Quantum oscillations of the gain and stimulated emission on intersubband transitions of hot holes in *p*-Ge

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(Submitted 26 February 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 7, 348–350 (10 April 1986)

Two regions of an emission of stimulated long-wave IR light by hot holes in *p*-Ge have been observed in crossed fields **E**⊥**H**. There is an abrupt change in the frequency of the stimulated emission at the transition from one of these emission regions to the other. This abrupt change is attributed to Landau quantization of light holes.

Previous discussion of and calculations on the characteristics of stimulated emission in the long-wave IR range [1–4] in transitions between subbands of light (l) and heavy (h) holes in Ge, when a population inversion is produced in fields **E**⊥**H** through the inelastic scattering of holes by optical phonons,[5] have ignored the quantization of states in the valence band (e.g., Refs. 4–7). This approach has made it possible to derive conditions required for the stimulated emission and to determine how the basic characteristics of this emission (the working conditions, the energies and energy relations, and the frequencies) depend on the strengths of the fields, the hole concentration, the temperature, the anisotropy of the band structure, and so forth.

The theoretical ideas which have been used are valid only when the drift energy of the holes, $\mathscr{E}^d_{l,h} = m_{l,h}c^2E^2/2H^2$, is significantly larger than the energy of the cyclotron motion of the holes, $\hbar\omega^c_{l,h} = \hbar eH/m_{l,h}c$, and the stimulated emission occurs at frequencies $\omega \gg \omega^c_l$. In Ge, stimulated emission has been observed[1–3] in fields $H \approx 4$–20 kOe with $E/H \approx 0.14$–0.18 kV/cm · kOe), in which cases we have $\mathscr{E}^d_l \simeq 3$–0.4 $\hbar\omega^c_l$, and $\omega \gtrsim 33\omega^c_l$. The quantization can therefore be important. In the present letter we report experimental results and calculations which reflect the effect of Landau quantization of the light-hole states on the characteristics of the stimulated emission.

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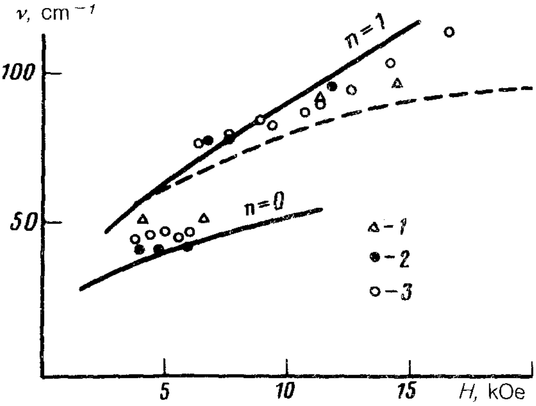

FIG. 1. Tuning of the frequency of the stimulated emission from p-Ge samples. 1—$N_A \simeq 8\times10^{13}$ cm^{-3}, dimensions of $50\times5\times4$ mm (Ref. 2); 2—$N_A\simeq4.5\times10^{13}$ cm^{-3}, $60\times5\times4$ mm (Ref. 3); 3—$N_A\simeq6\times10^{13}$ cm^{-3}, $125\times7\times5$ mm. Dashed and solid lines — Results of classical and quantum-mechanical calculations [$E/H=0.14$ kV/(cm · kOe)].

Figure 1 shows the field dependence $\nu(H)$ of the frequency ($\nu=\omega/2\pi c$) of the stimulated emission from p-Ge samples which are rectangular parallelepipeds combining an active medium with a total-internal-reflection resonator. The measurements are carried out on the basis of the cyclotron resonance of conduction electrons in n-InSb with a resolution $\Delta\nu/\nu\simeq0.1$. There is characteristically an abrupt change in the frequency of the stimulated emission, as was first observed in Ref. 3. The resonator is nonselective, and the frequency of the stimulated emission should correspond to the peak of the gain spectrum.

The zone in the E, H plane in which emission occurs (Fig. 2) consists of two regions, and the abrupt change in frequency corresponds to a transition from one of these regions to the other. As the extent of the doping of the p-Ge is increased ($N_A>0.8\times10^{14}$ cm^{-3}, $N_A \gg N_D$), and as the gain is reduced by changing the fields from the appropriate values, there are decreases in the resonator Q etc.; the two emis-

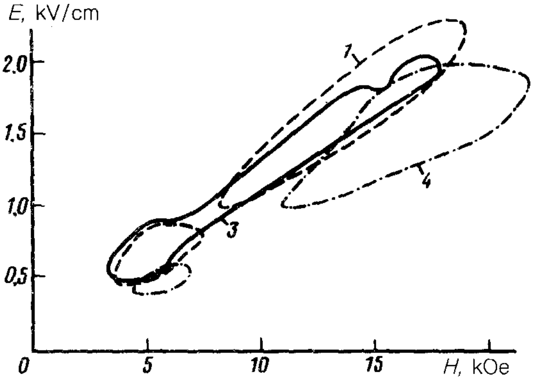

FIG. 2. Zone of stimulated emission. 1,3—See Fig. 1; 4—$N_A\simeq9.5\times10^{13}$ cm^{-3}, $50\times6\times3$ mm. Here E is the applied field. The data on sample 4 reflect the role of the Hall field and of doping. The heating of the lattice of the liquid-helium-cooled p-Ge samples does not exceed $T=10$–15 K.

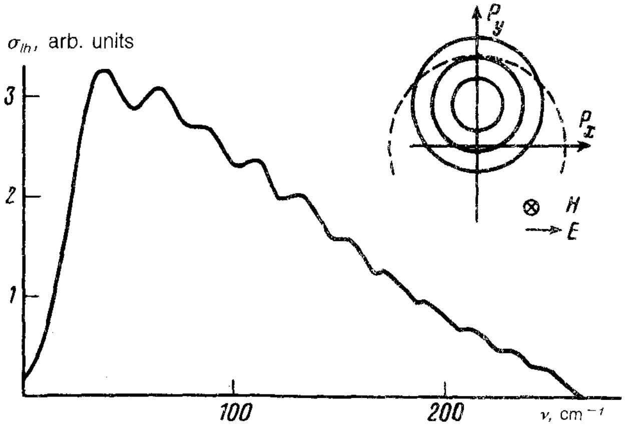

FIG. 3. Characteristic spectrum of the gain cross section for *l-h* transitions $H = 7$ kOe, $E/H = 0.14$ kV/(cm · kOe), $N_A = 10^{14}$ cm^{-3}, $T = 10$ K.

sion regions separate; and, at $N_A > 10^{14}$ cm^{-3}, the low-frequency region of stimulated emission disappears.

The frequency jump and the observed structure in the zone of stimulated emission can be explained on the basis of Landau quantization of light holes. Figure 3 shows the gain cross section for *l-h* transitions versus the frequency, $\sigma_{lh}(\nu)$, derived (by the method of Ref. 8) on the basis of a simplified model in which, in particular, the subbands of light and heavy holes are assumed to be isotropic and independent, with masses $m_l = 0.042m_0$ and $m_h = 0.35m_0$, where m_0 is the mass of a free electron, and spin splitting is ignored. A clear explanation of this behavior comes from the semiclassical picture of quantization, according to which the states of light holes group into Landau tubes (see the inset in Fig. 3). The local maxima of $\sigma_{lh}(\nu)$ arise because of the topological features of the intersection (or tangency) of the Landau tubes with constant-energy surfaces of the light-hole states (spheres) by means of corresponding direct optical *l-h* transitions at the frequency ν. Although these maxima are poorly defined, they are important for the characteristics of the stimulated emission because of the slight extent to which the gain on the *l-h* transitions, $\alpha_{lh} = N_A\sigma_{lh}$, exceeds the loss β and because of the exponential nature of the evolution of the process.

The frequency of the stimulated emission is determined by the local frequency maximum of σ_{lh} with the local value of $\alpha_\Sigma = \alpha_{lh} - \beta$. On the one hand, changes in E and H lead to a change in the relation between the $\sigma_{lh}(\nu)$ maxima, because the relative populations of the tubes depend on them; on the other hand, an increase in the fields is accompanied by an increase in the cross section for the absorption of IR light by intrasubband transitions of heavy holes as they are scattered by optical phonons, $\sigma_{hh} \sim \nu^{-2}$. As a result, as the fields E and H are increased, the higher-frequency local maximum may become predominant, leading to the observed abrupt changes. The highest populations of the zeroth and first Landau tubes, with $n = 0$ and 1, make these the most important tubes. The solid lines in Fig. 1 show possible curves of $\nu(H)$ in *p*-Ge for transitions from these tubes according to the semiclassical interpretation of the quantization. The dashed line is the result of a classical calculation of $\nu(H)$ by the Monte Carlo method $[N_A = p = 10^{14}\ \mathrm{cm}^{-3},\ E/H = 0.14\ \mathrm{kV}/\ (\mathrm{cm}\cdot\mathrm{kOe})]$.

According to the experimental data, the transition from the zeroth Landau tube is predominant in fields $H < 6$ kOe, while the transition from the first tube is predominant at fields $H > 6$ kOe. The switching between tubes is observed in fields at which the tube with $n = 1$ intersects the region of low kinematic momenta, where the scattering by impurities is strongest and where there is furthermore the possibility of a tunneling between subbands,[9] which reduces the population of this tube and causes a different frequency peak to become predominant.

In summary, quantization of the states of light holes must be taken into consideration in order to explain the observed characteristics of stimulated emission and in order to carry out theoretical calculations.

We wish to thank A. A. Andronov for a discussion of these results and S. A. Pavlov for collaboration in the experiment.

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Translated by Dave Parsons