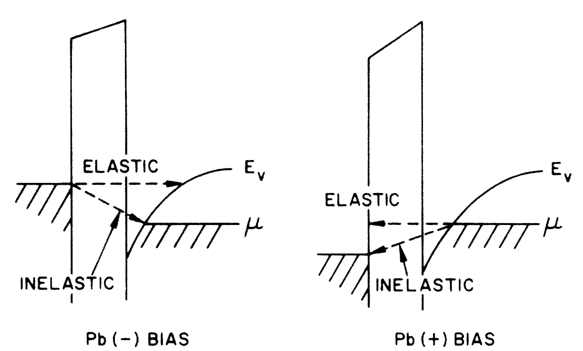

FIG. 1. Schematic potential-energy diagram for a p-type-semiconductor–Pb junction. In the Pb (−) (i.e., forward) bias, the inelastic tunneling path is shorter than the elastic tunneling path.

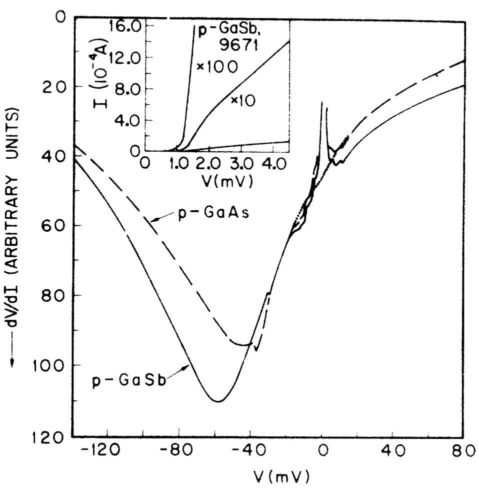

FIG. 2. dV/dI-V curves of a p-GaAs–Pb junction at 4.2 °K (dashed curve) and of a p-GaSb–Pb junction at 1 °K (solid curve). The dotted curve shows the dV/dI-V curve of the p-GaAs–Pb junction when the superconductivity of Pb is quenched by applying a magnetic field $H \approx 2.5$ kG. The hole concentration of the sample is p (GaAs) $= 2.5\times10^{19}/\text{cm}^3$ and p(GaSb) $= 1.4\times10^{19}/\text{cm}^3$. The insert shows the I-V characteristic of the same GaSb-Pb junction at 1 °K.

p-GaAs–Pb junctions using samples with hole concentration varying from $p = 5\times10^{18}/\text{cm}^3$ to $p = 1\times10^{20}/\text{cm}^3$.[10,11] It is found that V_m is at about 35 mV and has no observable dependence on p for $p \lesssim 2\times10^{19}/\text{cm}^3$. For samples having $p \gtrsim 2\times10^{19}/\text{cm}^3$, on the other hand, the relation $V_m \propto p^{2/3}$ is obeyed. In the case of p-GaSb, we have studied samples with $p = 1.4\times10^{19}/\text{cm}^3$, $3\times10^{19}/\text{cm}^3$ and $6\times10^{19}/\text{cm}^3$. For these samples, the carrier-concentration dependence of V_m again satisfies the $p^{2/3}$ relation.

The theoretical calculations of both the Schottky-barrier tunnel conductance by Conley, Duke, Mahan, and Tiemann[12] and the conductance of tunneling through a metal-insulator-semiconductor junction by Chang[13] and by Davis and Duke[14] predict a dV/dI maximum at a bias corresponding to the Fermi degeneracy μ of the semiconductor. This maximum occurs in the metal (–) bias for a p-type semiconductor. If we assume that, in this case, V_m observed in junctions made on the more heavily doped samples is equal to μ, and using the relation between μ and p from the parabolic band model,

$$\mu = (\hbar^2/2m_d^*)(3\pi p)^{2/3}, \tag{1}$$

we obtain an effective density-of-states mass $m_d^* = (0.6\pm0.1)m_0$ for p-GaAs and $m_d^* = (0.35\pm0.05)\times m_0$ for p-GaSb. On the other hand, the effective mass of the heavy hole and the light hole is known to be $m_h^* = 0.48m_0$ and $m_l^* = 0.09m_0$ for GaAs and $m_h^* = 0.35m_0$ and $m_l^* = 0.05m_0$ for GaSb.[15] The effective density-of-states mass, obtained from the parabolic band model using these values for the effective mass of the heavy and the light holes, is $m_d^* = 0.50m_0$ for GaAs and $m_d^* = 0.36m_0$ for GaSb, which agree well with those deduced from the tunneling data. In p-GaAs, the p independence of V_m for $p \lesssim 2\times10^{19}/\text{cm}^3$ has been attributed to the impurity band and the valence-band tailing.[10,11,16] We will see that, for $p \lesssim 2\times10^{19}/\text{cm}^3$, there is also an anomalous feature in the optical-phonon-induced tunneling structure of p-GaAs–Pb junctions.

A. GaAs

Figure 3 shows in detail the dV/dI and the d^2I/dV^2 curves of a p-GaAs–Pb junction (at 1 °K) in the bias range covering the enrgy of the optical phonons of GaAs. The hole concentration of the GaAs electrode, as measured by the Hall effect at 4.2 °K, is $p = 6.5\times10^{19}/\text{cm}^3$. It is known from previous studies that all the structure seen at $V < 30$ mV reflect the phonon-induced structure in the quasiparticle density of states of superconducting Pb.[3] In particular, it vanishes when the Pb electrode is driven into its normal state by the application of an external magnetic field ($H \approx 2.5$ kG).

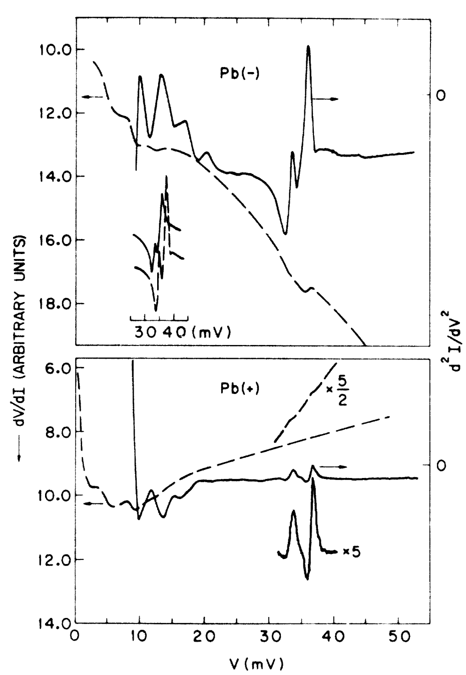

FIG. 3. The dV/dI-V (dashed curves) and d^2I/dV^2-V (solid curves) of a p-GaAs–Pb junction at 1 °K ($p = 6.5\times10^{19}/\text{cm}^3$). The insert shows the optical-phonon structure in the Pb (–) bias when the Pb electrode is superconducting (dashed curve) and when it is normal (solid curve). V is measured from the superconducting energy gap of Pb (Δ_{Pb}).

Our interest here is on the structure in the bias range from 30 to 40 mV. The more distinct features of this structure are the two d^2I/dV^2 peaks at $V = 33.5$ and 36.3 mV in the Pb(−) bias, and at $V = 33.9$ and 36.9 mV in the Pb(+) bias. These peaks correspond to sudden increases in conductance in the Pb(−) bias and sudden decreases in the Pb(+) bias. Such changes in conductance are in fact observable in the dV/dI curves of Fig. 3. When superconductivity of the Pb electrode is quenched by an external magnetic field, this structure decreases its bias position by an amount corresponding to the superconducting energy gap of Pb ($\Delta = 1.38$ meV) and reduces its sharpness. These changes are seen in the insert of Fig. 3, which shows this structure in the negative bias when Pb is normal (the solid curve) as well as superconducting (the dashed curve). The essential features of the structure are not altered when the Pb electrode becomes normal.

It is known from inelastic neutron scattering[17] and from optical studies[18] that the energies of the long-wavelength TO and LO phonons in GaAs are $\hbar\omega_{TO} = 33.7$ meV and $\hbar\omega_{LO} = 36.5$ meV, respectively. A consideration of these energies makes it obvious that the two d^2I/dV^2 peaks seen in Fig. 3 must arise from the interactions of holes with these TO and LO phonons of GaAs. The selection rule on nonpolar electron–optical-phonon interaction imposed by the symmetry of the electronic states becomes evident when we compare this optical-phonon structure with that shown in Fig. 4, which is taken from an n-type-GaAs–Pb junction at 1.2 °K. The GaAs electrode of this junction has an electron concentration $n = 7.5\times10^{18}/\mathrm{cm}^3$. The structure at $V \approx 36$ mV was first observed in the dV/dI-V curves of n-GaAs–Au junctions by Conley and Mahan[19] and was explained by them as being due to the interaction of electrons with the LO phonons of GaAs through the polar coupling. The d^2I/dV^2-V curves make it clear that this LO-phonon structure begins at $V = 33$ mV and ends at $V = 38$ mV. The distinct feature is the peak at $V = +36.3$ mV and at $V = -37$ mV, which is indeed identical to the LO phonon peak observed in the p-type sample.[20] The weaker feature preceding this peak, which may be associated with the LO-phonon dispersion when free-carrier screening is taken into account, is also discernible in p-type samples. The major difference in this optical-phonon structure between the n- and p-type samples is the conspicuous absence of the TO-phonon peak in the data from n-type samples. As discussed in I, this difference constitutes a direct confirmation of the selection rule on the nonpolar electron–optical-phonon interaction predicted by the deformation-potential theory. We estimate from the sensitivity of our measurement that the TO-phonon peak, if present in the data from n-type samples, must be approximately two orders of magnitude smaller than that in the p-type samples.

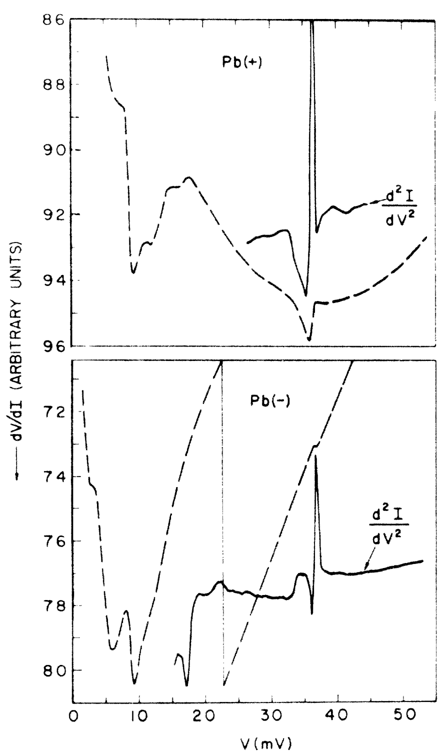

FIG. 4. The dV/dI-V (dashed curves) and the d^2I/dV^2-V (solid curves) of an n-GaAs–Pb junction at 1 °K ($n = 7.5\times10^{18}/\mathrm{cm}^3$). V is measured from Δ_{Pb}.

Figure 5 shows the d^2I/dV^2 data on this optical-phonon structure from four p-type samples to demonstrate the influence of hole concentration of the sample. In the Pb(−) bias, the relative strength of the TO- and the LO-phonon peaks shows no observable dependence on the hole concentration of the sample. In the Pb(+) bias, two effects have been observed. First, the TO-phonon peak, which is comparable to the LO-phonon peak for $p \approx 1\times10^{20}/\mathrm{cm}^3$, appears to decrease in strength with respect to the LO-phonon peak as p decreases. Second, a broad structure, which reaches a peak at $V \approx 32$ mV, becomes observable for $p \lesssim 2\times10^{19}/\mathrm{cm}^3$. For the sample having $p = 5.4\times10^{18}/\mathrm{cm}^3$, this structure becomes dominant and the TO-phonon peak is not discernible in this bias polarity.

There have been numerous theoretical papers on the electron-phonon interaction in tunneling between nonsuperconductors.[21] Here, we briefly reiterate some results as given by Appelbaum and Brinkman common to various recent formulations

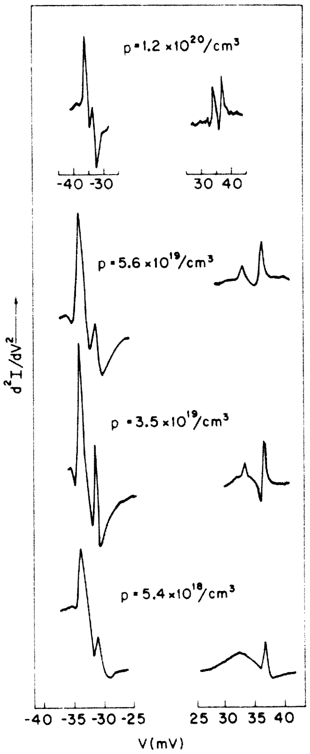

FIG. 5. d^2I/dV^2-V data on the optical-phonon structure from four p-GaAs–Pb junctions at 1 °K (V is measured from Δ_{Pb}). The amplitude of the modulation signal used to obtain the data in the two bias polarities is not the same.

of tunneling theory, to facilitate a qualitative understanding of our data. In recent literature, the electron-phonon interaction is described by an electron self-energy Σ, which is a complex quantity. Its imaginary part, $\mathrm{Im}\Sigma$, describes the phonon-emission lifetime of the electron; its real part, $\mathrm{Re}\Sigma$, is the energy which the electron acquires from the interaction. It has been shown that both $\mathrm{Im}\Sigma$ and $\mathrm{Re}\Sigma$ can alter the one-electron tunnel conductance of the junction at a bias corresponding to the energy of the phonon. If the bias dependence of the one-electron tunnel conductance is negligible, the contribution to the tunnel conductance from $\mathrm{Im}\Sigma$ is a step, even with respect to bias polarity, and the contribution from $\mathrm{Re}\Sigma$ is a logarithmic singularity, odd with respect to bias polarity. The magnitude and even the sign of these contributions depend most sensitively on the properties of the electron, the phonon, and their interaction in the immediate vicinity of the tunnel barrier. For example, if the interaction is localized in an electrode (i.e., in the electrode side of the electron's classical turning point), the contribution from $\mathrm{Im}\Sigma$ is a step decrease in conductance. On the other hand, if the interaction is in the tunnel barrier, this contribution is a step increase in conductance due to the opening up of inelastic channels for tunneling. It is clear that even if the bias dependence of the one-electron tunnel conductance is negligible, the phonon-induced changes in conductance, which is the sum of contributions from $\mathrm{Im}\Sigma$ and $\mathrm{Re}\Sigma$, can still assume a variety of line shapes in each bias polarity. At present, without any direct information on the interface properties of the tunnel junction, it is not possible to understand our data in any quantitative detail.

Several qualitative aspects of our data can be understood in terms of the general remarks made in the last paragraph. For example, the TO- and the LO-phonon peaks in the Pb(−) bias reflect step increases in conductance at the biases corresponding to the energy of the TO and LO phonons. This result can be interpreted as indicating that these peaks arise predominantly from inelastic tunneling of electrons with the emission of TO and LO phonons in the GaAs surface-depletion region immediate to the electron's classical turning point. Since free-carrier screening of the polar coupling between electrons and LO phonons has no effect on this emission process, we do not expect carrier-concentration dependence of these peaks. This expectation agrees with our observation that, in this bias polarity, the relative intensity of the TO- and the LO-phonon peaks are independent of the GaAs hole concentration. Moreover, the energy dependence of the width of the tunnel barrier, which is illustrated in Fig. 1, enhances inelastic tunneling of electrons from Pb into GaAs, for, in this bias polarity, the effective barrier seen by electrons tunneling inelastically through the barrier is narrower than that seen by the elastic tunneling electrons. On the other hand, this enhancement for inelastic tunneling does not exist in the Pb(+) bias, where the inelastic and the elastic tunneling electrons see the same barrier width (Fig. 1). The TO- and LO-phonon peaks in this bias polarity reflect step decreases in conductance at biases corresponding to energies slightly above those of the TO and the LO phonons. It appears reasonable to assume that the conductance contributions from $\mathrm{Im}\Sigma$ and $\mathrm{Re}\Sigma$ of holes interacting with the TO and the LO phonons in the GaAs electrode dominate these peaks. The observed hole-concentration dependence of their relative intensity may be attributed to free-carrier screening of the polar coupling, which must be operative in the electrode side of the electron's classical turning point.

Figure 6 shows that d^2I/dV^2-V curve of a p-GaAs–Pb junction for V ranging from 30 to 80 mV in the Pb(−) bias. The weak structure immediately following the LO-phonon peak, as pointed out previously,[3,22] results from the phonon-induced structure in the quasiparticle density of states of superconducting Pb, reflected from the emission thresholds of the GaAs TO and LO phonons. The arrows marked as (T_2, L_2) and (T_1, L_1) indicate the biases corresponding to the energy of transverse- and longitudinal-Pb-phonon peaks, measured from the GaAs TO- and LO-phonon peaks, respectively.

The weak structure near $V \approx 70$ mV is due to the interaction of holes with multiple optical phonons of GaAs. The arrows show the biases corresponding to the threshold energy for the emission of two TO phonons (2TO), one TO and one LO phonon (TO + LO), and two LO phonons (2LO). The 2LO and the 2TO peaks are approximately 50 times weaker than the LO- and TO-phonon peaks. This result indicates that the interaction of holes with two optical phonons is approximately 50 times weaker than that involving a single optical phonon.

We may also estimate the relative strength of hole–optical-phonon interactions through the polar coupling (P) and through the nonpolar coupling (N). If we recall that the observed LO-phonon peak results from both the polar and the nonpolar interactions and that $q \approx 0$ TO phonons are doubly degenerate, the strength of the polar and nonpolar interactions are related to the ratio (R) of the observed intensity of the LO-phonon peak to that of the TO-phonon peak by $P/N = 2R - 1$. We estimate $R \approx 4$ from the LO- and TO-phonon peaks in the Pb(−) bias (Fig. 3), and this result yields $P/N \approx 7$ for samples with no free carriers to screen the polar

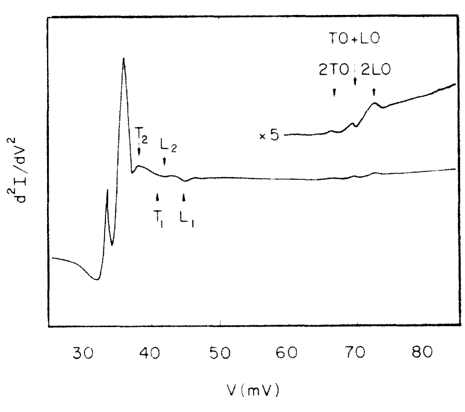

FIG. 6. d^2I/dV^2-V data (V is measured from Δ_{Pb}) in the Pb (−) bias of a p-GaAs–Pb junction at 1 °K ($p = 3 \times 10^{19}/cm^3$). ($T_2$, L_2) and (T_1, L_1) indicate the biases corresponding to the energy of the transverse and the longitudinal Pb phonon peaks, measured from the GaAs TO- and LO-phonon peaks. The arrows labeled 2TO, TO + LO, and 2LO indicate the biases corresponding to the threshold energy for emission of two TO, one TO and one LO, and 2LO phonons, respectively.

interaction. In a degenerate material, free-carrier screening will reduce the polar interaction. Our results on the relative intensity of the LO- and the TO-phonon peaks in the Pb(+) bias indicate that these two scattering mechanisms for holes in GaAs become comparable in samples having $p \gtrsim 10^{20}/cm^3$.

B. GaSb

We attempted similar experiments to observe the hole–TO-phonon interaction in two other direct gap (at $k = 0$) III-V compounds: GaSb and InSb. In the case of p-InSb, the best tunnel junctions, which we have fabricated using Pb as the counter-electrode, have approximately 7% excess current at 1 °K. The phonon-induced structure in the tunneling density of states of superconducting Pb, observed in these junctions, has approximately half its strength in the GaAs-Pb junctions. In the Pb(−) bias, the d^2I/dV^2 data show a broad peak (~ 2 mV half-width) at $V \approx 24$ mV, which must arise from the hole–LO-phonon interaction ($\hbar\omega_{LO} = 24.4$ meV[18]). We have not observed any d^2I/dV^2 structure which may be associated with the TO phonons ($\hbar\omega_{TO} = 22.8$ meV). We attribute our failure to observe the hole–TO-phonon interaction in InSb to the poor quality of our p-InSb–Pb junctions, as indicated by the tunneling characteristics of superconducting Pb in these junctions.

In the case of p-GaSb, we have fabricated p-GaSb–Pb junctions with less than 1% excess current and have observed the hole–TO-phonon interaction in these junctions. Figure 7 shows the dV/dI-V and d^2I/dV^2-V curves of a p-GaSb–Pb junction at 1 °K. In addition to the structure characteristic of superconducting Pb, these curves show a structure consisting of two peaks in the d^2I/dV^2-V data at $V = 28.5$ and 29.5 mV in the Pb(−) bias and at $V = 29.0$ and 30 mV in the Pb(+) bias. This structure must arise from the interaction of holes with the TO and LO phonons of GaSb, for it is known from optical studies that the energies of the TO and LO phonons are $\hbar\omega_{TO} = 28.5$ meV and $\hbar\omega_{LO} = 29.8$ meV.[18] We emphasize that while the LO-phonon peak has also been observed in n-GaSb–Pb junctions,[22,23] the TO-phonon peak has been observed only in junctions on p-type samples, consistent with the selection rule for nonpolar electron–optical-phonon interaction.

Our discussions on the optical-phonon structure in the data from p-GaAs can also be repeated here. For example, in the Pb(−) bias, the TO- and the LO-phonon peaks correspond to step increases in conductance at the energy of the TO and the LO phonons, and can be interpreted as being due to inelastic tunneling with the emission of TO and LO phonons in the GaSb surface-depletion region. We estimate the intensity of the LO-phonon peak to be approximately three times that of the TO-

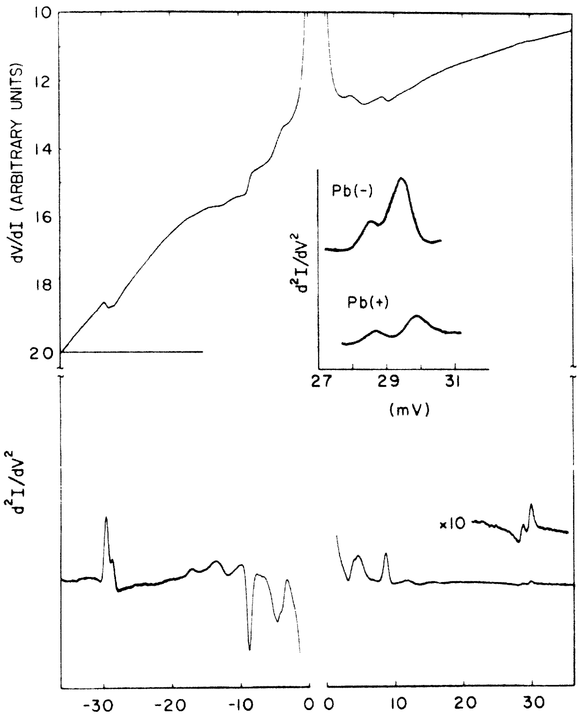

FIG. 7. The dV/dI-V and the d^2I/dV^2-V data of a p-GaSb–Pb junction at 1 °K ($p = 1.4\times10^{19}/\text{cm}^3$). V is measured from Δ_{Pb}.

phonon peak and obtain $P/N \approx 5$ for GaSb samples with no free carriers to screen the polar interaction.

In the Pb(+) bias, the TO- and the LO-phonon peaks correspond to step decreases in conductance at energies slightly above those of the TO and the LO phonons of GaSb. They may result from a combination of the conductance contributions from ImΣ and ReΣ of holes interacting with the TO and the LO phonons in the immediate vicinity of the electron's classical turning point in the GaSb electrode. We also examined the d^2I/dV^2 data in the bias range corresponding to the energy of two optical phonons and have not observed any structure which may be attributed to the interaction of holes with two optical phonons. We note that even in the best of our p-GaSb–Pb junctions, the junction noise does not allow the detection of a signal smaller than $\frac{1}{30}$ of the observed LO-phonon peak. In view of the weakness of the two-optical-phonon structure in p-GaAs, our failure to observe the two-optical-phonon structure in p-GaSb is to be expected.

IV. SUMMARY

This paper discusses an electron-tunneling experiment to study the nonpolar interaction of charged carriers with optical phonons in two direct-gap (at $k = 0$) III-V compounds: GaAs and GaSb. We used GaAs-Pb and GaSb-Pb tunnel junctions and made direct observation of the selection rule, predicted by the deformation-potential theory, that only holes in these materials interact with TO-phonons.

In the d^2I/dV^2-V data of p-GaAs–Pb and p-GaSb–Pb junctions, the optical-phonon-induced structure has peaks at biases corresponding to the energies of the TO and the LO phonons in the Pb(−) polarity and at slightly larger biases in the Pb(+) polarity. The peaks in the Pb(−) polarity are attributed to inelastic tunneling with the emission of TO and LO phonons at the surface-depletion layer of the semiconductor. We estimate that the ratio of the strength of hole–optical-phonon interaction through the polar coupling to that through the nonpolar coupling is approximately 7 for GaAs and approximately 5 for GaSb. The d^2I/dV^2 peaks in the Pb(−) polarity are attributed to a combination of the conductance contributions from ImΣ and ReΣ of holes interacting with the TO and the LO phonons in the immediate vicinity of the electron's classical turning point in the semiconductor electrode. The interaction of holes with two optical phonons has been observed in p-GaAs. Its strength is approximately 50 times weaker than the hole–optical-phonon interaction involving a single optical phonon.

Finally, we comment on two aspects of our results which need further investigation. First, the data from GaAs samples having $5\times10^{18}/\text{cm}^3 \lesssim p \lesssim 2\times10^{19}/\text{cm}^3$ show anomalous features. Namely, (i) V_m, the bias position of the junction resistance maximum, is independent of p, and (ii) a broad structure centered at $V \approx -32$ mV is observed in the d^2I/dV^2-V data. While the p independence of V_m has been attributed to the formation of an impurity band in these samples, the anomalous d^2I/dV^2 structure at $V \approx -32$ mV remains unexplained. Second, we have not attempted any quantitative account of either the line shape or the carrier-concentration dependence of the observed optical-phonon structure, for the lack of any direct information on the properties of the tunnel barrier of these junctions. In view of recent theoretical predictions that the phonon structure in nonsuperconducting tunneling is most sensitive to the interface properties of the tunnel junction, it is imperative to give future efforts to characterizing the tunnel barrier. It is hoped that a quantitative account of the observed phonon structure will also yield information on the lattice vibrational and the electronic properties in the immediate vicinity of the junctions.

ACKNOWLEDGMENTS

I am grateful to J. A. Appelbaum and J. M. Rowell for their interest in this work.

[1]H. Ehrenreich and A. W. Overhauser, Phys. Rev. 104, 331 (1956); H. Ehrenreich, Phys. Rev. 120, 1951 (1960).

[2]W. A. Harrison, Phys. Rev. 104, 1281 (1956).

[3]D. C. Tsui, Phys. Rev. Lett. 21, 994 (1968).

[4]See, for example, C. Hilsum, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. 1.

[5]J. D. Wiley and M. DiDomenico, Jr., Phys. Rev. B 2, 427 (1970).

[6]R. Kaplan, K. L. Ngai, and B. W. Henvis, Phys. Rev. Lett. 28, 1044 (1972); in *Proceedings of the Eleventh International Conference on the Physics Semiconductors, Warsaw, Poland*, 1972 (PWN-Polish Scientific Publishers, Warsaw, 1972).

[7]W. L. McMillan and J. M. Rowell, in *Superconductivity*, edited by R. D. Parks (Dekker, New York, 1969), Chap. 11.

[8]D. E. Thomas and J. M. Rowell, Rev. Sci. Instrum. 36, 1301 (1965).

[9]C. A. Mead and W. G. Spitzer, Phys. Rev. Lett. 10, 471 (1963).

[10]D. C. Tsui, J. Appl. Phys. 41, 2651 (1970).

[11]K. P. Abdurakhmanov, B. A. Kotov, N. M. Okuneva, E. L. Plachenova, and O. A. Usov, Fiz. Tverd. Tela. 14, 2581 (1972) [Sov. Phys.-Solid State 14, 2234 (1973)].

[12]J. W. Conley, C. B. Duke, G. D. Mahan, and J. J. Tiemann, Phys. Rev. 150, 466 (1966).

[13]L. L. Chang, J. Appl. Phys. 39, 1455 (1968).

[14]L. C. Davis and C. B. Duke, Phys. Rev. 184, 764 (1969).

[15]A. L. Mears and R. A. Stradling, J. Phys. C 4, 122 (1971); R. A. Stradling, Phys. Lett. 20, 217 (1966).

[16]G. D. Mahan and J. W. Conley, Appl. Phys. Lett. 11, 29 (1967).

[17]G. Dolling and J. L. T. Waugh, in *Lattice Dynamics*, edited by R. F. Wallis (Pergamon, New York, 1965).

[18]M. Hass, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1967), Vol. 3, p. 11, and the references there.

[19]J. W. Conley and G. D. Mahan, Phys. Rev. 161, 681 (1967).

[20]We note that the applied bias which reduces the electric field in the surface depletion layer (i.e., the forward bias) is the Pb (+) bias for n-type semiconductors and the Pb (−) bias for p-type semiconductors.

[21]See, for example, C. B. Duke, *Tunneling in Solids* (Academic, New York, 1969), Chaps. 6 and 7, for theories before 1969. More recent theories have been given by J. A. Appelbaum and W. F. Brinkman, Phys. Rev. 186, 464 (1969); Phys. Rev. B 2, 907 (1970); L. C. Davis, Phys. Rev. B 2, 1714 (1970); 2, 4943 (1970); C. Caroli, R. Combescot, P. Nozieres, and D. Saint-James, J. Phys. C 5, 21 (1972).

[22]M. Mikkor and W. C. Vassel, Phys. Rev. B 2, 1875 (1970).

[23]P. Guétin and G. Schreder, Phys. Rev. B 6, 3816 (1972).