Electrons and holes in InSb under crossed magnetic and stress fields. III. Magnetoreflection

B. Wolfstädter*
Physikalisches Institut, Universität Würzburg, D-8700 Würzburg, West Germany

H.-R. Trebin
Institut für Theoretische und Angewandte Physik, Universität Stuttgart, D-7000 Stuttgart 80, West Germany

H. Pascher
Physikalisches Institut, Universität Bayreuth, D-8580 Bayreuth, West Germany

H. G. Häfele
Physikalisches Institut, Universität Würzburg, D-8700 Würzburg, West Germany

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We have investigated the electronic interband transitions close to the band gap of InSb by observing magnetoreflectivity under uniaxial stress. The sensitivity of the experiment was increased by application of a magnetic-field-modulation technique. By this method we can resolve transitions from the conduction band to various valence-band Landau levels. The measurements were carried out with light polarized linearly along and perpendicular to the magnetic induction **B** (**E**$\|$**B** and **E**$\perp$**B**). In addition to well-known electric dipole resonances we observed new transitions induced by stress. These additional lines are connected with transition matrix elements which arise from lowering the symmetry. The observed transition energies are compared with band-structure calculations.

I. INTRODUCTION

The optical reflectivity of a semiconductor is, in general, modified by uniaxial stress.[1] The changes depend on the direction of stress, the Landau-level structure of the material, and the wavelength and polarization of light. They are most pronounced near the onset of the direct interband transitions and thus yield information about the levels involved. In InSb the valence-band Landau levels are anomalously spaced due to the degeneracy of heavy and light holes at $\mathbf{k}=0$.[2] By applying stress $T\|[100]$ and magnetic field $\mathbf{B}\|[001]$ the symmetry of InSb is lowered to C_2. In paper II of the current series of articles, this fact proved helpful in identifying optical transitions.[3] There, we explored interband transitions by optically pumped stimulated recombination radiation and measured the stress dependence of the valence-band levels 2V and 3V which carry oscillator and angular momentum quantum numbers $(0,\frac{1}{2})$ and $(0,-\frac{1}{2})$, respectively. Due to the different carrier occupation, in absorption other transitions are observed than in luminescence. But radiation with energy exceeding the fundamental gap is only transmitted by very thin samples which cannot be exposed to uniaxial stress. Therefore we decided to observe direct interband magnetooptical transitions using the reflection technique.[4]

II. EXPERIMENTAL TECHNIQUE

Reflection measurements are performed with photon energies, which differ only slightly from the gap energy of InSb. As a light source we used a liquid-nitrogen-cooled cw CO laser. A grating in the resonator made the laser emit one single vibration-rotation line. The sample was mounted in the Voigt configuration in the center of a split-coil superconducting magnet and was immersed in superfluid helium of 1.5 K.

The reflected radiation was detected with a cooled (77 K) Ge:Au detector. Because of the large dielectric constant the reflectivity of InSb is also very high (about 0.36) and is barely influenced by electronic interband transitions. To detect small changes caused by magnetooptical interband resonances it was necessary to apply a magnetic-field-modulation technique.[5,6] For this purpose an additional normal-conducting coil was fixed in the cryostat of the superconducting magnet, so that a sinus-shaped alternating field could be superposed to the static magnetic field. A modulation amplitude of 7×10^{-3} T proved suitable for our experiments. Only that part of the reflected radiation is measured which is produced by the periodic modulation of the magnetic field. It is separated by a lock-in amplifier, whose output is proportional to the first derivative of the reflectivity with respect to the magnetic field. Using constant laser frequencies this first derivative is recorded as a function of the magnetic field. By integration of the traces we recover the reflectivity.

Samples were cut from single crystals of p-doped InSb with carrier concentrations $p\leq10^{14}$ cm^{-3}. We used either cleaved surfaces or etched them by CP4.[7] It was found that the signal amplitudes strongly depend on the preparation of the sample surface.

III. EXPERIMENTAL RESULTS IN UNSTRESSED MATERIAL

For perpendicular incidence of the light the reflection coefficient is calculated as

$$R=\frac{(n-1)^2+\kappa^2}{(n+1)^2+\kappa^2} ,$$

where n is the real part and κ the imaginary part of the complex refractive index. κ changes resonantly in a magnetic field if the photon energy of the incident radiation coincides with the level spacing of an interband transition. Near the band gap there is a large dispersion. R as a function of B displays a dispersive line shape if the transition energy of an allowed interband transition is tuned through the fixed photon energy.[8] The resonant magnetic field can be taken from the point of inflection of this curve. In the measured first derivative this point shows up as a peak. Two typical recorder traces of dR/dB as a function of the magnetic field at constant laser frequency are presented in Fig. 1. In Fig. 1(a) the electric field vector **E** of the linearly polarized laser beam is parallel, in Fig. 1(b) perpendicular to the magnetic field **B**. Three sharp resonances corresponding to interband transitions appear in each trace. The shift caused by many-body interactions[9] between free carriers can be neglected, since we used p material with very small carrier densities and low sample temperatures. By means of the modulation technique we could resolve several transitions from valence-band levels near the edge to the $n=0$ and $n=1$ Landau levels of the conduction band with spin up or spin down, respectively. An identification of the different valence-band levels was possible by making use of the selection rules and the polarization characteristics.

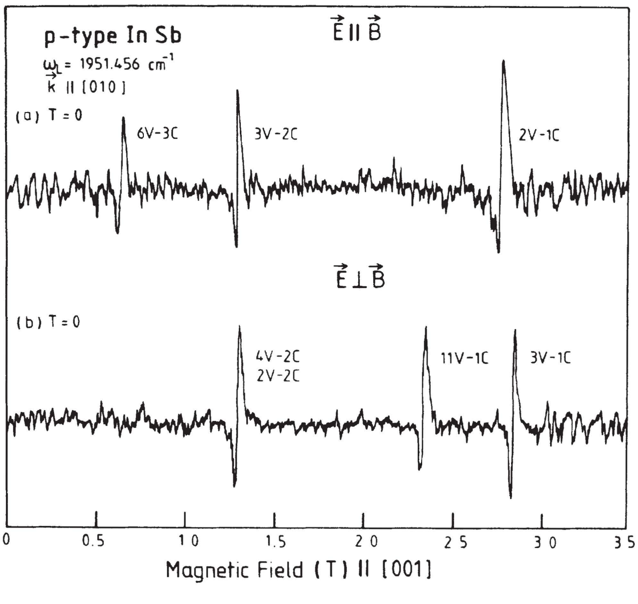

FIG. 1. Magnetoreflection of p-type InSb for (a) **E**$\|$**B** and (b) **E**$\perp$**B** interband transitions. Laser frequency 1951.456 cm^{-1}, **B**$\|$[001], **k**$\|$[010], stress $T=0$.

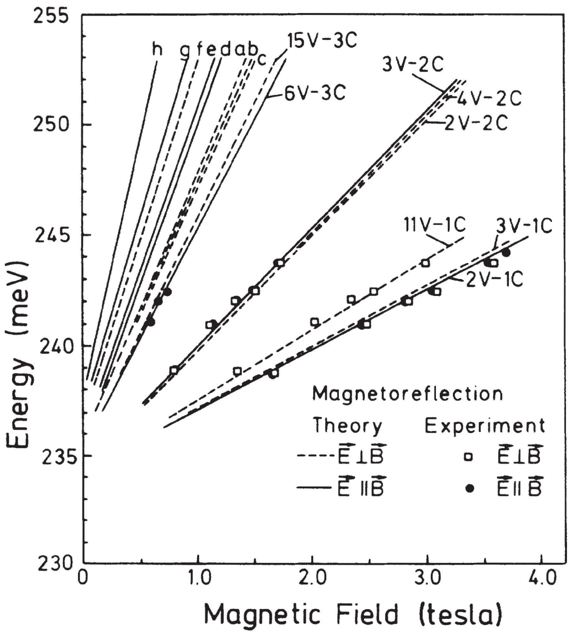

FIG. 2. Comparison of the theoretical energies of interband transitions with the resonances determined by magnetoreflection in unstressed material. The lines were calculated with a band parameter set $\gamma_1=37.1$, $\gamma_2=16.5$, $\gamma_3=17.7$, and $\kappa=15.6$, the remaining parameters being taken as in Ref. 10. All the lines have been shifted by 1 meV to lower energies. The theoretical lines at high energies are related with the following transitions: (a) 1V$\rightarrow$1C, (b) 7V$\rightarrow$3C, (c) 6V$\rightarrow$4C, (d) 7V$\rightarrow$4C, (e) 12V$\rightarrow$1C, (f) 10V$\rightarrow$5C, (g) 2V$\rightarrow$6C, and (h) 1V$\rightarrow$5C.

The results for the unstressed material, plotted in terms of photon energy versus magnetic field, are shown in Fig. 2 and are compared to theoretical calculations. There is an interband transition in **E**$\|$**B** polarization connecting the heavy-hole level 6V with the conduction-band level 3C (for the labeling of the levels see Ref. 10). Further transitions lead from 3V, 2V, and 4V to the 2C conduction-band level. The 2V$\rightarrow$2C and 4V$\rightarrow$2C transitions are polarized **E**$\perp$**B** and have nearly the same energy, so that their lines cannot be resolved. The oscillator strength of 4V$\rightarrow$2C is almost twice that of 2V$\rightarrow$2C, therefore this transition contributes most to the resonance. The transition 3V$\rightarrow$2C is excited only in polarization **E**$\|$**B**. Within the measuring accuracy the resonant magnetic field cannot be distinguished from that of the transitions 2V$\rightarrow$2C and 4V$\rightarrow$2C.

For the final state 1C three transitions are observed: 11V$\rightarrow$1C, 3V$\rightarrow$1C, and 2V$\rightarrow$1C. Without stress, the transition 4V$\rightarrow$1C, which should have almost the same energy as 2V$\rightarrow$1C, is forbidden. The transitions 11V$\rightarrow$1C and 3V$\rightarrow$1C appear in polarization **E**$\perp$**B**, while 2V$\rightarrow$1C, starting from a heavy-hole level, is excited in polarization **E**$\|$**B**. The resonances belonging to 2V$\rightarrow$1C and 3V$\rightarrow$1C are separated distinctly in our experimental spectra. Compared to the theoretical prediction, the transition 3V$\rightarrow$1C displays a smaller energy, in agreement with the experimental results described in paper II.[3]

IV. INTERBAND TRANSITIONS UNDER UNIAXIAL DEFORMATION

Figure 3 shows experimental traces for several stress values recorded with frequency $\omega_L = 1943.535\ \text{cm}^{-1}$ and polarization **E**⊥**B**. In the uppermost curve (stress $T=0$) we can recognize the same structures as discussed in Sec. III. The transition 3V→1C occurs with the highest oscillator strength. Applying uniaxial stress of 38 MPa to the sample only two resonances persist. The transition 11V→1C disappears, while 3V→1C is shifted to lower magnetic fields. With increasing stress the resonant magnetic field for 3V→1C is further reduced, whereas the 2V→2C structure tends slightly towards higher fields. These experimental features are well explained by the stress dependence of the energy levels calculated in paper I [Fig. 2(b)]. When increasing stress from zero value the energy of the 3V level rises until about 100 MPa is reached. Therefore, the transition 3V→1C always takes place at lower magnetic fields. The same argument holds for 11V→1C, but the oscillator strength is strongly diminished and the structure can no longer be observed at 38 MPa. Since the energy of the 2V level decreases with increasing stress, higher magnetic fields are necessary for the 2V→2C resonance at higher stress. In Fig. 4 the magnetoreflection is shown for the same laser line as in Fig. 3, but with polarization **E**‖**B**. The resonance of the transition 2V→1C shifts to higher magnetic fields with increasing stress. This behavior again corresponds to the calculated energy diagram, where the energy difference is diminished with increasing deformation. The valence-band levels 2V and 3V are of special interest at low stress down to $T=0$, because below 30 MPa transitions involving the 2V level could not be observed in stimulated recombination radiation (paper II). Under uniaxial deformations greater than 30 MPa the emission frequencies show a linear behavior for the 2V level. Our magnetoreflection measurements indicate that for $T < 30$ MPa the 2V energy remains nearly constant.

For polarization **E**‖**B** at 38 MPa two new structures appear, which are associated with higher Landau levels in the valence band. The increasing oscillator strength of

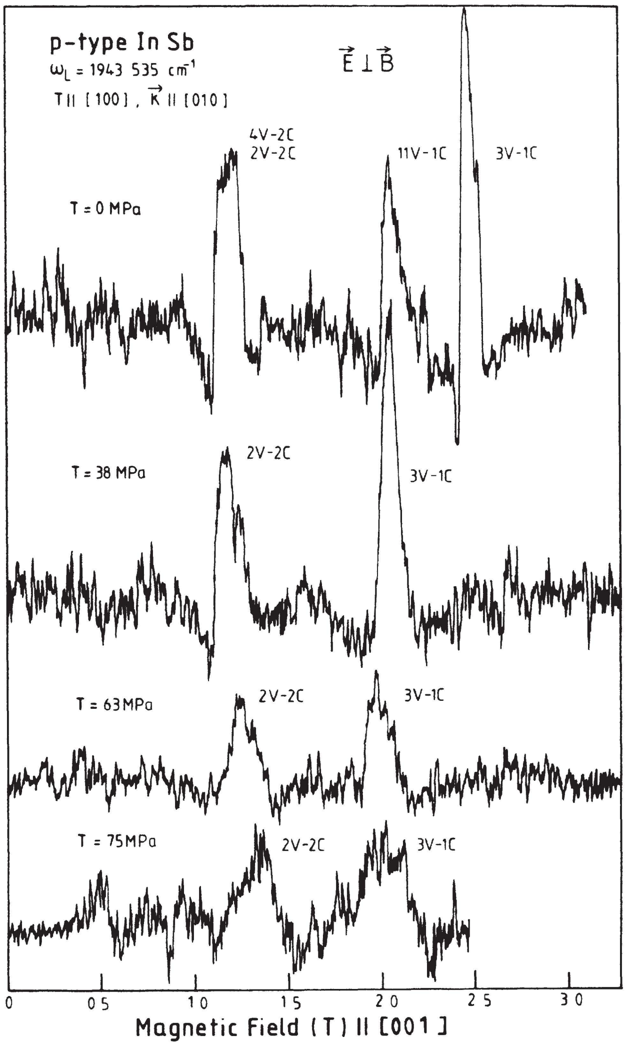

FIG. 3. Magnetoreflection under different uniaxial deformations. **B**‖[001], laser frequency 1943.535 cm^{-1}, polarization perpendicular to the magnetic field.

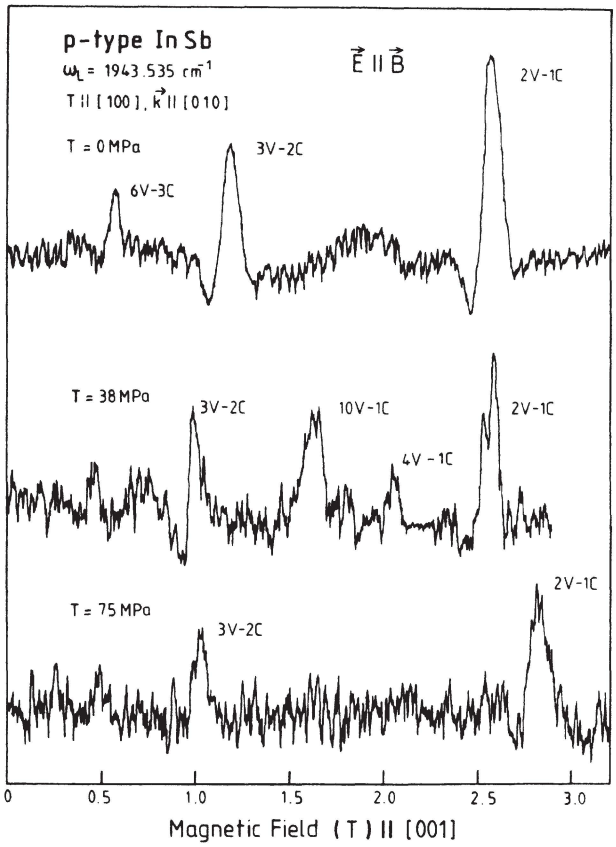

FIG. 4. Magnetoreflection under different uniaxial stresses. **B**‖[001], laser frequency 1943.535 cm^{-1}, polarization **E**‖**B**.

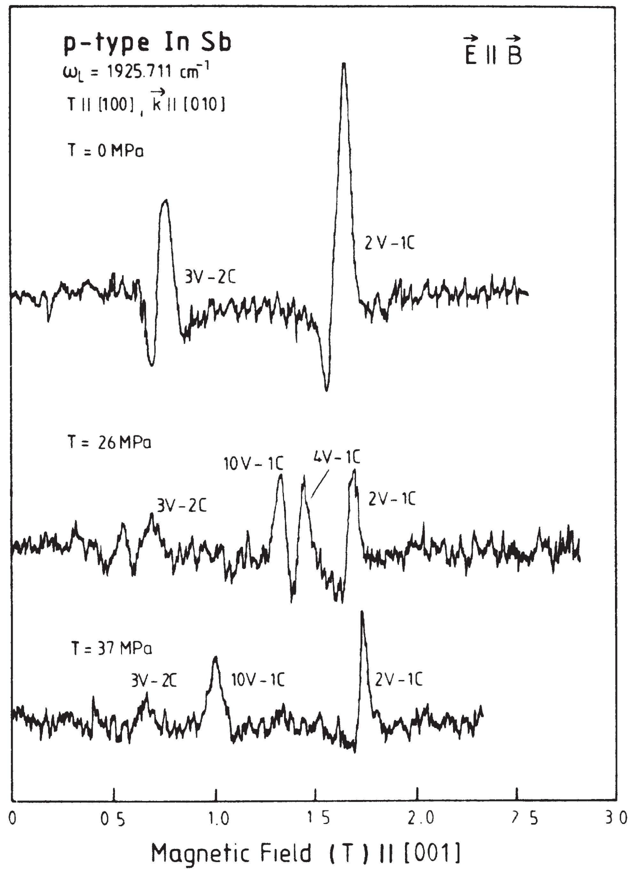

FIG. 5. Magnetoreflection under different uniaxial deformations. **B**∥[001], laser frequency 1925.711 cm^{-1}, polarization **E**∥**B**.

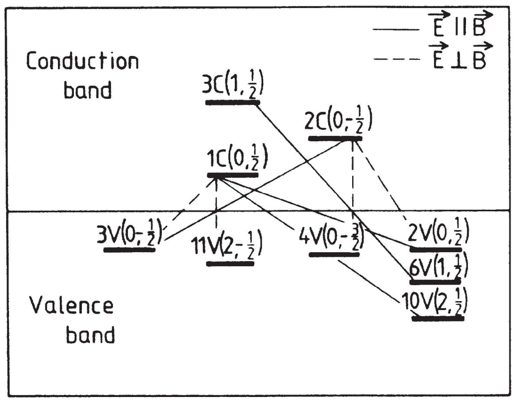

FIG. 6. Classification of the observed energy levels of the conduction band and valence band for **B**∥[001] near the band gap. The lines mark identified interband transitions.

the transitions 10V→1C and 4V→1C at small stresses is in agreement with theory. In unstressed material 4V→1C is completely forbidden. High stress reduces the oscillator strength of these resonances again, and at 75 MPa they are no longer detectable. These observations are confirmed in measurements with other frequencies, as represented in Fig. 5. For a smaller frequency ($\omega_L = 1925.711$ cm^{-1}), where the structures occur at lower magnetic fields, the shifts of the 2V→1C and 3V→2C resonances and the increase and decrease of the 4V→1C and 10V→1C intensities have the same stress dependence as discussed.

It should be noticed that the linewidths of the resonances in Figs. 3 and 4 become larger with growing stress. This broadening connected with a diminishing intensity might be due to slightly bending the sample, which causes an inhomogeneous stress in the surface. As the laser focus has a definite size an average of this distribution is measured. In the scheme of Fig. 6 all interband transitions are drawn which have been observed in magnetoreflection. The dashed lines correspond to transitions in polarization **E**⊥**B**, the solid lines to **E**∥**B**.

V. SUMMARY

Interband transitions in InSb in an external magnetic field have been observed in magnetoreflection. Uniaxial stress modifies both the transition frequencies and the oscillator strengths. Using a magnetic-field-modulation technique numerous transitions were recorded. They could be interpreted as transitions between the valence-band levels 2V, 3V, 4V, 6V, 10V, and 11V and the conduction-band levels 1C, 2C, and 3C. The observed influence of uniaxial stress is in accordance with the theory of paper I. With increasing stress several transitions become observable because the symmetry of the sample is lowered.

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*Present address: Telefunken Electronic, D-7100 Heilbronn, West Germany.

[1]G. B. Wright and B. Lax, J. Appl. Phys. Suppl. **32**, 2113 (1961).

[2]C. R. Pidgeon and R. N. Groves, Phys. Rev. **146**, 575 (1966).

[3]B. Wolfstädter, H.-R. Trebin, H. Pascher, and H. G. Häfele, preceding paper, Phys. Rev. B **37**, 10256 (1988) (paper II).

[4]J. L. Shay, R. E. Nahory, and C. K. N. Patel, Phys. Rev. **184**, 809 (1969).

[5]R. L. Aggarwal, *Semiconductors and Semimetals* (Academic, New York, 1972), Vol. 9, p. 151.

[6]H. Kahlert and D. G. Seiler, Rev. Sci. Instrum. **48**, 1017 (1977).

[7]A. F. Bogenschütz, *Ätzpraxis für Halbleiter* (Hanser Verlag, München, 1967).

[8]B. Lax, J. G. Mavroides, H. J. Zeiger, and R. J. Keyes, Phys. Rev. Lett. **5**, 241 (1960).

[9]G. Beni and T. M. Rice, Phys. Rev. B **18**, 768 (1978).

[10]H.-R. Trebin, B. Wolfstädter, H. Pascher, and H. G. Häfele, this issue, Phys. Rev. B **37**, 10249 (1988) (paper I).