PHYSICAL REVIEW B VOLUME 12, NUMBER 12 15 DECEMBER 1975

Landau-level spectra of conduction electrons at an InAs surface

D. C. Tsui
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 4 August 1974)

I report magneto-oscillatory effects in tunneling through InAs-oxide-Pb junctions, which reflect the Landau levels of conduction electrons near the InAs-oxide interface. These oscillatory effects, which have been observed in transverse as well as longitudinal magnetic fields, are understood in terms of a qualitative theoretical picture. From the longitudinal magneto-oscillations, we have obtained that the effective cyclotron mass $m_0^*/m = 0.0215 \pm 0.0005$ at the conduction-band edge and that, at energies within 400 meV above the band edge, it increases linearly with increasing energy at a rate of 1.2×10^{-4}/meV. This value of m_0^* is $\sim 7\%$ smaller than that obtained from cyclotron resonance and magneto-phonon experiments on bulk InAs. The transverse magneto-oscillations are identified with Landau levels of electrons whose cyclotron orbits graze the oxide potential barrier. The level broadening Γ, as deduced from the magnetic field dependence of the oscillation amplitude, corresponds to a relaxation time $\sim 10^{-14}$ sec. Within our experimental uncertainties, Γ increases linearly with increasing excitation energy.

I. INTRODUCTION

Chynoweth, Logan, and Wolff[1] first reported that, in the presence of a longitudinal magnetic field H, the tunnel current I of an InSb p-n junction oscillates as a function of $1/H$. They attributed their result to fluctuations in the density of states resulting from Landau quantization of the InSb conduction band. However, theoretical calculations by Haering and Adams[2] and Argyres[3] failed to produce this oscillatory effect and, subsequently, Haering and Miller[4] suggested quantum oscillations in the Fermi level of InSb as an alternative explanation. Several years later, Bernard *et al.*[5] reported similar magneto-oscillatory behavior in the direct interband tunneling in Ge. They observed oscillations in the tunnel current as a function of the longitudinal magnetic field H at fixed biases V and also as a function of V at fixed H. Their experiment demonstrated that these magneto-oscillations are indeed a "density-of-states" effect and not from quantum oscillations in the Fermi level of the semiconductor.

It has been known for many years that electron accumulation layers exist at InAs surfaces.[6] As an effort to apply electron-tunneling techniques to study quantized surface states in the accumulation layers of degenerate semiconductors,[7] we fabricated InAs-oxide-Pb tunnel junctions and made tunneling measurements on them at 4.2 °K. In previous publications, we discussed results on the quantized surface states[8] and only briefly reported the observation of magneto-oscillations arising from Landau quantization of conduction electrons in the InAs electrode.[9] These oscillations have been observed in transverse (H perpendicular to tunnel current) as well as longitudinal magnetic fields. Moreover, since magnetic quantization in the Pb electrode (which is a polycrystalline film) can be neglected, the observed magneto-oscillations measure directly the magnetic field dependence of Landau levels of electrons in the InAs electrode. In this paper, we present in greater detail additional data on these magneto-oscillatory effects and discuss them in relation to the structure of conduction-electron Landau levels at the InAs-oxide interface. At the present, we do not have a quantitative theory which explains all the magneto-oscillatory effects. However, all our observations can be qualitatively explained in terms of a theoretical picture discussed in Sec. II. In Sec. III, we discuss all the experimental data in terms of this qualitative theoretical picture, and a summary of this paper is given in Sec. IV.

II. MODEL

A. InAs-oxide-Pb junctions

Electron-tunneling measurements have yielded direct results on the accumulation layer at the InAs-oxide interface in InAs-oxide-Pb tunnel junctions.[8] Here, we give a brief description of the energy structure of this accumulation layer to facilitate subsequent discussions.

Figure 1 shows an energy diagram of an n-type InAs-oxide-Pb junction (at $V=0$) with an electron-accumulation layer at the InAs-oxide interface. E_c is the conduction-band edge in bulk InAs, and E_F is its Fermi level. We choose the z axis normal to the junction surface and measure energy from E_c (energy above E_c is positive). The one-dimensional potential well $U(z)$ associated with the accumulation layer results from downward bending of the InAs conduction band at the surface. Since

$U(z)$ is an attractive potential, the energy associated with the electronic motion normal to the surface, E_z, can be either positive or negative. For $E_z < 0$, the electronic motion normal to the surface is quantized and E_z takes on discrete values. Figure 1 illustrates the case for InAs samples having $n > 1\times 10^{17}/\text{cm}^3$, where only one quantum level E_0 is allowed. The continuum of states associated with the electronic motion parallel to the surface forms a two-dimensional (2D) energy band. E_0 is the band edge of this 2D subband. For $E_z > 0$ a continuum of values is allowed for E_z, and the electronic states form a three-dimensional (3D) conduction band, whose band edge is E_c. The wave functions for these conduction states[10,11] differ from those of bulk InAs only near the surface where $U(z)$ is appreciable. It can be seen from the classical picture that, because of $U(z)$, a conduction electron near the surface has a larger local velocity than those inside the bulk. In bulk InAs, $E_F > E_c$. Consequently, the 3D conduction band as well as the 2D surface subband are occupied at the InAs-oxide interface. In the rest of this paper, our discussions will be entirely on the properties of these 3D conduction electrons near the InAs-oxide interface.

B. Magneto-oscillatory effects

At present, we have no quantitative theory which explains all the magneto-oscillatory effects. All our observations, however, can be understood qualitatively as a band-edge effect. In the case of a 3D energy band, the band-edge effect in tunneling is weak and has only been observed in special cases when the tunneling probability near the band edge enhances the effect.[12,13] In the presence of a magnetic field, the electronic motion normal to the magnetic field is quantized and the energy band breaks up into Landau subbands. When the Fermi level in the Pb electrode is moved (by changing the applied bias) across the band edge of a Landau subband, the tunnel conductance shows a structure reflecting this band edge. The strength and the line shape of this structure will depend on the electron tunneling probability near the subband band edge, which is determined by the tailing of the electron wave function into the oxide barrier.

In the case of a longitudinal magnetic field, Bar'yakhtar and Makarov[14] and also Kulik and Gogadze[15] have shown the existence of an oscillatory component in the tunnel current. Here, we give a qualitative theoretical picture to indicate the origin of this component. Since the longitudinal magnetic field does not alter the electronic motion in the direction of tunneling, the tunnel current density at $T=0$ is given by[12]

$$J(H,V)=C_H\sum_l\int_{E_F-eV}^{E_F}d\epsilon\, P(\epsilon,l,eV), \tag{1}$$

where l is the Landau quantum number for conduction electrons in InAs, P is the electron-tunneling probability, and $C_H=2e^2H/h^2c$. The tunnel conductance ($G\equiv dJ/dV$) at V is given by

$$G(H,V)=C_H\sum_l P(\epsilon,l,eV)\Big|_{\epsilon=E_F-eV} +C_H\sum_l\int_{E_F-eV}^{E_F}d\epsilon\,\frac{\partial P}{\partial V}. \tag{2}$$

The second term in Eq. (2) is due to the explicit bias dependence of the electron-tunneling probability. The existence of magneto-oscillatory effects in G can be demonstrated most simply by considering the first term on the right-hand side alone. In this case, the conductance at a bias V is given by the electron-tunneling probability in all the subbands at an energy eV away from the Fermi energy. When the bias is such that the Fermi level in Pb passes a subband band edge, G attains a singular structure (square-root singularity if a sharp-barrier approximation is used), and the resulting G-vs-V curve shows periodic structure. Inclusion of the second term on the right-hand side in (2) will change the strength and the phase of the oscillatory structure, but not its periodicity which measures the Landau-level separation, $\hbar\omega_c$ (ω_c is the cyclotron frequency, given by $\omega_c=eH/m^*c$, with m^* being the effective cyclotron mass).

In the experiment, the second derivative d^2I/dV^2 is usually recorded. The oscillations in d^2I/dV^2 can be described by

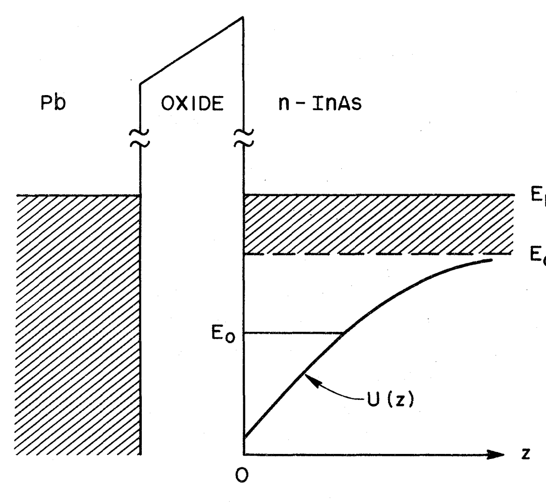

FIG. 1. Energy diagram of an n-type InAs-oxide-Pb tunnel junction at $V=0$ with an electron-accumulation layer at the InAs-oxide interface.

$$\frac{d^2I}{dV^2}=A\exp\left(-\frac{2\pi\Gamma}{\hbar\omega_c}\right)\cos 2\pi\left(\frac{eV}{\hbar\omega_c}+\Phi\right), \qquad (3)$$

where A is a constant independent of the magnetic field, Φ is a phase factor, and Γ is a parameter characterizing the level broadening of the Landau levels. It turns out that Eq. (3) adequately describes our observations in both the transverse field geometry and the longitudinal field geometry.

In the case of a transverse magnetic field, the electronic motion along the direction of tunneling is quantized. However, at a given magnetic field, the cyclotron energy for a given Landau quantum number l depends on the location of the orbit center with respect to the oxide potential barrier.[16] In fact, the energy levels of electrons whose orbit centers are located at a distance less than their cyclotron radius away from the oxide barrier, form a continuum. Consequently, the electrons whose cyclotron orbits are far inside the sample have negligible tunneling probability and do not contribute to tunnel conductance. The electrons whose cyclotron orbits intersect the oxide barrier, though they have large tunneling probability, do not contribute to oscillatory tunnel conductance because their energy levels form a continuum. Therefore, only electrons whose cyclotron orbits graze the oxide barrier (skimming orbits) contribute to oscillatory conductance.

We note that two results follow from this model. First, the oscillatory component of the conductance is relatively small, since a fraction of tunneling electrons near the surface does not contribute to oscillations. Second, the oxide potential barrier will increase the quantum energy $\hbar\omega_c$ associated with the grazing orbits and increase the period of the oscillations. These results are in qualitative agreement with experimental observations discussed in Sec. III.

III. RESULTS AND DISCUSSION

The experimental details on fabricating InAs-oxide-Pb tunnel junctions and making tunneling measurements have been given elsewhere.[8] The data discussed here were taken on a large number of tunnel junctions fabricated on InAs samples having $n=5.5\times10^{17}/\text{cm}^3$ and some on $n=2.1\times10^{16}/\text{cm}^3$. Most of the data were taken on junctions fabricated on (111) oriented surfaces. We also studied junctions fabricated on (100) and on (110) oriented surfaces, and have not observed any differences.

A. Longitudinal field

Figure 2 shows two (dI/dV)-vs-V curves taken from a junction, fabricated on a (111) surface of InAs ($n=5.5\times10^{17}/\text{cm}^3$), at 4.2 °K. The dashed curve, taken with $H\sim 2$ kG to quench the superconductivity of Pb, is the zero-field normal-state conductance, which shows the weak structures that are due to Pb phonons ($\lesssim 10$ mV) and the LO phonons of InAs (~ 30 mV).[8] The solid curve was taken with $H=40$ kG, applied parallel to the tunnel current. In general, the conductance oscillations become discernible at $H\sim 25$ kG for samples having $n=5.5\times10^{17}/\text{cm}^3$ and at $H\sim 15$ kG for samples having $n=2.1\times10^{16}/\text{cm}^3$. The oscillation period, ΔV, which measures $\hbar\omega_c$ directly, increases linearly with increasing H and extrapolates to $\Delta V=0$ at $H=0$. This magnetic field dependence is demonstrated in Fig. 3, where the oscillation period at $V=-15$ mV (we follow the convention that V is the voltage applied to the Pb electrode) is plotted as a function of H. These data were taken on a sample having $n=2.1\times10^{16}/\text{cm}^3$. The slope of the straight line gives a direct measure of the effective cyclotron mass, $m^*/m=0.025$, at an energy $E=15$ meV above the Fermi level of InAs.

The use of second-derivative techniques has allowed the separation of the oscillatory components from the background conductance of the junction. Figure 4 shows the magneto-oscillations in d^2I/dV^2 vs V, taken at $T=4.2$ °K and $H=35$ kG. This sample ($n=5.5\times10^{17}/\text{cm}^3$) has a Fermi energy $E_F=98$ meV in bulk InAs and has a quantized surface state in the accumulation layer at 183 meV below E_F. The oscillations at $V>100$ mV are due to electrons in the $2D$ subband associated with this surface state. In addition, weak oscillations with long periods are resolved at large negative biases. These oscillations have been identified as due to oscillations in the self-consistent potential of the accumulation layer when a Landau level in the $2D$ subband is swept across E_F by changing V.[8] The dom-

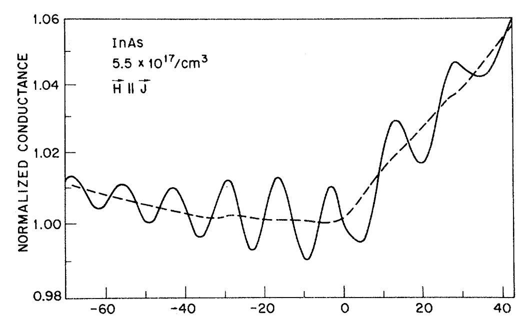

FIG. 2. (dI/dV)-vs-V data from an InAs-oxide-Pb junction at 4.2 °K. The tunnel junction was on a (111) surface of an InAs with $n=5.5\times10^{17}/\text{cm}^3$. The dashed curve was taken with $H\approx 2$ kG and the solid curve with $H=40$ kG applied perpendicular to the sample surface. The sign of V refers to that on the Pb electrode.

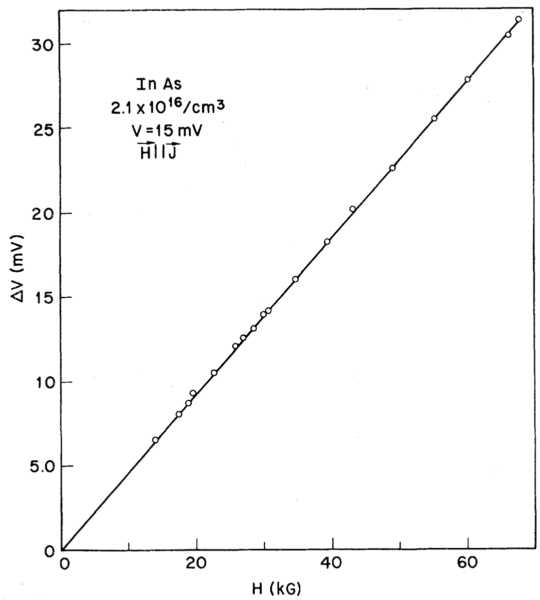

FIG. 3. Magnetic field dependence of the period of the oscillation in dI/dV vs V at $V=-15$ mV. The data were from a junction on a (111) surface of InAs with $n=2.1\times10^{16}/\text{cm}^3$ with H applied perpendicular to the surface.

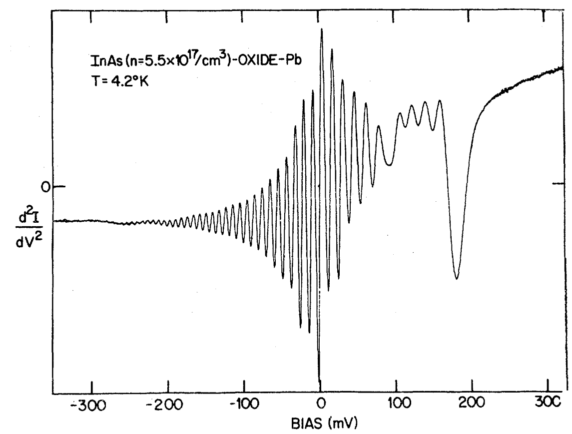

FIG. 4. d^2I/dV^2 vs V from an InAs($n=5.5\times10^{17}/\text{cm}^3$)-oxide-Pb junction at $H=35$ kG, applied perpendicular to the plane of the junction.

inant oscillations for $V\lesssim 100$ mV are due to the $3D$ conduction electrons at the InAs surface, and the apparent bias dependence of the oscillation period on V reflects the nonparabolicity of their energy structure.

From the data on magneto-oscillations in d^2I/dV^2 vs V, we are able to obtain m^* for electrons at energies within 400 meV above the conduction-band edge of InAs. Figure 5 shows these data. The dif-

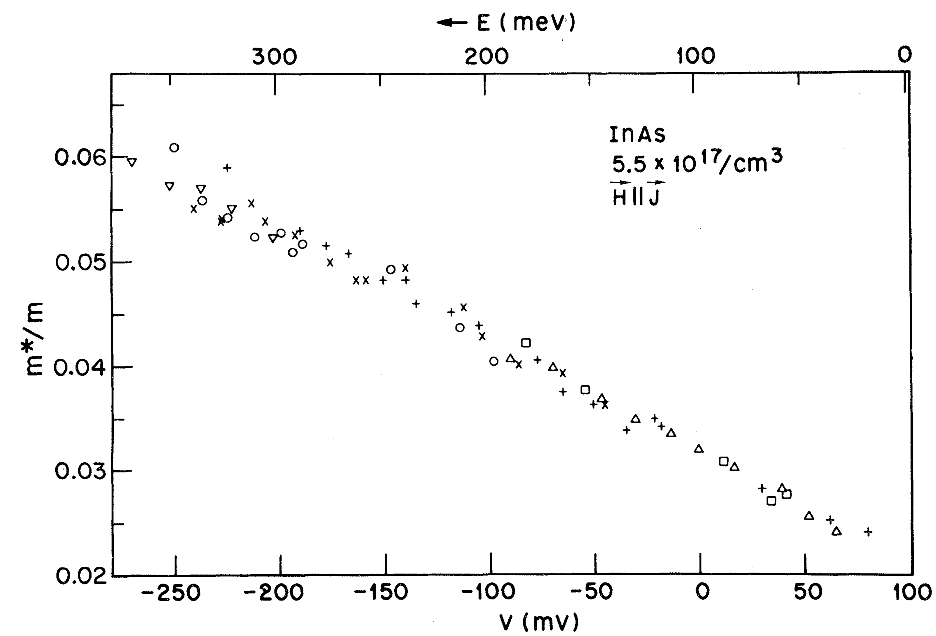

FIG. 5. m^*/m_0 vs V obtained from longitudinal magneto-oscillations in (d^2I/dV^2)-vs-V curves measured on InAs-oxide-Pb tunnel junctions.

ferent symbols designate data from different junctions all fabricated on InAs samples having $n = 5.5 \times 10^{17}/\text{cm}^3$. Data obtained from samples having $n = 2.1 \times 10^{16}/\text{cm}^3$ agree well with these data when the Fermi energies of the samples are correctly taken into account. It is clear from Fig. 5 that, within our experimental uncertainties, m^*/m increases linearly with energy at a rate of $\sim 1.2 \times 10^{-4}/\text{meV}$. An extrapolation of these data gives $m^*/m = 0.021$ at the conduction-band edge.

It is also apparent from discussions in Sec. II that if V is fixed, magneto-oscillations can be observed in (dI/dV)-vs-H or in (d^2I/dV^2)-vs-H curves. Figure 6 shows (d^2I/dV^2)vs-H data taken at $V = 0$. The oscillations, similar to those in the Shubnikov–de Haas effect and in the de Haas–van Alphen effect,[17] are periodic in $1/H$ (Fig. 7). The frequency F of these oscillations measures the k-space cross-sectional area A_k enclosed by the $k_z = 0$ (k_z is the electron wave vector along the magnetic field) cyclotron orbit at an energy $E = eV$. Using $A_k = (2\pi e/\hbar c)F$, we find that, at $V = 0$, $A_k = 1.93 \times 10^{13}\ \text{cm}^{-2}$ for the $n = 5.5 \times 10^{17}/\text{cm}^3$ sample, and $A_k = 2.8 \times 10^{12}\ \text{cm}^{-2}$ for the $n = 2.1 \times 10^{16}/\text{cm}^3$ sample. These values agree reasonably well with $A_k = 2.0 \times 10^{13}\ \text{cm}^{-2}$ for the $n = 5.5 \times 10^{17}/\text{cm}^3$ sample and $A_k = 2.3 \times 10^{12}\ \text{cm}^{-2}$ for $n = 2.1 \times 10^{16}/\text{cm}^2$ sample, calculated from n, using $A_k = \pi k_F^2 = \pi(3\pi^2 n)^{2/3}$.

In Fig. 8, we summarize the magneto-oscillatory data from one sample ($n = 5.5 \times 10^{17}/\text{cm}^3$) by plotting the bias position of dips in the d^2I/dV^2 oscillations as a function of H. The circles are from (d^2I/dV^2)-vs-V curves at fixed H, and the crosses are from (d^2I/dV^2)-vs-H curves at fixed V. The dip in a d^2I/dV^2 oscillation corresponds to a sudden increase in conductance when tunneling into a new Landau subband starts, and it can be identified as registering an event of the Pb Fermi level

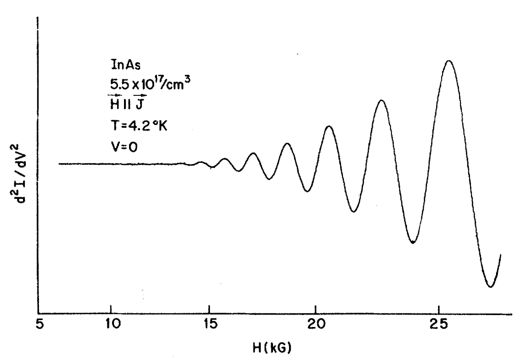

FIG. 6. d^2I/dV^2 vs H from an InAs($n = 5.5 \times 10^{17}/\text{cm}^3$)-oxide-Pb junction at $V = 0$ and $T = 4.2\ ^\circ\text{K}$. H was applied perpendicular to the surface.

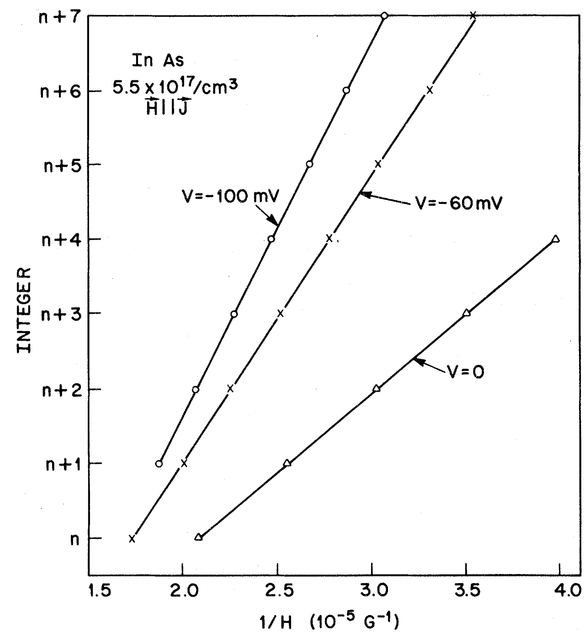

FIG. 7. Plots of the oscillation number vs $1/H$ obtained from (d^2I/dV^2)-vs-H curves.

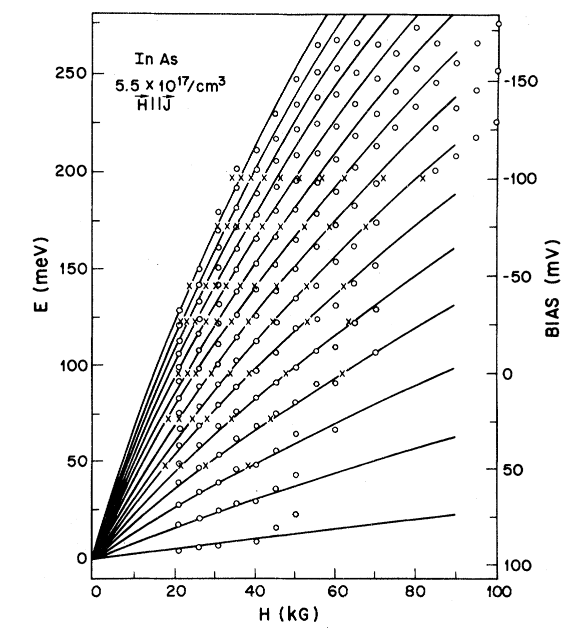

FIG. 8. Bias position of dips in d^2I/dV^2 oscillations as a function of H from an InAs($n = 5.5 \times 10^{17}/\text{cm}^3$)-oxide-Pb junction. The circles (O) are from d^2I/dV^2 vs V at fixed H, and the crosses (X) are from d^2I/dV^2 vs H at fixed V. The solid curves are the Landau levels calculated by using the Kane model.

being aligned with a Landau level in InAs. Consequently, its bias position measures the energy of the Landau level with respect to E_F in InAs, and the plot in Fig. 8 displays the magnetic field dependence of the various Landau levels of conduction electrons close to the InAs-oxide interface. This identification is physically and operationally simple, and also consistent with all our observations in this experiment and with the zero-field band-edge conductance structure predicted by Zavadil.[13] However, as noted earlier, the strength and the line shape of the conductance structure at a Landau level depends on the details of the electron wave functions near the InAs-oxide interface and also on lifetime broadening effects. When these effects are rigorously included, the position of the Landau level may not occur exactly at the dip of a d^2I/dV^2 oscillation. Thus, a quantitative estimate of the accuracy of this Landau level identification must await more rigorous theoretical calculations.

The solid curves in Fig. 8 show the Landau levels calculated by using the Kane model[18]:

$$\epsilon_l(H) = H\frac{e\hbar}{m_0^* c}(l+\tfrac{1}{2})\frac{\epsilon_g(\epsilon_g+\lambda)}{3\epsilon_g+2\lambda}\left(\frac{2}{\epsilon_l+\epsilon_g}+\frac{1}{\epsilon_l+\epsilon_g+\lambda}\right), \tag{4}$$

where ϵ_g, λ, and m_0^* are the direct energy gap, the spin-orbit gap, and the band-edge effective mass, respectively. The calculation was done using $\epsilon_g = 0.41$ eV and $\lambda = 0.38$ eV,[19] both well known for bulk InAs, and $m_0^* = 0.0215m$, as determined from the best fit of the resulting Landau levels to the experimental data. The fit (Fig. 8) is reasonably good for $E \lesssim 200$ meV, and its failure becomes more apparent at higher energies. The value of $m_0^* = (0.0215 \pm 0.0005)m$, as expected, agrees with that determined more directly from data in Fig. 5. It should be compared with the bulk value as determined from recent cyclotron-resonance experiments: $m_0^* = 0.024m$ (Ref. 20) and $m_0^* = (0.023 \pm 0.00003)m$ (Ref. 21) and from magnetophonon experiments: $m_0^* = 0.0240m$.[22] The difference (~ 7%) appears to be outside of experimental uncertainties.

In the case of a parabolic band model, it is apparent from our considerations in Sec. II that m_0^*, determined from the longitudinal magneto-oscillations, is characteristic of the electronic motion parallel to the surface and not altered by a one-dimensional potential $U(z)$. The surface effects, such as image forces owing to both the close proximity of the Pb electrode and the dielectric discontinuity at the InAs-oxide interface, and the coupling between electrons in the InAs and electrons in the Pb electrodes through the thin oxide, can also be represented by one-dimensional potentials depending on z alone and, therefore, have no effect on m_0^*. It should be interesting to see if this difference in m_0^* can be explained by such a simplified model of the surface effects when the nonparabolic nature of the InAs conduction band is properly taken into account.

B. Transverse field

The magneto-oscillatory effects observed in the transverse field geometry are illustrated in Figs. 9 and 10. These data were taken on an InAs-oxide-Pb junction whose InAs electrode has $n = 5.5\times10^{17}/\text{cm}^3$. In Fig. 9 the dI/dV curve taken at 55 kG is displaced 0.18 units upwards from the dI/dV curve at 2 kG for clarity. In all the junctions we have studied, the magneto-oscillations in the transverse field geometry are always weaker than that in the longitudinal field geometry. Usually, the amplitude of the transverse field conductance oscillations is approximately one-third that of the longitudinal field conductance oscillations. This observation is consistent with discussions in Sec. II that, in the transverse field geometry, the oscillations reflect Landau levels of electrons whose cyclotron orbits graze the oxide potential barrier. The fact that electrons whose cyclotron orbits intersect the oxide potential barrier do not contribute to oscillatory conductance makes the magneto-oscillatory effect weaker in this geometry.

Figure 11 shows m^*/m obtained from the oscillation period in (d^2I/dV^2)-vs-V curves. The energy dependence of m^*/m, within our experimental uncertainties, is the same as that for the longitudinal field geometry shown in Fig. 5. It increases linearly with increasing E at a rate of $\sim 1.2\times10^{-4}$/meV. At a given energy, however, m^*/m is a few

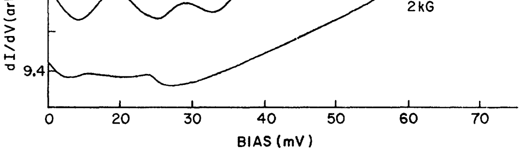

FIG. 9. Magneto-oscillations in dI/dV vs V and in d^2I/dV^2 vs V of an InAs($n = 5.5\times10^{17}/\text{cm}^3$)-oxide-Pb junction in a transverse magnetic field in Pb(−) bias. The dI/dV curve at 55 kG is displaced 0.18 units upwards from the dI/dV curve at 2 kG for clarity.

percent smaller than that for the longitudinal field case. This difference is expected because the presence of the oxide potential barrier increases the quantum energy $\hbar\omega_c$ of grazing orbits and thus decreases the effective cyclotron mass of electrons in these orbits.

In Fig. 12, the dips in the d^2I/dV^2 oscillations are plotted as a function of the transverse field. These data, which show the magnetic field dependence of the Landau levels of electrons having grazing orbits, were taken on the same sample on which the longitudinal field data in Fig. 8 were taken. The circles are data from oscillations in (d^2I/dV^2)-vs-V curves at constant H, and the triangles are from (d^2I/dV^2)-vs-H curves at constant V. The solid lines in this case are drawn through the data points which belong to the same Landau level.

C. Level broadening

We have found that the amplitude of the magneto-oscillations in both the longitudinal and the transverse fields can be satisfactorily described by Eq. (3). At a fixed V, the magnetic field dependence of the amplitude of d^2I/dV^2 oscillations follows $A_2 \propto \exp(-H_0/H)$. Some examples of this result are shown in Fig. 13, where A_2 is plotted as a function

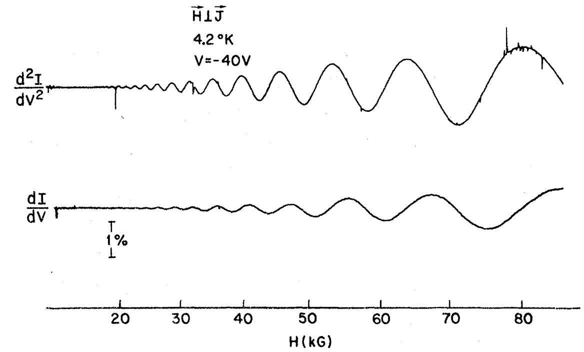

FIG. 10. Magneto-oscillations in dI/dV vs H and d^2I/dV^2 vs H of the junction of Fig. 9 at $V=-40$ mV. H was applied parallel to the plane of the junction.

of $1/H$. H_0, which determined the slope of the resulting straight lines, is related to the level-broadening parameter Γ through the relation $\Gamma = e\hbar H_0/2\pi m^* c$. For a sample having $n = 5.5\times10^{17}$/cm^3 and a dc mobility $\mu = 1.5\times10^4$ cm^2/V sec at 4.2 °K, Γ at the Fermi level deduced from the H dependence of magneto-oscillations at $V=0$ in the longitudinal field geometry is $\Gamma = 3.8$ meV. In the transverse field geometry, we expect the grazing

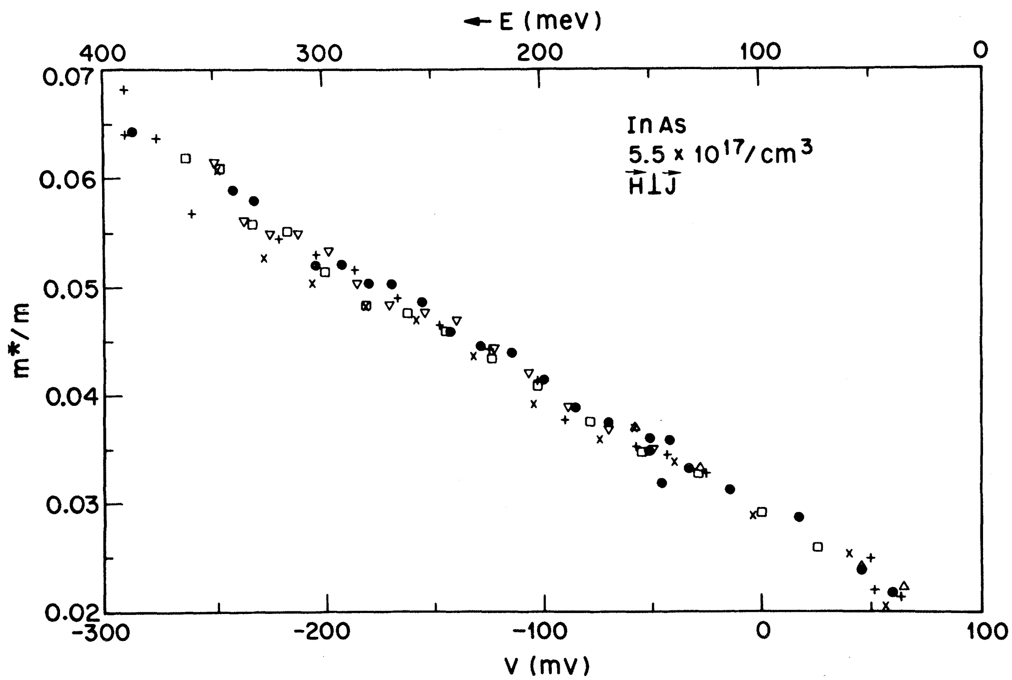

FIG. 11. m^*/m obtained from the period of oscillations in d^2I/dV^2 vs V from InAs($n = 5.5\times10^{17}$/cm^3)-oxide-Pb junctions in transverse magnetic fields.

orbits to be more sensitive to scattering centers at the InAs-oxide interface, and a larger value, $\Gamma = 5$ meV, was obtained. In both cases, Γ is considerably larger than that deduced from the dc mobility of bulk InAs through $\Gamma = e\hbar/2m^*\mu = 1.6$ meV. In view of the fact that the dc mobility is characteristic of the bulk material, the observation of a larger Γ in these tunneling measurements is reasonable.

The amplitude of the magneto-oscillations decreases with increasing V (Figs. 2, 4, and 9). This bias dependence reflects primarily the energy dependence of Γ, which is shown in Fig. 14 for the transverse field case. Similar energy dependence has been observed for Γ deduced from longitudinal magneto-oscillations at $V < 100$ mV. In this case, beating with oscillations from subband electrons makes analysis of the H dependence of A_2 unreliable at larger biases. It should be noted that the scattering time corresponding to the observed Γ ($\tau = \hbar/2\Gamma$) is $\sim 10^{-14}$ sec, which is much shorter than the characteristic times for energy relaxation through phonon emission ($\sim 10^{-8}$ sec for relaxation through acoustic-phonon emission[23] and $\sim 10^{-13}$ sec for LO-phonon emission[24]). Relaxation time for electron-electron scattering is not known. However, Γ due to electron-electron scattering should increase quadratically with increasing energy at low energies (i.e., $E < E_p$, with E_p being the plasma energy), and becomes essentially energy inde-

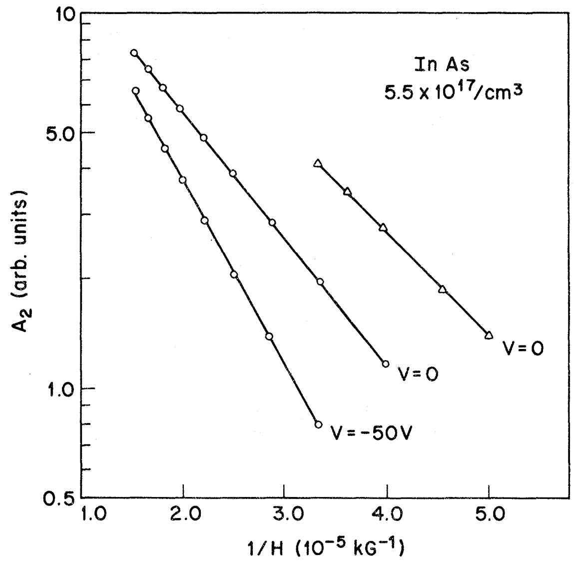

FIG. 13. Amplitude of oscillations in d^2I/dV^2 as a function of $1/H$ at fixed V. The longitudinal field data are shown as triangles (△) and the transverse field data as circles (○).

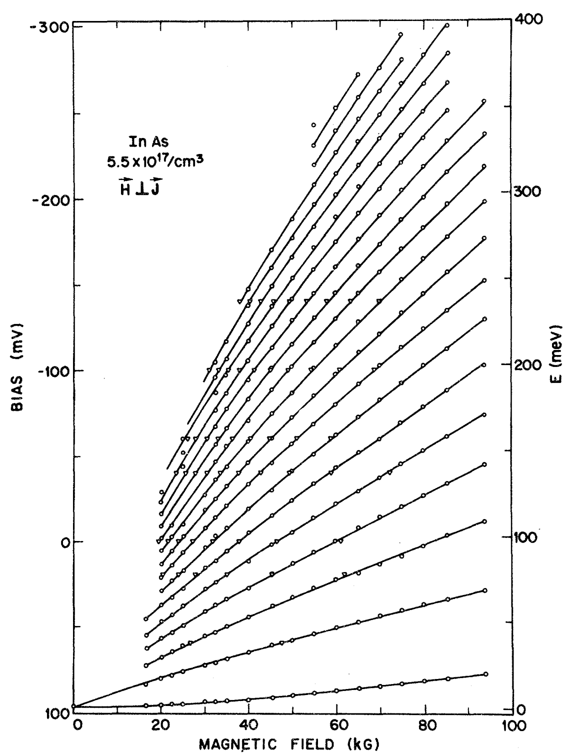

FIG. 12. Bias position of dips in the d^2I/dV^2 oscillations as a function of H, applied parallel to the plane of the junction, taken from the junction of Fig. 8.

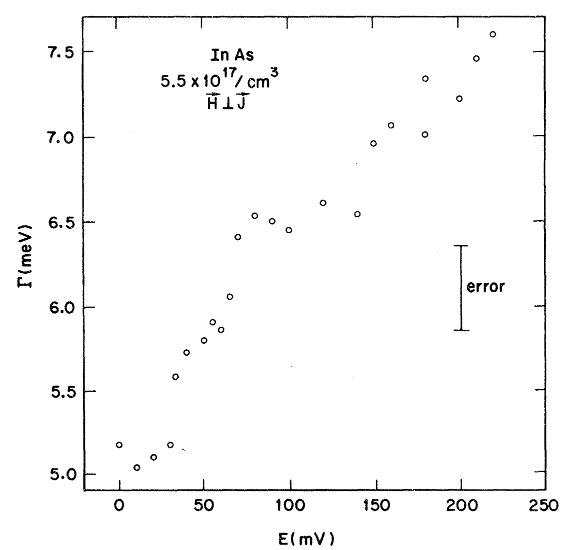

FIG. 14. Γ vs E. Γ is the level-broadening parameter deduced from H dependence of the amplitude of d^2I/dV^2 oscillations at fixed V and $E = eV$.

pendent at $E > E_p$.[25] In our sample, $E_p \sim 50$ meV. The observed energy dependence of Γ (Fig. 14) does not bear resemblance to that expected for electron-electron scattering and thus suggests that the observed scattering time is not limited by electron-electron scattering either. We believe that Γ deduced from the magnetic field dependence of the oscillation amplitude at V reflects the momentum relaxation time of an electron at $E = eV$ above E_F, and it is limited by scattering from impurities and imperfections of the InAs-oxide interface. Within our experimental uncertainties, Γ can be described as increasing linearly with increasing E. This energy dependence differs from that expected from the energy dependence (square-root) of the density of the final states into which the electron at $E = eV$ can be scattered. It appears to reflect some energy dependence of the scattering matrix as well.

IV. SUMMARY

We have described the magneto-oscillatory effects in tunneling through InAs-oxide-Pb junctions and deduced from them the structure of Landau levels of conduction electrons at the InAs-oxide interface. These oscillatory effects, which have been observed in transverse as well as longitudinal magnetic fields, are understood in terms of a qualitative theoretical picture. From the longitudinal magneto-oscillations, we have obtained that the effective cyclotron mass $m^*/m = 0.0215 \pm 0.0005$ at the conduction band edge and that, at energies within 400 meV above the band edge, it increases linearly with increasing energy at a rate of 1.2×10^{-4}/meV. This value of m_0^* is ~7% smaller than that obtained from cyclotron resonance and magnetophonon experiments on bulk InAs. The transverse magneto-oscillations are identified with Landau levels of electrons whose cyclotron orbits graze the oxide potential barrier. The level broadening, as deduced from the magnetic field dependence of the oscillation amplitude, corresponds to a scattering time ~10^{-14} sec. Within our experimental uncertainties, Γ increases linearly with increasing energy. The bias dependence of the magneto-oscillation amplitude is due to this energy dependence of Γ and the energy dependence of m^*.

This experiment, together with the earlier experiments by Chynoweth *et al.*[1] and by Bernard *et al.*,[5] have made it clear that electron tunneling can be a useful tool to study electronic properties related to Landau quantization of carriers in a semiconductor. However, two pertinent points should be emphasized here. First, the semiconductor, which forms at least one of the two electrodes of the tunnel junction, is required to be degenerate (or "metallic"). Second, tunneling electrons do not penetrate deep into the bulk electrode, and consequently this experimental tool probes excitations close to the tunnel barrier. These considerations also point out the limitations of using magneto-oscillatory effects in tunneling as a tool for semiconductor research. The condition that level broadening must be kept smaller than the separation between Landau levels at available magnetic fields requires relatively pure semiconductors which usually are not degenerate. In practice, this restricts our sample material to narrow-gap semiconductors, which in some cases can be made relatively pure and still degenerate. Moreover, after the tunnel junction is fabricated on the semiconductor, carriers close to the junction interface must retain their relatively long scattering times to give rise to distinct Landau levels. Thus, it is not surprising that magneto-oscillatory effects in tunneling have thus far been observed in only a few semiconductors.

ACKNOWLEDGMENTS

I am grateful to G. A. Baraff, J. M. Rowell, and T. M. Rice for many helpful discussions.

[1]A. G. Chynoweth, R. A. Logan, and P. A. Wolff, Phys. Rev. Lett. 5, 548 (1960).
[2]R. R. Haering and E. N. Adams, J. Phys. Chem. Solids 19, 9 (1961).
[3]P. N. Argyres, Phys. Rev. 126, 1386 (1962).
[4]R. R. Haering and P. B. Miller, Phys. Rev. Lett. 6, 269 (1961).
[5]W. Bernard, S. Goldstein, H. Roth, W. D. Straub, and J. D. Mulbern, Jr., Phys. Rev. 166, 785 (1968).
[6]C. A. Mead and W. G. Spitzer, Phys. Rev. Lett. 10, 471 (1963); T. E. Fischer, F. G. Allen, and G. W. Gobeli, Phys. Rev. 163, 703 (1967).
[7]D. C. Tsui, in *Proceedings of the Eleventh International Conference on the Physics of Semiconductors, Warsaw, 1972* (PWN-Polish Scientific Publisher, Warsaw, 1972), Vol. 1, p. 109.
[8]D. C. Tsui, Phys. Rev. B 4, 4458 (1971); B 8, 2657 (1973).
[9]D. C. Tsui, Solid State Commun. 8, 113 (1970).
[10]C. B. Duke, Phys. Rev. 159, 632 (1967).
[11]G. A. Baraff and J. A. Appelbaum, Phys. Rev. B 5, 475 (1972).
[12]C. B. Duke, *Tunneling in Solids* (Academic, New York, 1969), Sec. 7.
[13]J. Zavadil, Phys. Lett. A 43, 437 (1973).
[14]V. G. Bar'yakhtar and V. I. Makarov, Dokl. Akad. Nauk.

SSSR 1646, 63 (1962) [Sov. Phys.—Dokl. 7, 799 (1963)].
[15]I. O. Kulik and G. A. Gogadze, Zh. Eksp. Teor. Fiz. 44, 530 (1963) [Sov. Phys.—JETP 17, 361 (1963)].
[16]See, e.g., R. Vawter, Phys. Rev. 174, 749 (1968).
[17]See, for e.g., L. M. Roth and P. N. Argyres, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. I, Chap. 6.
[18]B. Lax, J. G. Mavroides, H. J. Zeiger, and R. J. Keyes, Phys. Rev. 122, 31 (1961).
[19]C. R. Pigeon, D. L. Mitchell, and R. N. Brown, Phys. Rev. 154, 737 (1967); C. R. Pigeon, S. H. Groves, and J. Feinlieb, Solid State Commun. 5, 677 (1967).
[20]E. D. Palik and J. R. Stevenson, Phys. Rev. 130, 1344 (1963).
[21]C. W. Litton, R. B. Dennis, and S. D. Smith, J. Phys. C 2, 2146 (1969).
[22]R. A. Stradling and R. A. Wood, J. Phys. C 3, L94 (1970).
[23]G. Bauer and H. Kahlert, Phys. Rev. B 5, 566 (1972).
[24]D. C. Tsui, Phys. Rev. B 10, 5088 (1974).
[25]J. J. Quinn, Phys. Rev. B 126, 1453 (1962); L. Hedin and S. Lundquist, in *Solid State Physics*, edited by F. Seitz, D. Turnbull, and H. Ehrenreich (Academic, New York, 1972), Vol. 32, p. 93.