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Influence of impurities on broadband p-type-Ge laser spectra under uniaxial stress

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We have investigated the stimulated emission of a broadband p-type-Ge laser (light- to heavy-hole laser) with uniaxial stress up to 500 bars. The emission spectra can be divided into two ranges, the low- and the high-frequency ranges. Between these ranges a region without emission occurs (emission gap) which is explained by impurity absorption. This emission gap vanishes for stress values larger than 400 bars. The structure of the stimulated emission in the low-frequency range is explained by impurity absorption lines. The spectral features of the stimulated emission in the high-frequency range with applied stress suggest that the emission of the p-type-Ge laser is not caused by transitions between the light- and the heavy-hole subbands. Rather, the emission is generated by optical transitions between Landau levels of the light holes and excited impurity states.

Since the realization of p-type-Ge far-infrared lasers the emission spectra were investigated by several authors.[1-3] The results of these measurements were interpreted by a population inversion between the light and the heavy holes of the valence band. This inversion is built up under crossed electric and magnetic fields when the heavy holes are in streaming motion while the light holes are accumulating. The lifetime of the carriers in streaming motion is determined by the strong interaction of the holes with optical phonons while the lifetime of the accumulating carriers is delimited by acoustical phonon and impurity scattering.

Recently it was proposed that impurity states are involved in the laser transitions.[4,5] Two narrow emission lines in the low-frequency range which are not tunable with magnetic field (B) were attributed to optical transitions of holes captured to excited acceptor states into the impurity ground state.[4,5] In a subsequent paper Kremser *et al.*[6] have shown that an essential part of the spectrum can be explained by transitions between light-hole Landau levels and impurity states. Further it was demonstrated that the frequency range without emission ("emission gap"[7]) is caused by impurity absorption.

The behavior of the stimulated emission with uniaxial stress was first investigated by Komiyama and Kuroda.[7] They found that the "emission gap" is narrowing with increasing stress and vanishes at a stress value of 450 bars. This was explained in a semiclassical picture by a reduced impurity scattering probability between the light- and heavy-hole subbands, because the valence band is split at the Γ point by applying uniaxial stress. Gavrilenko *et al.*[8] explained the same experimental fact by a change of the intersubband tunneling rates caused by the mixing of the wave functions of the light and heavy holes in crossed fields.

In this paper we present measurements of the stimulated emission of a p-type-Ge laser in Faraday configuration with uniaxial stress up to 500 bars. From the analysis of the results we suggest a possible interpretation of the spectral behavior of the broadband p-type-Ge laser on one hand due to impurity absorption and on the other hand due to optical transitions between Landau levels of the light holes and acceptor states.

We used a Ga-doped Ge crystal with an acceptor concentration of $N_A = 6\times10^{13}$ cm^{-3}. The sample was cut to form a parallelepiped with a size of $28\times4\times6$ mm^3. The magnetic field B ($B < 3$ T) was applied parallel to the longitudinal axis of the sample and the electric field E ($0.3 < E < 4.0$ kV/cm) was applied perpendicular to the magnetic field and parallel to the [001] direction. Uniaxial stress was applied parallel to B and parallel to [100] using a metallic piston and a sapphire anvil serving as output coupler. The compression was applied by a prestressed spring which was calibrated at room temperature. The pressure could be varied between 0 and 1000 bars continuously. The stimulated emission was measured in a frequency range between 35 and 140 cm^{-1} by a narrow-band, magnetically tunable n-type-GaAs photoconductive detector.[9]

For the discussion of the spectral behavior of the p-type-Ge lasers under uniaxial stress we discuss first the energy spectrum of a single charged acceptor. Figure 1 shows the calculated energy levels of odd-parity acceptor states as well as of the impurity ground state (GS) in germanium for stress parallel to the [100] direction.[10] The symmetry group of the acceptor states is O_h; the energy levels are labeled according to the irreducible representation of this point group[11] (in Fig. 1, 6 and 7 denote energy levels with Γ_6 and Γ_7 symmetry). Optical transitions are allowed between the GS ($1\Gamma_8^+$) and all states with odd parity (Γ^-). Without pressure these transitions are usually labeled with capital letters.[12] Thus the transitions $1\Gamma_8^+$-$1\Gamma_8^-$, $1\Gamma_8^+$-$2\Gamma_8^-$, and $1\Gamma_8^+$-$3\Gamma_8^-$ (or to the degenerated $1\Gamma_7^-$) are named G, D, and C, respectively. For the sake of simplicity we introduce a notation of the excited

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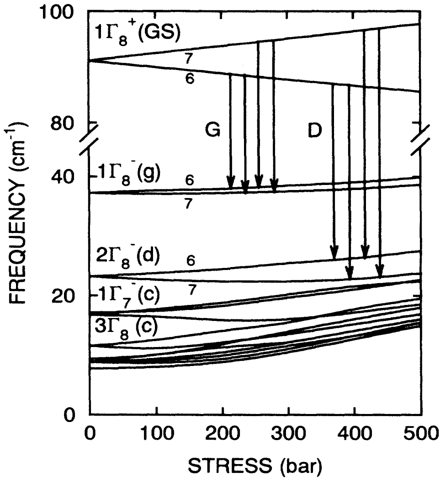

FIG. 1. Calculated energy levels of the acceptor ground state ($1\Gamma_8^+$, GS) and excited impurity states with odd parity (Γ^-) as a function of uniaxial stress $p \| [100]$ in respect to the valence-band edge (Ref. 10). G and D denote optically allowed transitions. g,d,c: for brevity the acceptor levels are named like the corresponding optical transitions (C,G,D).

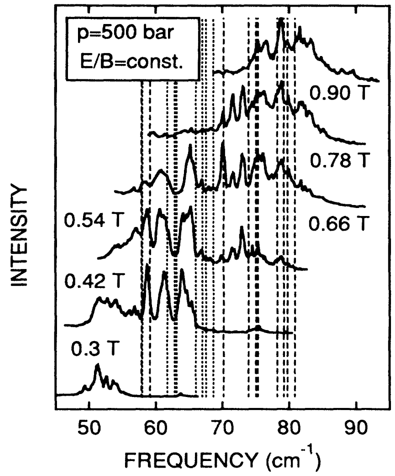

FIG. 2. Emission spectrum of the p-type-Ge laser under a uniaxial stress of 500 bars for a fixed value of $E/B = 1.42 \times 10^5$ m/s. The dotted lines represent optical transitions between the Γ_6 ground state and the dashed lines between the Γ_7 GS and higher excited acceptor states.

acceptor states: The end states of the observed impurity transitions are labeled after the corresponding absorption lines (g,d,c). With pressure the degeneracy of the Γ states is lifted partially, and the fourfold-degenerated Γ_8 state splits into twofold-degenerated Γ_6 and Γ_7 states (marked with numbers 6 and 7 in Fig. 1). Therefore, under applied stress, the G and D impurity absorption lines divide into four lines and the C line into six lines.

Without external pressure two emission ranges of the p-type-Ge laser are observed. In the low-frequency range (45–66 cm^{-1}) there are two remarkable emission maxima which are independent of the applied external fields. In the high-frequency range (75–135 cm^{-1}) the maxima of the stimulated emission are shifting to higher transition energies with increasing magnetic field. The two ranges are separated by an "emission gap" which is caused by self-absorption due to impurity absorption.[6]

By applying uniaxial stress up to 300 bars the "emission gap" is nearly unaffected. Above 400 bars the low-frequency emission range merges with the high-frequency range and the "emission gap" vanishes completely. Figure 2 shows spectra of the stimulated emission for a uniaxial stress of 500 bars for a constant value of $E/B = 1.42 \times 10^5$ m/s in the frequency range of the low stress "emission gap." In this range the spectrum consists of several narrow emission lines which are independent of the applied external fields. In contrast to this the emission outside of this range shows rather smooth and broadband spectral features. The strong modulation of the emission in the range between 58 and 82 cm^{-1} is caused by impurity absorption lines. This is seen from Fig. 2 where the emission minima are compared to dotted and dashed lines. The dashed lines represent impurity transitions between the Γ_7 ground state and higher excited acceptor states and the dotted lines indicate transitions between the Γ_6 GS and higher excited acceptor states. These transition energies are taken from Fig. 1. The discrepancies between the drawn impurity absorption lines and the minima of the emission spectra are caused by neglecting the influence of E and B on the acceptor states and by taking theoretical values for the binding energies of the impurity states. The occurrence of emission in the low stress "emission gap" is explained by an increased gain coefficient overcoming the self-absorption process for stress values larger than 400 bars.[6,7]

Figure 3 shows the emission spectra of the p-type-Ge laser in the low-frequency range for different applied stress values. Without stress the emission spectrum can be divided into two emission bands. At a frequency of $\nu = 54$ cm^{-1} an emission minimum is observed. With increasing stress the higher-frequency band is shifted to higher frequencies; the emission minimum is also tuned to higher frequencies. With increasing pressure the lower-frequency band with a maximum at $\nu = 52$ cm^{-1} is broadening and additional emission minima are occurring. The frequencies of all these emission features are independent of the magnetic and electric field. In Fig. 3 we compare the spectra of the stimulated emission with impurity absorption lines marked by triangles above the spectra. Without stress only a single absorption line lies within the low-frequency range (G line). With increasing pressure this line splits into four lines (see Fig. 1).

The agreement of the impurity absorption lines with the emission minima shows that the structure of the stimulated emission in this low-frequency range may be related to acceptor absorption. Furthermore the observed independence of the emission maxima on E and B is explained by the very small Zeeman splitting and Stark shift of the impurity states [the Zeeman splitting of the D

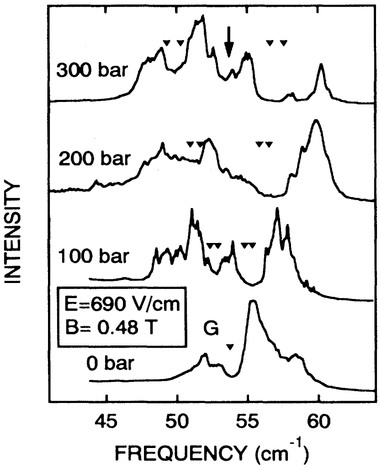

FIG. 3. Emission spectra of the p-type-Ge laser at $B = 0.48$ T and $E = 690$ V/cm for increasing stress in the low-frequency range. The triangles mark transition energies of acceptor absorption lines taken from Fig. 1. The influence of the magnetic and electric field on the transition energies is neglected. The arrow indicates a minimum which cannot be explained by impurity absorption.

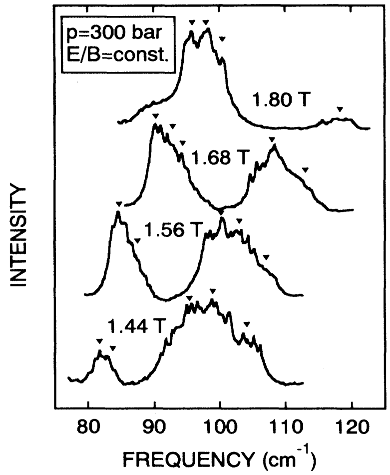

FIG. 4. Spectra of the p-type-Ge laser under a uniaxial stress of 300 bars for a constant ratio of $E/B = 1.42 \times 10^5$ m/s. The triangles mark frequencies where maxima of the stimulated emission are occurring.

line at a magnetic field of 0.48 T is 1.4 cm^{-1} (Ref. 13)]. The minimum at $p = 300$ bars and $\nu = 54$ cm^{-1} marked by an arrow in Fig. 3 cannot be explained by impurity absorption. We believe that this single minimum originates from the intrinsic emission process which will be discussed in the following. Other authors have observed very similar spectra to that in Fig. 3.[14,5] Our analysis gives an alternate explanation of the spectra in the low-frequency range.

For a complete understanding of the emission process of p-type-Ge lasers we want now to discuss the energy levels involved in the lasing transitions. Kuroda and Komiyama[15] have computed matrix elements considering optical transitions between the Landau levels of the light and the heavy holes. The maxima of these transitions plotted as function of B give a fairly good qualitative agreement between theory and emission spectra. In this model the authors do not take into account that the heavy holes are interacting strongly with optical phonons (streaming motion) which causes a significant lifetime broadening and subsequently leads to the disappearance of the corresponding Landau states.

It was also suggested that the stimulated emission of the p-type-Ge laser is caused by higher harmonic transitions between the Landau levels of the light holes.[16] We believe that such transitions should yield a linewidth similar to that of the p-type-Ge light-hole cyclotron resonance laser (0.2 cm^{-1}). This is in contrast to the observed linewidth of up to 20 cm^{-1}.

We want to use the picture suggested by Kremser *et al.*[6] where impurity states are considered as end states for optical transitions instead of heavy-hole states for the following reasons. Between the accumulating light holes and the impact ionized impurity states a population inversion is built up.[4,5] The existence of impurity states under the applied crossed fields is confirmed because impurity absorption is observed. Optical transitions between impurity states and Landau levels or associated impurity states are detected in absorption measurements without electric fields.[17,18]

In Fig. 4 we present spectra of the broadband Ge laser with uniaxial stress of 300 bars for different magnetic fields. The electric field was chosen to give a constant value for the ratio $E/B = 1.42 \times 10^5$ m/s. Each spectrum consists of two emission bands with a spectral width of up to 20 cm^{-1}. The bands are separated by a 5-cm^{-1}-wide gap. With increasing magnetic field the emission

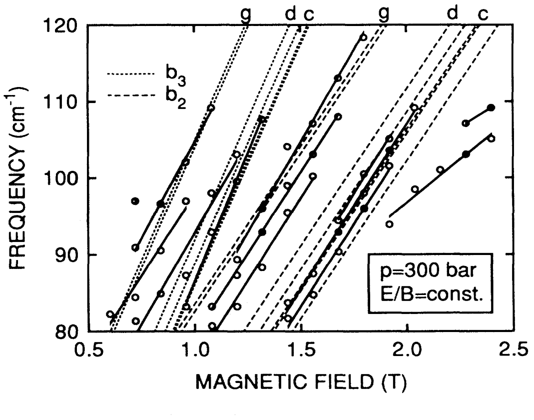

FIG. 5. Spectral behavior of the p-type-Ge laser under a uniaxial stress of $p = 300$ bars, $p \parallel [100]$. The open circles represent maxima of the emission spectra. The solid lines illustrate the tuning of the particular maxima. The spectral behavior of the p-type-Ge laser in the high-frequency range is compared to the tuning of transitions between the Landau levels of the light holes (b_2, b_3) and excited impurity levels (g,d,c). The dependence of the Landau levels on pressure and magnetic and electric field is taken into account (Refs. 15 and 19).

bands and the gap are shifted to higher frequencies. The particular emission bands show nonsymmetric shapes and several emission peaks. These peaks (marked by triangles) tune with B and can therefore be distinguished from features caused by internal reflection modes or outcoupling effects.

In Fig. 5 the spectral behavior of the p-type-Ge laser under 300 bars is shown in the high-frequency range. In this range no impurity absorption is expected, because the transition energies are larger than the binding energy of the acceptor gallium. The frequencies of the different emission maxima (open circles which correspond to the triangles of Fig. 4) are plotted as a function of magnetic field. The dashed and dotted lines in Fig. 5 show transition energies for transitions between the b set of the light-hole Landau levels (b_2,b_3) and excited impurity states (g,d,c) as a function of the magnetic field. The dependence of the Landau levels on E and B is taken from Ref. 15 and that on the pressure from Ref. 19. The values of the binding energies of the impurity states are taken from Fig. 1 neglecting the influence of E and B. The comparison of the evaluated transition energies (dashed and dotted lines) with the experimentally observed tuning behavior of the stimulated emission (solid lines) gives a good quantitative agreement with both the energy position of the emission maxima and the shift of the different maxima with magnetic field (Fig. 5), which approves the new model.

In conclusion, we have investigated the stimulated emission of a p-type-Ge laser with uniaxial stress up to 500 bars. For low pressure values ($p < 400$ bars) the spectrum can be divided into two emission regions with different behavior separated by an "emission gap." The nature of the low-frequency range and the occurrence of the "emission gap" may be caused by acceptor absorption lines. The spectral features of the stimulated emission in the high-frequency range with applied stress suggests that the emission of the p-type-Ge laser is caused by optical transitions between Landau levels of the light holes and excited impurity states.

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