Stimulated emission in the long-wavelength IR region from hot holes in Ge in crossed electric and magnetic fields

A. A. Andronov, I. V. Zverev, V. A. Kozlov, Yu. N. Nozdrin, S. A. Pavlov, and V. N. Shastin

Institute of Applied Physics, Academy of Sciences of the USSR

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Stimulated emission at a power $P \simeq 10$ W has been observed in the wavelength interval $\lambda = 100$–$300\ \mu$m from inter-subband transitions of hot holes in germanium.

A population inversion for direct optical transitions between the subbands of light and heavy holes can be arranged[1] in p-type semiconductors at low temperatures in cross electric (E) and magnetic (H) fields. Correspondingly, lasing can be achieved in the long-wavelength part of the IR range (Fig. 1). The population inversion arises as heavy holes undergo a dynamic heating and are scattered predominately by optical phonons due to a buildup in the number of magnetized light holes at energies $\mathscr{E} < \hbar\omega_0$ ($\hbar\omega_0$ is the energy of an optical phonon), where the scattering is relatively weak.[2,3] The optimum conditions for a population inversion arise at a certain ratio E/H, where the drift velocity is

$$v_{\rm dr} = cE/H = (0.7-1)\, v_{01}, \tag{1}$$

where $v_{01} = \sqrt{2\hbar\omega_0/m_1}$ is the velocity of heavy holes with an energy $\mathscr{E} = \hbar\omega_0$. In p-Ge, calculations show that the population inversion should increase with increasing fields E and H, up to $E \simeq 3$ kV/cm ($H \simeq 20$ kOe). Recent numerical and experimental studies by a variety of approaches (see Ref. 4, for example) confirm the feasibility of arranging a population inversion for holes in p-Ge. On the other hand, there has been only a single report[5] of the observation of lasing (at a power on the order of a milliwatt) in p-Ge at transitions between the subbands of light and heavy holes. The observed emission was not studied in detail, and there are difficulties in comparing the results with the arguments above.

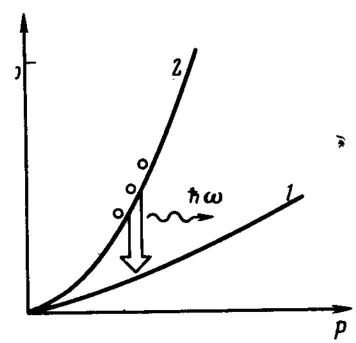

FIG. 1. Diagram illustrating the possibility of an intensification at transitions between the subbands of light (2) and heavy (1) holes. Here $\hbar\omega_0$ is the energy of an optical phonon.

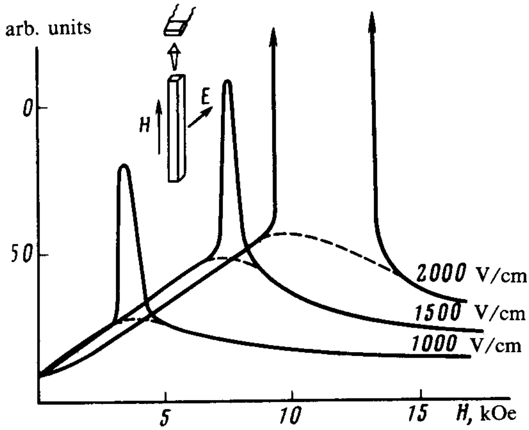

FIG. 2. Intensity of the IR emission detected by the Ge:Ga photodetector versus the magnetic field **H**∥[111] for the specified values of the applied electric field **E**∥[110]. The arrows indicate the boundaries of the threshold region in which the intensity of the IR emission rises abruptly along the H scale.

The long-wavelength IR luminescence of hot holes in p-Ge in fields **E**⊥**H** was studied in the band of a Ge:Ga photodetector for optically thick samples in Ref. 6. A brightening of a samples was observed, and an amplification (by a factor α up to 0.05 cm^{-1}) of the spontaneous emission was also observed. In the present study we have continued this work. We report here observation of rather intense stimulated emission from p-Ge in fields **E**⊥**H**, good agreement with the mechanism proposed in Ref. 1.

The Ge:Ga samples with $N_A - N_D \simeq 7\times 10^{13}$ cm^{-3} and $N_D/N_A \simeq 0.3$ were fabricated in the form of rectangular parallelepipeds $50\times 5\times 4$ mm in size. The opposite faces were parallel within 1′ and could thus serve as internal-reflection resonators. Figure 2 shows the orientation of the fields and the direction in which the emission is detected. The sample is cooled to $T\simeq 4.2$ K. The IR light is detected by Ge:Ga and epitaxial GaAs detectors cooled to 4.2 K. The measurements are taken in single electric-field pulses 1.5 μs long. The results of the measurements with the Ge:Ga photodetector are shown in Fig. 2. At a certain threshold ratio of the fields E and H there is an abrupt increase in the emission intensity (at a field $E\simeq 2$ kV/cm, the emission intensity in the lasing region is 3–4 orders of magnitude greater than the intensity in a zero magnetic field). This abrupt increase is preceded by a gradual intensification of the spontaneous emission with increasing H due to the buildup of holes in the light subband (cf. Ref. 4). It is important to note that the lasing regions lie at the maximum of the intensification of the spontaneous emission along the H scale (the dashed line) and satisfy condition (1). This result shows convincingly that the lasing is due to a population inversion for the transition between the subbands of light and heavy holes. Figure 3 shows the corresponding results on the intensity of the IR emission found with the GaAs photodetector. In contrast with the results found with the Ge:Ga photodetector, there is a significant intensification (by 3–4 orders of magnitude) of the long-wavelength IR emission even at weaker fields, $E\simeq 1$ kV/cm. The length of the stimulated-emission pulse in each case is substantially shorter than the length of the spontaneous-

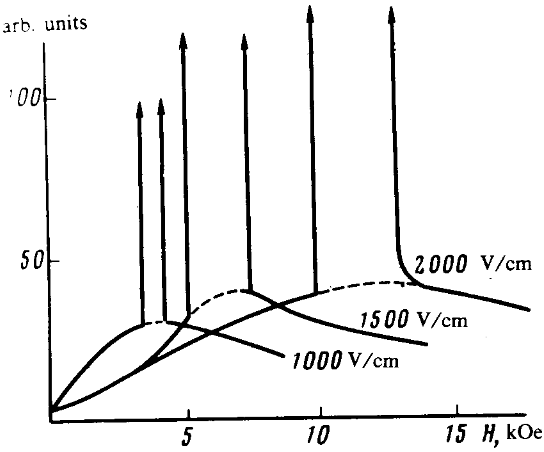

FIG. 3. Intensity of the IR emission detected by the epitaxial GaAs detector versus the magnetic field H||[111] in an applied electric field E||[110].

emission pulse. The results found with the two detectors and with some filters (InSb and fused quartz) lead to the conclusion that the stimulated emission occurs in the wavelength interval $\lambda = 100\text{–}300\ \mu\text{m}$. We wish to emphasize that the mechanism for the stimulated emission[1] and the nonselectivity of the resonator allow lasing to occur simultaneously over a broad wavelength interval, and this is apparently what is happening. Estimates based on the change in the resistance of the photodetectors caused by the light put the output power of the stimulated emission on the order of 10 W.

Stimulated emission in the band of a GaAs photodetector was observed in purer *p*-Ge samples in fields **E**⊥**H** in Ref. 7. That emission occurred in a region along the *H* scale beyond the maximum in the intensification of the spontaneous emission, which corresponds to a cyclotron resonance of light holes. Therefore, in contrast with the present experiments, that emission was attributed to a stimulated cylotron radiation due to a possible population inversion among Landau levels.[8]

In summary, we have observed rather intense stimulated emission at inter-sub-band transitions of hot holes in Ge in crossed electric and magnetic fields. There is the hope that hot-hole lasers may find widespread use.

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