Electrons and holes in InSb under crossed magnetic and stress fields. II. Recombination radiation

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Stimulated recombination radiation and spin-flip Raman scattering have been observed in InSb with uniaxial stress T applied perpendicular to a magnetic field $\mathbf{B}$ ($T \| [100]$, $\mathbf{B} \| [001]$). A $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian was established within an 8×8 Kane model and diagonalized exactly for this particular geometry. Energy levels, transition energies, and corresponding oscillator strengths were calculated and compared to the experimental data.

I. INTRODUCTION

In zinc-blende-type semiconductors the valence-band Landau levels are anomalously spaced due to the degeneracy of heavy- and light-hole bands at $\mathbf{k}=\mathbf{0}$. Uniaxial stress lifts the degeneracy[1] and provides additional information for the interpretation of the optical spectra.[2] From intraband quantum cyclotron-resonance transitions in the valence bands of uniaxially stressed InSb a set of band parameters was deduced,[3] which, however, disagrees with data derived from interband absorption experiments and intra-conduction-band transitions. In an attempt to resolve the discrepancies we performed a series of magnetooptical experiments. Here we report on stimulated recombination radiation (SRR) and spin-flip Raman (SFR) scattering in InSb under uniaxial stress T. The stress was applied parallel to the [100] direction and perpendicular to the magnetic field, $\mathbf{B} \| [001]$.

II. COMPUTATIONAL METHODS

For the calculation of the magnetic states we used a $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian acting in the eight-dimensional space of the Γ_6 conduction band and the spin-orbit split Γ_8 and Γ_7 valence-band states at the zone center:

$$H = H^{cc} + H^{vv} + H^{ss} + [(H^{cv} + H^{cs} + H^{vs}) + \text{H.c.}] \ .$$

The influence of the higher spin-orbit split Γ_5 conduction-band states, separated by about 3 eV from the band edge, was treated carefully in second-order perturbation theory. In H^{cc} these states modify the bare electron mass and g factor, and in H^{cv} they add additional terms of tetrahedral symmetry. The Hamiltonian matrix was diagonalized exactly up to the desired numerical accuracy. The details of the calculation are described in the preceding paper.[4] In Fig. 2(b) of that article the energy of the band-edge Landau levels is plotted versus stress at a magnetic field $B = 2.0$ T and $k_B = 0$ for $T \perp \mathbf{B}$. When conduction-band levels 1C and 2C are initial states, Fig. 2(b) directly shows the stress dependence of the frequencies for radiation emitted in the recombination to different valence-band levels. Due to stress-induced k_B-linear terms, off-center extrema appear in the k_B dependence of the valence-band energies for $T \perp \mathbf{B}$. In recombination radiation these will not cause any noncentral transitions since the dispersion relations of the conduction-band Landau levels remain strongly parabolic at $k_B = 0$.

III. EXPERIMENTAL METHODS

Two kinds of experiments were carried out in order to observe interband transitions and spin resonances in the conduction band. The effective g values were determined by SFR gain measurements and four-wave mixing spectroscopy, respectively, with the experimental setups described in Refs. 5 and 6. The interband transitions were measured by optically pumped stimulated recombination radiation. The experimental arrangement for these investigations is described in Ref. 7. In all experiments the sample (n-type InSb; $n = 9\times 10^{14}$ cm^{-3}) was mounted in the Voigt configuration ($\mathbf{k}_L \perp \mathbf{B}$, $\mathbf{k}_L$ is the wave vector of optical radiation) in a split-coil superconducting magnet at the temperature of pumped liquid helium. Uniaxial stress T up to 400 MPa was applied perpendicular to the magnetic field ($T \| [100]$; $\mathbf{B} \| [001]$; $\mathbf{k}_L \| [010]$).

Figure 1 displays a typical spectrum of the emitted SRR taken at a magnetic field $B = 1.037$ T and a stress

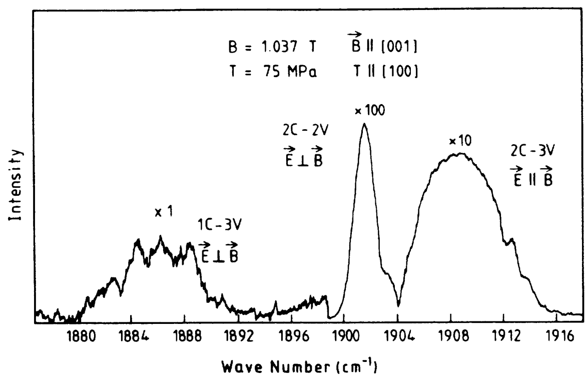

FIG. 1. Spectrum of the stimulated recombination radiation at a magnetic field of 1.037 T and a uniaxial stress of 75 MPa.

$T=75$ MPa. Three transitions with different intensities, linewidths, and polarizations can be seen. The frequencies of the peaks are evaluated and either plotted versus magnetic field with the stress held fixed or versus stress at constant magnetic field.

IV. RESULTS AND DISCUSSION

The effective g value of the conduction band turned out to be independent of stress, in accordance with Ref. 8. In uniaxial stress up to 300 MPa the absolute value of the g factor decreased by less than 0.5%, compared to zero stress. This result is also predicted by our theoretical calculations. In order to obtain information about the band structure from SRR measurements one needs a model for the generation of the radiation. Due to the high concentration of photocreated carriers (about 10^{16} cm^{-3} in our experiment) one has to take into account modifications of the band structure by exchange and correlation effects.[9,10] We assume exchange and correlation energy to be independent of strain and magnetic field.[11] Therefore the only many-body effect is a reduction of the energy gap of the order $\Delta E_g = 5$ meV.[12] This value is confirmed by comparing spontaneous photoluminescence with the stimulated one. The intensity of the SRR is proportional to $\exp(\gamma-\alpha)x$ where γ is the gain factor, α the absorption coefficient for the SRR, and x the distance traversed through the sample. Due to the high mass of the heavy holes, γ is proportional to the density of occupied states, and α to the density of unoccupied states in the conduction band only. Thus, at a given magnetic field the frequency of the emitted radiation can be calculated from the maximum of $\gamma-\alpha$, the energy gap (reduced by many-body effects), and the energy of the final states in the valence band. Because the linewidth of the stimulated emission is very narrow, we judge this method to be more exact for the investigation of the valence bands than cyclotron resonance.

In Fig. 2 for two different magnetic fields the experimental data of the SRR are compared with the theoretically calculated stress dependence of the transition energies. In Fig. 2(a) the magnetic field is fixed at 1.037 T. At this magnetic field value only the two spin states 1C and 2C of the $n=0$ conduction-band Landau level are occupied and therefore only the transitions from these levels can be observed (the labels of the states are defined in Fig. 1 of paper I, Ref. 4). According to the polarization selection rules described in paper I (Ref. 4), electrons, which recombine from the conduction-band level 2C, emit two lines of final states 2V and 3V, respectively, in the valence band. The first is polarized perpendicular to the magnetic field and with increasing stress declines monotonically in frequency; the second, of polarization $\mathbf{E}\|\mathbf{B}$, rises to a frequency maximum before decreasing. Recombination radiation from the conduction-band level 1C shows the same frequency dependence, but shifted by an amount $g^*\mu_B B$ to lower energies; the polarization type of the two lines is exchanged. Thus two series of lines will be observed, each one a copy of the other and resembling the stress behavior of the valence-band levels. Inter- and intraband features appear simultaneously in the spectra.

The transition from the conduction-band level 1C to the valence-band level 2V is not recorded at $B=1.037$ T, while the transition 1C$\rightarrow$3V has a low intensity, as can be seen in the spectrum of Fig. 1. The transitions recombining from the upper spin level in the conduction band to the valence-band levels 3V and 2V are more intense by 1 or 2 orders of magnitude, respectively. But there is no emission $\mathbf{E}\perp\mathbf{B}$ connected with the transition 2C$\rightarrow$2V at a stress lower than about 30 MPa. The calculations of oscillator strengths show that other transitions to the valence band starting from the levels 1C and 2C are by far weaker and cannot be observed in SRR.

The transitions starting from the conduction-band levels 1C and 2C to the valence-band level 3V differ in energy by 23.5 cm^{-1}. This is exactly the value of the spin splitting as was determined by means of SFR gain measurements at the same magnetic field. The agreement of the data obtained by the two different methods also proves that the high excitation of the sample and the originating many-body interaction, which in this case causes a reduction of the energy gap by 5 meV, does not affect the spin splitting. Figure 2(b) shows the corresponding results for a magnetic field of 1.789 T. The levels 2V and 3V preserve their characteristic features also at the higher magnetic field. The recombination energy of the transitions has increased, and both series are separated more strongly because of the enhanced spin splitting. But at 1.789 T only the 1C level in the conduction band is populated, and hence only the low-energy series of recombination transitions is observed.

In all magnetic fields investigated no transition from the conduction-band levels 1C or 2C to the valence-band level 2V can be recorded, if stress is lower than 30 MPa. At magnetic fields greater than 2 T the transition 1C$\rightarrow$3V does not occur when stress exceeds 30 MPa, because level 3V is not within the quasi-Fermi-level in the valence band.

The shape of the tuning curves is well described by the theory and the band parameters used. The energy differences between tuning curves with the same final states E(2C)-E(3V), E(1C)-E(3V) or E(2C)-E(2V), E(1C)-E(2V) agree with the value $g^*\mu_B B$ with g^* as measured by SFR scattering. The relative intensities of the

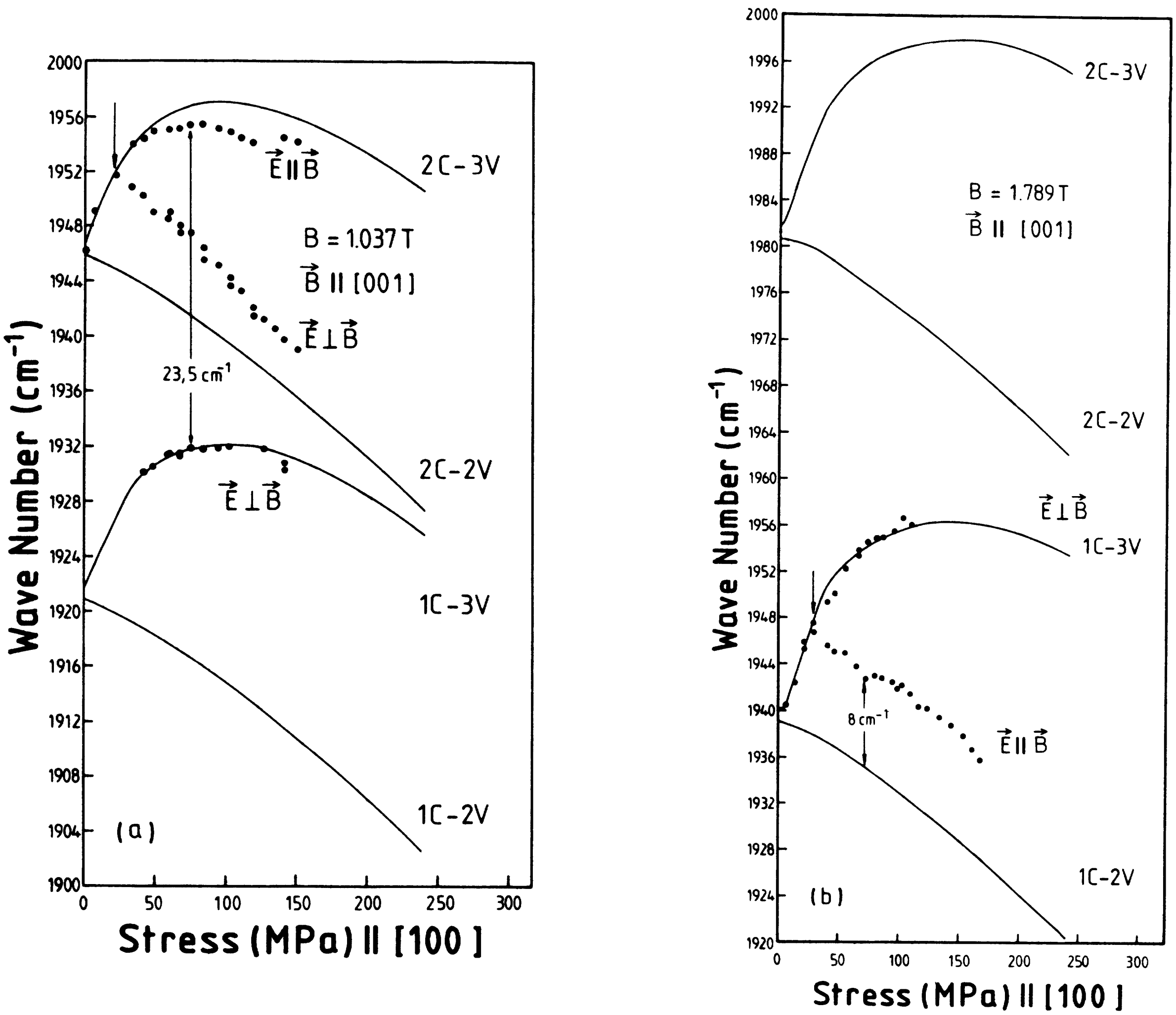

FIG. 2. Stress dependence of the recombination frequencies at two magnetic fields: (a) $B = 1.037$ T, and (b) $B = 1.789$ T.

different lines correspond well to the occupation probability of the conduction-band levels and the oscillator strength calculated. But there is one remarkable discrepancy between experiment and theory. The transitions to the 2V levels have a higher energy than calculated (8 cm^{-1} at 1.789 T). At 30 MPa the 2V and 3V levels cross each other (arrows) in contradiction to our calculations and to the data derived from cyclotron-resonance experiments.[3] This crossing was observed at all magnetic fields investigated.

Extrapolation of the tuning curves to zero stress leads to an energy of the level 2V, which is lower than that of level 3V by 8 cm^{-1}. This discrepancy between experiment and theory also appears in magnetoreflection measurements (paper III, Ref. 13). In these experiments the transition 1C→2V can be observed down to zero stress. It turns out that the linear extrapolation yields too large a difference of the two transition energies. This indicates that level 2V runs more flat for $T < 30$ MPa than is described by linear extrapolation.

Since the energy difference of the oppositely polarized transitions 1C→3V and 2C→3V agrees with direct measurements of the spin splitting in Raman gain experiments, the screening effect for the transition 1C→3V can be considered negligible within the accuracy of our experiment. This should also hold for the other transitions with polarizations **E**⊥**B**. From the existence of a crossing of the tuning curves at $T = 30$ MPa one can conclude that the 2V level lies below the 3V level in the valence band at zero stress. Such a level crossing is not forbidden by symmetry since the two states belong to different representations. But in the framework of the present theory we have not met any set of band parameters which describes this observation. Since there is no indication for experimental errors this discrepancy remains to be solved.

V. SUMMARY

Under uniaxial stress electrons, which recombine from the lowest conduction-band level 1C, emit a pair of spectral lines at high intensities. The final states in the valence band could be identified as 2V and 3V levels. Crossover and split-up of these two levels were studied with increasing stress in different constant magnetic fields. As the energy separation of the spin-split conduction-band levels 1C and 2C does not change with stress, the stress dependence for recombination radiation, which is emitted from 2C, is the same as for radiation from level 1C. The only difference is a shift by $g^*\mu_B B$ and the inverted polarization. So two series of lines, which are exact copies, reflect the valence-band structure of the levels 2V and 3V under stress.

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