Anticrossing of Landau levels and stimulated emission of hot holes in germanium in the cyclotron-transition region

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The energy spectrum of the valence band of germanium in an electric field crossed with a magnetic field is calculated. An interaction effect and also a repulsion of Landau levels of light and heavy holes with the same total energy are found. These effects are used to explain the stimulated submillimeter emission in the interval $\nu = 70$–$90\ \text{cm}^{-1}$ which was observed in this study in *p*-Ge in strong magnetic fields, 35–45 kOe.

Two mechanisms have been identified for stimulated emission in a system of hot charge carriers in strong crossed fields E and H, as observed in *p*-Ge crystals. One mechanism, a lasing mechanism involving intersubband hole transitions, is manifested in doped crystals ($N_{\text{imp}} = 5\times10^{13}$–$10^{15}\ \text{cm}^{-3}$).[1,4] The other mechanism, which is responsible for emission in pure crystals ($N_{\text{imp}} < 10^{13}\ \text{cm}^{-3}$), is attributed to transitions in a light-hole subband between Landau levels among which there is a population inversion.[2,3,5]

In this letter we report results of a study carried out to observe both types of emission in the same samples of lightly doped germanium (with an impurity concentration of $7\times10^{13}\ \text{cm}^{-3}$). We compare the emission spectra, which are quite different, and we discuss a model of a cyclotron type for the stimulated emission. This model is based on intersubband transitions. The interaction of the Landau levels of light and heavy holes near their crossings is taken into account.

Figure 1 shows the intervals of the electric and magnetic fields in which lasing was detected in *p*-Ge crystals ($2\times5\times50$ mm; $N_{\text{imp}} = 7\times10^{13}\ \text{cm}^{-3}$; $H \parallel [111]$). The samples are immersed in liquid helium near a superconducting solenoid. An electric field $E \perp H$ is applied to the sample in pulses 0.5×10^{-6} s long at a frequency of 1–10 Hz. The emission spectra are measured on a Fourier spectrometer through the use of fast cooled Ge (Ga) and *n*-GaAs photodetectors.[1,4] It can be seen from Fig. 1 that there are two intervals of E and H in which submillimeter emission is observed. Region 1 corresponds to the well-studied emission on intersubband hole transitions (transitions between subbands of light and heavy holes).[1,4] Region 1′ contains an emission of a new type. According to spectral studies which have been carried out, the emission observed in fields in the interval 35–45 kOe is represented in the spectrum by a single narrow line, in contrast with the emission corresponding to intersubband hole transitions (which is characterized by broad bands with a mode fine structure[1,4]). The width of this single narrow line does not exceed the instrumental width of the spectrometer, $\delta\nu \leqslant 0.1 - 0.2\ \text{cm}^{-1}$. The frequency of the line of stimulated emission increases linearly with the magnetic field, in roughly the same way as has been found[3,5]

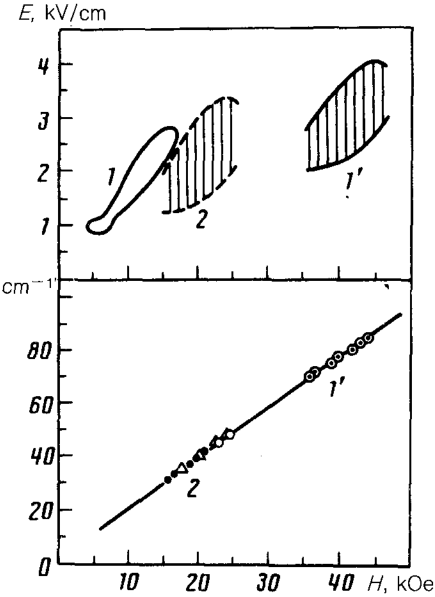

FIG. 1. Regions of stimulated emission in p-Ge on intersubband hole transitions (region 1) and on transitions of a cyclotron type (regions 1' and 2), according to measurements in samples with the following impurity concentrations: 1, 1'—7×10^{13} cm^{-3}; 2—6×10^{12} cm^{-3}. Shown at the bottom is the frequency dependence $\nu(H)$ of the cyclotron emission line in the same samples. Experimental points: ●—1.6 kV/cm; △—1.9 kV/cm; ○—2.4 kV/cm; and ⊙—3.0–3.2 kV/cm.

for the emission at 30–50 cm^{-1} in pure p-Ge crystals ($N_{imp} < 10^{13}$ cm^{-3}). All of the experimental points conform well to a common straight line, whose slope corresponds to a cyclotron mass $m_2^* = 0.046m_0$ of the light holes in the germanium.

These results on the spectra are evidence that the stimulated emission in pure and lightly doped p-Ge crystals at the cyclotron-resonance of light holes are of a common nature. In principle, these results are consistent with the arguments of Refs. 2, 3, 6, and 7 regarding an intraband lasing on transitions between Landau levels of light holes among which a population inversion has formed, as a result of the emptying of low-lying levels because of impurity scattering and the tunneling of light holes into the heavy subband at momenta near $p = 0$ (Refs. 6 and 7). The actual picture, however, seems to be more complicated. The observation of emission in strong magnetic fields (~40 kOe), at which estimates indicate that below the energy of an optical phonon there are only two Landau levels of light holes whose momentum-space trajectories pass far from the region $p = 0$, obviously complicates an interpretation based on emptying effects. In this situation we find extremely probable a different emission mechanism, which involves intersubband hole transitions and an interaction of Landau levels of light and heavy holes in regions of crossing and a hybridization of their wave functions in these states. This model is based on the data from a numerical calculation of the energy spectrum and matrix elements between the light- and heavy-hole subbands in crystals of the germanium type with a degenerate valence band, in fields $E\perp H$ (Ref. 8). It can be seen from Fig. 2 that an initial degeneracy of the upper branches of the Ge valence band is not completely lifted under these conditions, so that there is repulsion (anticrossing) of the levels of light and heavy holes in states with an identical total energy. The effects of the interaction and the mixing of the wave functions are

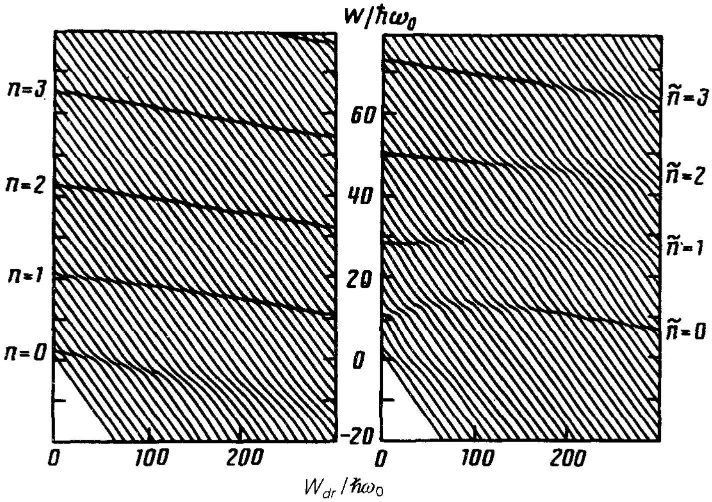

FIG. 2. Calculated energies W of the Landau levels of the light holes (the curves with a small slope) and of heavy holes (with a large slope) as functions of the fields E and H, in arbitrary units. Here $\hbar\omega_0^c = \hbar eH/m_0c$, where m_0 is the mass of a free electron, and $W_{dr} = (m_0/2)(cE/H)^2$. Shown at the left are data for a series with quantum numbers $M_j = -3/2, +1/2$,; shown at the right are data for series with $M_j = +3/2, -1/2$. Here n and $\tilde{n}$ are the light-hole Landau levels.

different for the series with $M_j = -3/2$ and $+3/2$ (in the first of these series, the interaction is less obvious), as can be seen from Fig. 1. The effect increases significantly in certain intervals of E and H, but these intervals differ for different Landau levels. As a result of this interaction and mixing of wave functions, a sharp structural feature

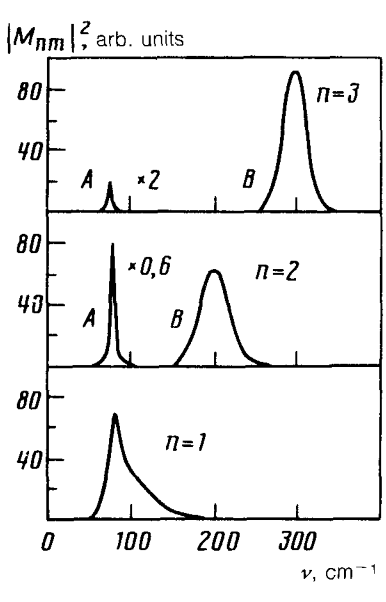

FIG. 3. Theoretical predictions of the matrix elements $|M_{nm}|^2$ of optical dipole transitions from Landau levels $n = 1, 2, 3$ (series with $M_j = -3/2, +1/2$) to corresponding Landau levels m of the heavy-hole subband. These calculations were carried out for $H = 40$ kOe and $E = 3.2$ kV/cm.

(band A) appears in the matrix element for intersubband hole transitions near the cyclotron-resonance frequency of light holes, on the side of the maximum due to ordinary intersubband hole transitions (band B; Fig. 3). In contrast with ordinary intersubband transitions, which have a well-known classical analog [the maximum of $|M_{nm}|^2$ corresponds to a frequency $\hbar\omega_{21} \cong (m_2/2)(v_{c2} + cE/H)^2$; Ref. 9], the intersubband hole transitions near the cyclotron-resonance frequency of the light holes (cyclotron transitions within the light-hole subband were not considered in the calculations) are of a purely quantum-mechanical nature.

The effect described here is similar in nature to the tunneling effects discussed in Refs. 3 and 7. It is quite possible that this effect would be capable of explaining stimulated emission of a cyclotron type even in pure *p*-Ge crystals (in the frequency interval $\nu = 30\text{–}50\ \text{cm}^{-1}$).[3,5] Lasing in this case does not require a population inversion of Landau levels within the light-hole subband; it is sufficient that there be an inverted distribution of carriers between the light- and heavy-hole subbands, as in the experiments of Refs. 1, 4, and 8.

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