Tunable Cyclotron-Resonance Laser in Germanium

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We report strong narrowband *stimulated* far-infrared *cyclotron-resonance* emission from the light holes in germanium in crossed electric and magnetic fields. The emission spectrum consists of a single line which is linearly tunable with magnetic field. The *gain* of the cyclotron-resonance laser is determined to be 0.05 ± 0.02 cm^{-1}. For the first time we have identified the *lasing transition* to be the $n=2$ to $n=1$ Landau-level transition of the *b*-set light holes by a comparison of absorption and emission spectra with calculations of the band structure including nonparabolicity corrections.

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The possibility of using a population inversion of hot carriers in bulk semiconductors to generate stimulated far-infrared (FIR) radiation has been considered for many years.[1-4] Broadband stimulated FIR emission due to transitions between the light- and heavy-hole bands in germanium was observed in a crossed-field situation.[5-7] Recently, Vasil'ev and Ivanov[8] reported stimulated cyclotron-resonance (CR) emission in the frequency range 40 cm^{-1} $< \nu <$ 50 cm^{-1} from light holes in germanium for electric fields between 1 and 1.5 kV/cm and orthogonal magnetic fields between 1.5 and 2.2 T. Stimulated CR emission was also observed at higher magnetic fields with frequencies in the range 65 cm^{-1} $< \nu <$ 85 cm^{-1}; however, the power of this emission was 3 orders of magnitude smaller than that of the light- to heavy-hole transitions.[9,10] The transitions involved were not identified.

In this Letter we report the study of strong narrowband stimulated CR emission in the frequency range between 65 and 85 cm^{-1} due to Landau-level inversion within the light-hole subband of Ge with the magnetic field applied parallel to the [110] and the electric field parallel to the $[1\bar{1}0]$ crystallographic direction. In this configuration the emission power is comparable to the stimulated light- to heavy-hole emission. Using different output couplers we have determined the gain to be 0.05 ± 0.02 cm^{-1} The emission spectrum consists of a single line which is linearly tunable with magnetic field. For the first time we have identified the Landau levels involved in the lasing process.

For the experiments samples with a carrier concentration of $N_A - N_D = 6 \times 10^{13}$ cm^{-3} were used. The samples were cut out from the crystal to form a parallelepiped. The length of the samples parallel to the [110] crystallographic direction was between 20 and 40 mm. The cross-section dimensions were 7 and 5 mm parallel to the $[1\bar{1}0]$ and the [001] directions, respectively. All faces of the samples were polished and were parallel within 30 in. Electrical contacts were made by evaporating indium (with 5% gold) or aluminum and alloying at 400 °C. To form an external resonator, two copper mirrors were fixed to the end faces of the sample with a thin insulating layer between the sample and the metal mirrors. Mirrors with different bores between 0.7 and 1.5 mm were used as output couplers. The experiments were performed at 4.2 K, so the sample was immersed in liquid helium at the center of a superconducting solenoid. Voltage pulses of up to 2000 V with 1-μs duration were applied to the sample with a high-power, low-impedance pulse generator.[7]

Figure 1 shows the emission signal of sample 1 as a function of the applied magnetic field recorded with a broadband Ge:Ga detector. The resonator configuration is shown in the inset. The detector signal due to stimulated emission is 2 to 3 orders higher than that from the spontaneous emission. Lasing was observed for two different ranges of the magnetic field. The lower range (1 T $< B <$ 2 T) is due to light- to heavy-hole transitions. The spectrum of this emission is broadband.[6,7] The higher-field range (3 T $< B <$ 4 T) corresponds to *stimulated cyclotron-resonance* emission (see also spectra in Fig. 3). For higher electric fields the intensity of the

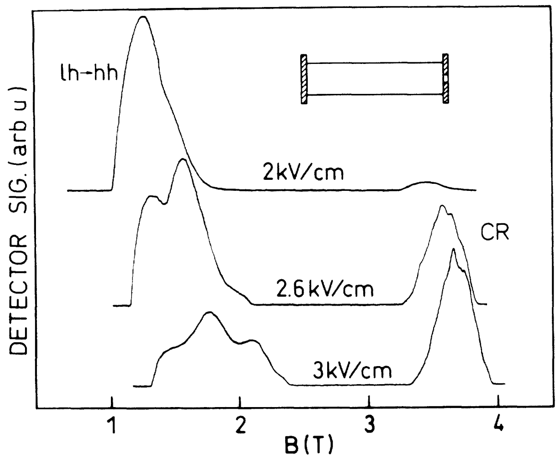

FIG. 1. Stimulated FIR emission from sample 1 as a function of the magnetic field for different electric fields, recorded with the Ge:Ga detector. At lower magnetic fields the emission signal is due to stimulated light- to heavy-hole transitions; at higher fields the signal is due to the stimulated CR emission of the light holes. Inset: The resonator configuration.

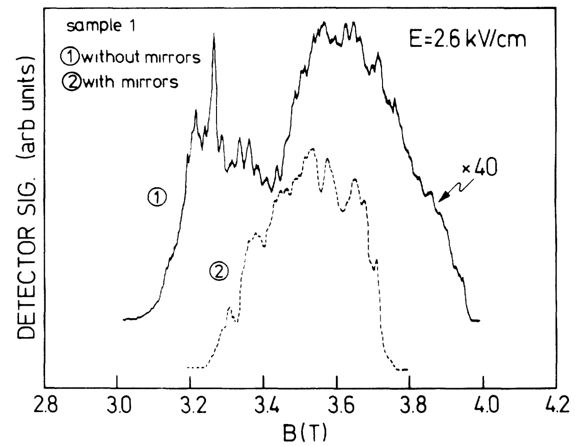

FIG. 2. Stimulated CR emission of sample 1 without external resonator (solid curve) and with external resonator (dashed curve) as a function of the sample magnetic field, detected by a Ge:Ga detector.

stimulated CR emission increases while the intensity of the emission from light- to heavy-hole transitions diminishes. The peak power of the stimulated CR emission is of the same order of magnitude as that of the interband emission which was estimated earlier by comparison with a FIR gas laser to be about 500 mW.[7]

In Fig. 2 the emission is shown as a function of the magnetic field detected with the Ge:Ga detector for sample 1 with external mirrors (dashed curve) and for comparison without external mirrors (solid curve). Without an external resonator the emission power fluctuates by about 40% within the tuning range due to the occurrence of waveguidelike modes caused by internal reflection at the sample surfaces.[6,7] The output power with the external resonator is a factor of 40 larger than without the resonator and the fluctuations are only 20%. In this resonator configuration longitudinal modes are able to oscillate. Since these modes do not undergo total reflections at the sample end faces, more power is coupled out by the hole of the mirror and the necessary gain for threshold is increased. Thus the range of the stimulated emission is smaller than without resonator. By controlling the output power with mirrors with different holes and therefore different transmission we calculate the gain to be 0.05 ± 0.02 cm^{-1}.

For a detailed analysis of the stimulated CR emission a magnetic-field tunable, high-resolution ($\Delta\nu = 0.25$ cm^{-1}) GaAs detector was used.[11] Figure 3 shows spectra (intensity versus frequency) from sample 1 for different electric and magnetic fields: Each spectrum consists of a single line. The position of the line can be changed linearly with the magnetic field in a range between 65 and 85 cm^{-1} (see inset in Fig. 3). The emission frequency corresponds to the cyclotron-resonance frequency of the light holes $\omega_c = eB/m^*$, where $m^* = (0.0466 \pm 0.0001)m_0$. The measured linewidth is about 0.45 cm^{-1}; by taking into account the resolution of the GaAs detector, we conclude that the real linewidth of the emission is about 0.2 cm^{-1}. We believe that the linewidth in our case is determined by the fact that the magnetic field of the solenoid used is not homogeneous over the whole length of the sample.

In order to help with the identification of the lasing transition we performed a CR absorption measurement with sample 1 and compared the results to the emission data. Figure 4 shows the transmission of sample 1 obtained with the 75.12-cm^{-1} line of an external FIR gas laser as a function of the applied magnetic field, detected

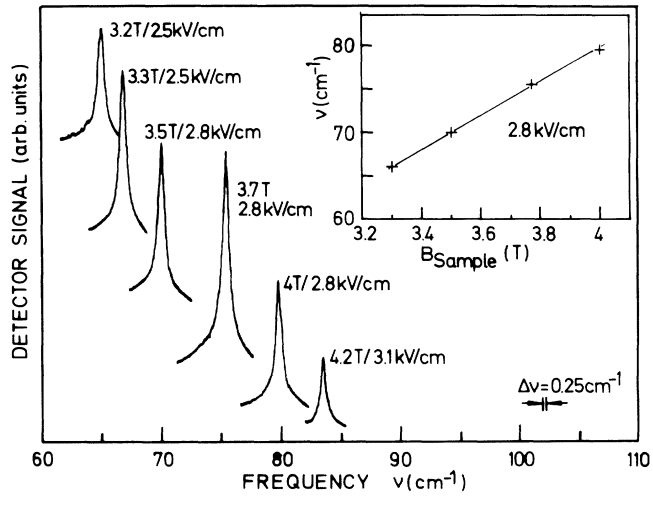

FIG. 3. Spectra of the stimulated emission from sample 1, recorded with a GaAs detector. The spectra consist of a single line which is tunable with the magnetic field. Inset: The frequency of the emission lines vs applied magnetic field.

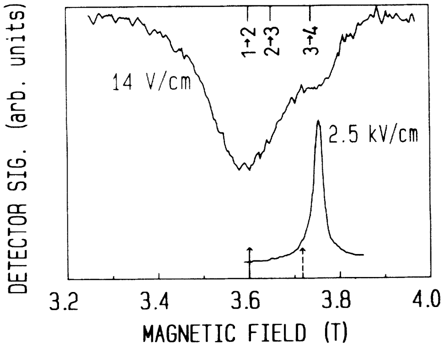

FIG. 4. Transmission of the 78.12-cm^{-1} line of an external FIR gas laser in sample 1: At low electric field cyclotron-resonance absorption occurs. In the lower part the spectrum stimulated CR emission is shown, recorded with a GaAs detector set to 78.12 cm^{-1}. The vertical lines at the top represent the positions of the first three light-hole transitions (see text). At the bottom, the dashed arrow shows the $n=2$ to 1 lasing transition shifted to higher effective-mass separation according to Eq. (3). The solid arrow shows the position at zero electric field.

with the GaAs detector. When the carriers are heated by small electric fields (15 V/cm) a minimum occurs due to CR absorption of the light holes. The absorption line has a shoulder at the high-magnetic-field side. In the lower part of Fig. 4 the spectrum of the stimulated CR emission is recorded with the GaAs detector set to 75.12 cm^{-1}. The maximum of the signal is at higher magnetic fields than the minimum of the absorption.

Because of the coupling between light- and heavy-hole bands, the light-hole levels are not equidistant.[12,13] The Landau-level spacing may also be influenced by the electric field.[9,14] In addition, the influence of the conduction and spin-orbit splitoff bands are important at these fields and energies, giving a significant nonparabolicity correction to the relevant light-hole energy levels (typically, of about 5% in the effective mass value). Thus, for a quantitative determination of the light-hole transitions we use the Pidgeon and Brown (PB) model[15] which includes these effects, but has not previously been used by authors working on the hot-hole laser field. Our method is to take the exact PB computation for Ge to give the *unperturbed* eigenvalues and eigenvectors for light- and heavy-hole Landau levels. We then go to the uncoupled (Luttinger) scheme to calculate the *shift* of these Landau levels in the electric field by second-order perturbation theory.[14,16] At $k_z=0$ the valence-band wave functions are written in conventional notation[15,16] as

$$\begin{aligned} |na^{\pm}\rangle &= a^{\pm}_{3,n}\phi_{n-2}u_{3,0} + a^{\pm}_{5,n}\phi_n u_{5,0}\,, \\ |nb^{\pm}\rangle &= a^{\pm}_{6,n}\phi_{n-2}u_{6,0} + a^{\pm}_{4,n}\phi_n u_{4,0}\,, \end{aligned} \tag{1}$$

where the coefficients are obtained from the PB computation for light- (+) and heavy- (−) hole states, respectively. The Landau quantum numbering has been adjusted to start with $n=0$ for the lowest level to conform with the uncoupled scheme convention.

In first order all the levels undergo the same shift. In second order we have to evaluate matrix elements like

$$\begin{aligned} \langle nai\,|\,eEy\,|\,n'aj\rangle &= A^{ij}_{n,n'}eEL_m\,, \quad L_m=(\hbar/eB)^{1/2}\,, \\ A^{ij}_{n,n-1} &= a^i_{3,n}a^j_{3,n-1}[(n-2)/2]^{1/2} \\ &\quad + a^i_{5,n}a^j_{5,n-1}(n/2)^{1/2}\,, \\ A^{ij}_{n,n+1} &= a^i_{3,n}a^j_{3,n+1}[(n-1)/2]^{1/2} \\ &\quad + a^i_{5,n}a^j_{5,n+1}[(n+1)/2]^{1/2}\,. \end{aligned} \tag{2}$$

i and j run over both + and −, $A^{ij}_{n,n'}=0$ for $|n-n'|>1$. For the b series we replace the a by b coefficients and A's by B's. The second-order shift for the nth light-hole level in the b series is given by

$$\Delta\epsilon^{b+}_n = (eE)^2L^2_m\left\{\frac{(B^{++}_{n,n-1})^2}{\epsilon^{b++}_{n,n-1}} + \frac{(B^{++}_{n,n+1})^2}{\epsilon^{b++}_{n,n+1}} + \frac{(B^{+-}_{n,n-1})^2}{\epsilon^{b+-}_{n,n-1}} + \frac{(B^{+-}_{n,n+1})^2}{\epsilon^{b+-}_{n,n+1}}\right\}, \tag{3}$$

where $\epsilon^{b++}_{n,n-1}=\epsilon^{b+}_n-\epsilon^{b+}_{n-1}$, etc., and ϵ^{b+}_n is the eigenvalue for the nth b-series light-hole Landau level. This expression for the shift is anisotropic in the magnetic field through the denominators obtained from the PB computation.

The PB computation for zero or very low electric field shows that the three "lowest mass" light-hole transitions that can occur in absorption are, in order, $n=1$ to 2, $n=2$ to 3, and $n=3$ to 4 in the b set (the a-set transitions have higher "effective mass" and, in any event, are not expected to support a population inversion[9,17]). These transitions are indicated above the absorption spectrum in Fig. 4, and show very good agreement with the features observed. Evaluating the electric-field shifts from Eq. (3), we find that only the $n=1$ to 2 transition is shifted significantly to higher magnetic field; at the experimental value of 2.5 kV/cm for the laser observation this accords well with the measured position for laser emission, as indicated below the emission spectrum of Fig. 4 (in practice, the effective internal electric field is higher due to the Hall field making the agreement with the experiment even better). The reason for this anomalous shift is that the $n=1$ level is affected differently by the electric field from the higher-n levels as a result of quantum effects referred to above. Vrehen, Zawadzki, and Reine[16] showed that for values of $eEL_m/\hbar\omega_c \ll 1$, perturbation theory is valid for the b-set levels (N.B. for the condition of Fig. 4, this quantity is equal to 0.37). In fact, we find that the $n=2$ to 3 transition is shifted to lower magnetic field by 0.4%. The magnitude of the shift is clearly subject to a large error, but the direction appears to exclude it from the lasing process. At the field ranges where stimulated emission is observed the

$n=4$ level would be above the optical-phonon frequency, making the $n=3$ to 4 transition ineligible for population inversion; thus, the spectroscopy identifies the lasing transition to be $n=2$ to 1.

For the [110] direction the $n=1$ Landau level of the light holes is strongly mixed with higher Landau levels of the heavy holes.[9,17] Because of this mixing the lifetime of the $n=1$ Landau level of the light holes is influenced by the lifetime of the heavy-hole Landau levels. The heavy holes are strongly interacting with the optical phonons for the fields used (streaming motion) and this scattering rate is further increased due to our cross-section geometry which causes a drift parallel to the direction of the heaviest effective mass ([111]) of the heavy holes. As a result the lifetime of the carriers in the $n=1$ Landau level of the light holes is shorter than in the $n=2$ level, which is necessary for a population inversion. The pumping mechanism is based on streaming motion of the hot holes. A quantitative description taking into account the complete band structure and all relevant scattering processes has to be developed.

In conclusion, we have observed strong stimulated CR emission from the light holes in germanium. The spectrum consists of a single line with a linewidth of about 0.2 cm^{-1} and is linearly tunable between 65 and 85 cm^{-1}. With external mirrors the output power is increased and the fluctuations within the tuning range are reduced. We determine the gain to be $0.05 \pm 0.02\ \mathrm{cm}^{-1}$ and identify the lasing transition to be the $n=2$ to 1 Landau-level transition of the light holes.

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