also obtained the Voigt effect using the above procedure. However, for more general application to semiconductors with heavier masses, it is desirable to modify the procedure. This is so because the phase shifts are less than $\pi/2$ for wavelengths for which the materials are transparent and for the available static magnetic fields. We again start with radiation polarized 45° to the magnetic field but now observe the major axis, the ratio of axes, and the orientation of the resultant elliptically polarized radiation due to double refraction for a fixed magnetic field and wavelength by rotating a linear polarizer before the detector.

Recently Gurevič et al.[4] have independently discussed magnetic double refraction properties of semiconductors which may be similar to those considered in the present Letter.

We gratefully acknowledge many informative discussions with Dr. R. F. Wallis of this Laboratory. We also acknowledge an interesting discussion concerning magneto-optic effects with Dr. R. A. Toupin.

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EFFECT OF LANDAU LEVELS UPON TUNNEL CURRENTS IN INDIUM ANTIMONIDE

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It has already been shown[1-3] that when a magnetic field, H, is applied to an InSb Esaki junction there is a reduction in the tunnel current due to the change in the tunnelling probability that arises primarily through the increase in the energy gap with H. An additional effect has now been observed at low temperatures, namely, an oscillation of the tunnel current with H.

The junctions used in this work were made by alloying pellets of 0.1% Cd in In into n-type InSb containing an average excess donor density of 10^{17} cm^{-3}. The excess acceptor concentration on the p side was estimated to be 10^{18} cm^{-3}. Results obtained from two junctions are described in this paper; one was an Esaki junction, the other a backwards diode. Although these junctions were made from the same crystal, it is believed that the well-known inhomogeneities in the donor concentration were responsible for the observed spread in the junction characteristics. Results basically similar to those described here were obtained with several other junctions.

Current-voltage characteristics taken at 4°K showed that as H was increased from zero to 85000 gauss, the tunnel current underwent an oscillation superimposed on the decrease of current noted previously. The oscillations were observed with $H \parallel E$, the junction field, and not with $H \perp E$. For more detailed studies, a constant current was passed through the junction and the potential drop across the junction was plotted continuously as a function of H on an X-Y recorder. (Plotting voltage was virtually equivalent to plotting current since the current was roughly proportional to the bias for small changes in the latter.) Figure 1 shows the results obtained with the Esaki junction at small

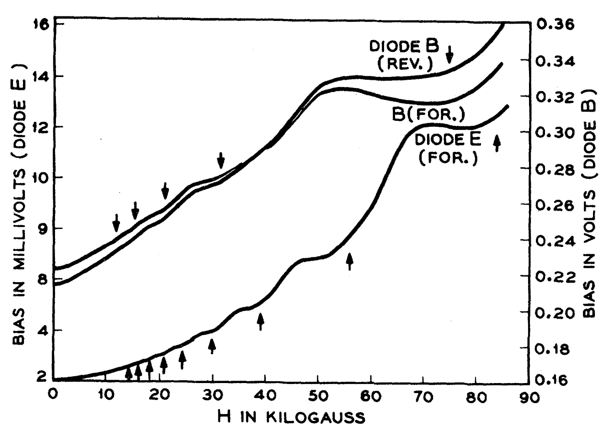

FIG. 1. The bias required to maintain a constant tunnel current as a function of magnetic field for two different junctions: Junction E was an Esaki diode; junction B was a backwards diode. The oscillations in bias are attributed to the Landau levels in the conduction band.

forward bias and with the backwards diode at larger biases, the forward bias being such as to operate the junction in the excess current range. It is apparent that as H increases, small voltage oscillations appear, that the amplitudes and field spacings of these oscillations increase with H, and that the oscillations are similar for both forward and reverse biases.

To establish whether the oscillations were caused by a series magnetoresistance effect, the location of the phonon-bump on the current-voltage characteristics was examined as a function of H using equipment[4] that automatically plotted (d^2I/dV^2) against V. At $H=0$ the phonon bump occurred at a forward bias of 24.5 ± 0.5 mv, in agreement with other measurements,[5] and it remained at this value to within 1.0 mv up to the highest values of H, thereby eliminating series resistance effects as the cause of the voltage fluctuations. This is in line with previous observations.[2]

It is possible to ascribe the oscillations to the oscillatory variation in the density of electrons available for tunnelling brought about by the Landau quantization in the conduction band on the n-type side. At low biases most of the tunnelling transitions are to and from energy levels located near the Fermi levels on both sides of the junction. For electrons and light holes the density of states at the Fermi surface is proportional to

$$\sum_n \frac{(2\epsilon_F+\epsilon_G)}{\{(\epsilon_F+\epsilon_G)\epsilon_F-\epsilon_G[(n+\frac{1}{2})\hbar\omega_c\pm\mu gH]\}^{1/2}}, \quad (1)$$

where ϵ_F is the Fermi energy, ϵ_G the energy gap, ω_c the cyclotron frequency, and μg the spin moment. This function has a sharp maximum whenever the bottom of a Landau sub-band crosses the Fermi level and thereby gives rise to fluctuations in the tunnel current.

Expression (1) predicts that if H^{-1} for the nth maximum is plotted against n, a straight line should result. Such plots are shown for the two junctions in Fig. 2 where it is apparent that very good straight lines are obtained. The slope of the line, which is proportional to $m^*\epsilon_F(\epsilon_F+\epsilon_G)/\epsilon_G$, is greater for the Esaki junction than for the backwards junction by a factor of 2.4. This ratio can also be estimated from the current densities of the two diodes. At small biases, the current density in the Esaki junction was 70 times that of the backwards diode so that the junction width constants differed by about 470 A whereas their average width was about 1440 A. Hence, the donor concentration for the Esaki junction was about 2.5 times that for the backward junction, thereby making the predicted ratio of the slopes about 1.9, in reasonable agreement with the observed value. The values of m^* derived from the two lines of Fig. 2 were equal to within ±5%, their average value of $0.011m_0$ being in reasonable agreement with other determinations of the electron mass at the bottom of the conduction band,[6] considering the uncertainties in the estimates of ϵ_F.

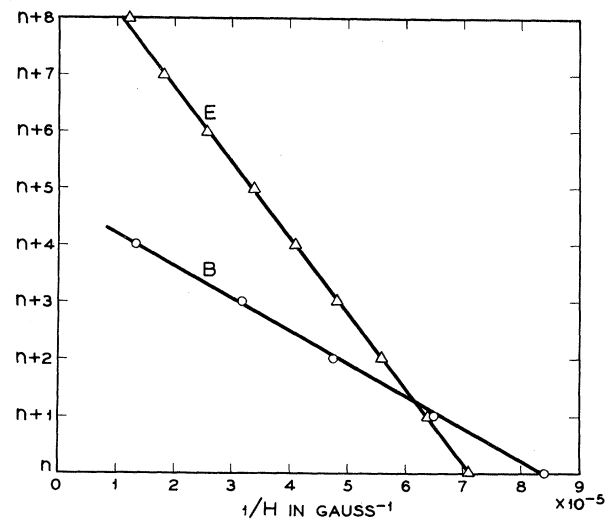

FIG. 2. Plots of the oscillation number versus H^{-1} derived from the curves of Fig. 1.

These data show that the oscillations in the tunnel current are due to fluctuations in level density of the Fermi surface in the n-type sides of the diodes only. It is important to realize that these current maxima [see Eq. (1)] are due to carriers whose energy is entirely transverse to the junction field. Thus the observation of oscillations indicates that an appreciable fraction of the tunnel current is carried by electrons whose velocity is, initially, perpendicular to the field. In electron-light hole tunnelling, this transverse energy must be conserved. From the known band structure of InSb, and noting that the Fermi energy on the n side (0.05 - 0.10 ev) is considerably greater than that (0.02 ev) on the p side, it is, therefore, impossible (in our junctions) for a carrier with entirely transverse energy to tunnel from the Fermi surface in the conduction band to the light-hole band. Thus, the observed oscillations must be due to electron-heavy hole tunnelling, in which case the selection rules are relaxed and the dependence of the amplitude of the oscillations on H will not be simple.

Some remarks can be made on the absence of a second component in the oscillations contributed by Landau levels in the valence band. Because of instrumental limitations, fields of 15 kgauss or more are required for the observation of the electron Landau levels. Hence, those for the heavy holes would require considerably higher fields. Another factor tending to obscure the Landau levels on the p side will be the greater scattering frequency due to the relatively greater impurity concentration. On the other hand, it might be possible, in principle, to detect oscillations in the tunnel current of electrons from well below the Fermi level in the conduction band to the Fermi surface in the light-hole band. However, these have not been observed, the probable reason being that at the fields at which oscillations can just be detected (~15 kgauss), the maximum energy of the light-hole band is already lower than the Fermi energy in the valence band.

In the case of $E \parallel H$, the infinite degeneracy of Landau states is responsible for the sharp peaks in the density of states. In the $E \perp H$ geometry, this degeneracy is broken since the energy of a Landau level now depends upon the position of the electron in the plane normal to H. Thus the density of states will vary with H in the perpendicular geometry, so accounting for the absence of oscillations.

The fact that, to within experimental error, the Landau spacings at the Fermi level in the conduction band determine the current oscillations at relatively high biases implies that the tunnel current is still dominated by transitions to or from states close to the Fermi level on the n side.

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LOW-TEMPERATURE TRANSPORT IN "SPLIT p-GERMANIUM"

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By measuring conductivity and Hall mobility of p-Ge at low temperature under large strains ($>10^{-3}$), we have been able to determine the sign, the ratio, and the approximate magnitude of the two deformation potentials that describe the change, under shear, of the valence band. In addition we have been able to verify that the velocity dependence of the hole-acceptor recombination cross section is independent of the acceptor ground-state energy over a limited range, in agreement with the prediction of the trap mechanism proposed by Lax.[1]

When germanium is subjected to a shear stress the valence band, normally 4-fold degenerate (including spin) at the Brillouin zone center, splits into two doubly degenerate bands separated by an energy $\delta\mathcal{E}$.[2-5] In a neighborhood within an energy $\ll \delta\mathcal{E}$ of each (new) band edge, the surfaces of constant energy are ellipsoids of revolution about the stress direction, and the effective masses are functions of the geometry of the strain, and not its magnitude.[2,3,5]

For a uniaxial stress χ in either the $\langle 100\rangle$ or $\langle 111\rangle$ directions, the splitting is given by

$$\delta\mathcal{E}_{100} = 2\Delta_{100} = 2S_{11}(1+\lambda)|b\chi| = 4S_{11}(1+\lambda)|D_u\chi|/3$$
$$= 2|b|\epsilon_{100} = 2.44\times10^{-12}|\chi b| \text{ ergs}, \quad (1a)$$

$$\delta\mathcal{E}_{111} = 2\Delta_{111} = \sqrt{3}S_{44}|d\chi|/3 = 2S_{44}|D_u'\chi|/3$$
$$= \sqrt{3}|d|\epsilon_{111}S_{44}/(S_{11}+2S_{12}+S_{44})$$
$$= 0.838\times10^{-12}|\chi d| \text{ ergs}, \quad (1b)$$

and $b = -2D_u/3$; $d = -2D_u'/\sqrt{3}$. Here b is the deformation potential constant (for hole energies) appropriate to a strain of tetragonal symmetry (with respect to the conventional cubic basis) as