Observation of hot-hole long-wave IR emission in germanium in crossed electric and magnetic fields

L. E. Vorob'ev, F. I. Osokin, V. I. Stafeev, and V. N. Tulupenko
M. I. Kalinin Leningrad Polytechnical Institute

(Submitted 1 March 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 9, 360–362 (5 May 1982)

Far-IR emission ($\lambda \simeq 100$ μm) by hot holes in p-type germanium has been observed in crossed electric and magnetic fields at $T = 10$ and 80 K. There is a threshold in the field dependence of the emission intensity.

PACS numbers: 78.30.Er, 78.20.Jq, 78.20.Ls

Our earlier experiments[1] showed that the light-hole distribution function $f(\epsilon_2)$ becomes inverted with respect to that of heavy holes, $f(\epsilon_1)$, in p-type germanium when there is intense, low-temperature scattering of hot holes by optical phonons in crossed electric (E) and magnetic (H) fields. This inversion raises the possibility of generating and amplifying long-wave IR light ($\lambda > 60$ μm). The physical reason for the inversion of the distribution function is an accumulation of holes in a trap in the light-hole band.[2,3]

For experiments on the emission of light, a p-Ge sample with an impurity of concentration $N_i \simeq 10^{15}$ cm^{-3} was placed in an optical cavity (shown schematically in the inset in

Fig. 1). One of the cavity mirrors (the output mirror) had an effective reflectance $R_{\text{eff}} \simeq 96$-98%, while the other had $R=100\%$. A vacuum gap $d=50$ μm wide served as a longitudinal-mode selector, allowing emission only near $\lambda \simeq 100$ μm. Shorter wavelengths ($\lambda = 2d/m$, $m=2.3, \ldots$) could not be emitted, since the level of the inversion $f(\epsilon_2) > f(\epsilon_1)$ required for emission is reached only at $\lambda > 60$ μm. As a photodetector we used Ge⟨Ga⟩ at $T=4.2$ K. The region of the spectral sensitivity of this detector, along with the system of quartz and fluoroplastic filters and a black polyethylene filter (cooled to $T=4.2$ K), is $\lambda \simeq 80$-120 μm, with a peak at $\lambda \simeq 100$ μm. The light emitted by the p-Ge crystal, in a vacuum cryostat cooled to $T=10$ or 80 K, was carried to the photodetector by a light-guide and displayed on an oscilloscope screen. The pulses of the strong electric field had a length $\simeq 0.5$-0.8 μs. Figure 1 shows the E dependence of the emission intensity I with $H=22.5$ kOe at $T=10$ and 80 K. The emission intensity is estimated to be on the order of a milliwatt. Because of the complex shape of the sample (an "I-beam"), the total field E was determined only approximately.

There are several pieces of evidence pointing to stimulated emission. First, without the optical cavity, we observed an integrated spontaneous emission I_{sp} which was weak (1.5-2 orders of magnitude weaker); in the case $N_i \simeq 10^{15}$ cm^{-3}, this weak emission did not have a threshold in its dependence on the electric field. It increased smoothly with increasing E and was essentially undetectable at $H=0$. A long-wave spontaneous emission from p-Ge with a lower hole concentration and a lower value of N_i was observed in Refs. 4-6 in crossed E and H fields at $T_0 \leqslant 4.2$ K. In the present case, N_i, E, and H are all higher than in Refs. 4 and 5, so that the $I_{\text{sp}}(E)$ and $I_{\text{sp}}(H)$ dependences are smoother, in qualitative agreement with Ref. 6. Spontaneous emission could not be detected when the p-Ge crystal was placed in the cavity, because of the low transmittance of the output mirror of the cavity, $T=I-R_{\text{eff}} \simeq 2$-$4\%$. There is a threshold in the field dependence of I when the p-Ge crystal is in the cavity. Emission is observed at fields at which a significant inversion of the distribution functions, $f(\epsilon_2) > f(\epsilon_1)$, occurs.[1] The threshold field is approximately that which satisfies the relation $p_{1_H} \simeq p_{1_0}$, where $p_{1_H} = m_1^* cE/H$, $p_{1_0} = \sqrt{2m_1^* \epsilon_0}$, and ϵ_0 is the energy of the optical phonon. At $p_{1_H} \gg p_{1_0}$ the trap ceases to

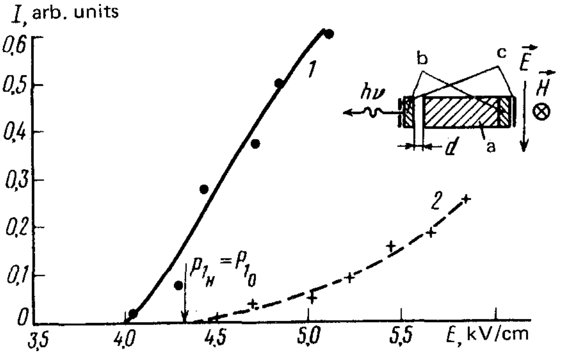

FIG. 1. Dependence of the intensity of the emission at $\lambda \simeq 100$ μm on the electric field E. $H = 22.5$ kOe. 1–$T=10$ K; 2–$T=80$ K. The inset is a schematic diagram of the cavity. a–p-Ge; b–high-resistivity Ge; c–Au.

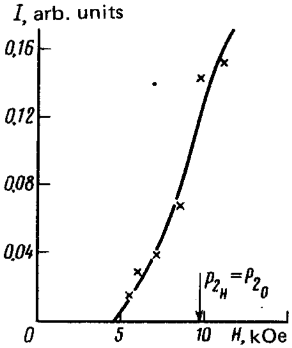

FIG. 2. Dependence of the intensity of the emission at $\lambda \simeq 100$ μm on the magnetic field H. $T = 80$ K, $E = 5.4$ kV/cm.

exist in the heavy-hole band, while the primary trajectory in the light-hole band[2] is closed ($p_{2_H} < p_{2_0}/2$), and the trap in this band occupies a substantial part of the phase volume in the passive region,[1-3] $\epsilon_2 < \epsilon_0$. With increasing E, the emission intensity increases, since the inversion of the distribution function increases, as does the amplification α_{12} (Fig. 3). The physical reason for this behavior is an increase in the frequency at which the heavy holes are scattered, ν_{1_0}; this frequency is determined by the transit time to the boundary of the active region, p_{1_0} ($\nu_{1_0} \simeq (\omega_{c_1}/2\pi)[\pi/\mathrm{arctg}(p_{1_0}/\sqrt{4p_{1_H}^2 - p_{1_0}^2})]$), and thus by the higher population of the trap in the light-hole band. At impurity concentrations $N_i \simeq 10^{15}$ cm^{-3} the primary scattering mechanism for $\epsilon_2 > \epsilon_0$ is the T-independent impurity scattering, which determines the extent to which the trap is filled in the light-hole band. It is thus not surprising to observe emission at $T = 80$ K. Experiments similar to those in Ref. 1 have shown that at $T = 80$ K the distribution function is again inverted, although the quantity $f(\epsilon_2)/f(\epsilon_1)$ is smaller in corresponding fields. The primary reason for the decrease in $f(\epsilon_2)/f(\epsilon_1)$ is an increase in the contribution to the scattering in the passive region by acoustic phonons; this contribution increases with increasing T. The emission intensity is therefore lower, and the threshold field for emission is higher at $T = 80$ K than at $T = 10$ K. Another reason for the increase in the threshold field is an increase in the absorption coefficient corresponding to absorption by lattice vibrations (α_p) and

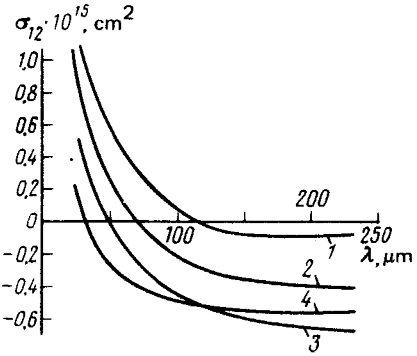

FIG. 3. Spectrum of the cross section for IR absorption by hot holes in transition between the light-hole and heavy-hole bands in crossed electric and magnetic fields. $T = 18$ K, $H = 23$ kOe. 1–E=2.14; 2–E=4.3; 3–E=5.3; 4–E=6.4 kV/cm.

intraband absorption by light and heavy holes ($\alpha_{11}+\alpha_{22}$). Figure 2 shows the H dependence of I. In weak H fields, with $p_{2_H} > p_{2_0}$, there are no traps in the light-hole band, an inversion is not possible, and emission does not occur. As H is increased, and a trap appears ($p_{2_H} \leqslant p_{2_0}$), emission begins. With increasing H, there is an increase in the phase volume of the trap and in the frequency ν_{1_0}, which create an inversion and increase the emission intensity. So far we have not found an explanation for the smearing of the emission threshold in weaker magnetic fields. For stimulated emission the following condition must be satisfied:

$$\alpha_{12} \geqslant \alpha_p + (\alpha_{11} + \alpha_{22}) + (1/2L)\ln R_{\text{eff}} \ . \qquad (1)$$

The last term in (1) incorporates the radiative loss (L is the distance between the mirrors). The diffraction loss by the mirrors in our case is much weaker than the reflection loss. Two-phonon absorption in Ge(α_p) is allowed near $\lambda \simeq 100$ µm for the combination $TO(X)$ $-LA(X)$ and $LA(L)-TA(L)$. At $T=10$ K, according to our estimates, the absorption should not exceed $\alpha_p \simeq 5\times10^{-3}$ cm^{-1}. According to the experiments of Ref. 7, this absorption coefficient is $\alpha_p < 0.2$ cm^{-1} at $T = 1.5$ K and $\lambda = 100$ µm. According to calculations incorporating acoustic and impurity scattering, with $T=20$ K, $E\simeq 4$ kV/cm, and $N_i \simeq 10^{15}$ cm^{-3} we would have $\alpha_{11}+\alpha_{22} \simeq 3\times10^{-2}$ cm^{-1}. With $L = 2$ cm we would have $(1/2L)\ln R_{\text{eff}} \simeq 5\times10^{-3}$ cm^{-1}. Following Ref. 8, we can calculate $\sigma_{12}(\lambda)$ (Fig. 3), using the functions $f(\epsilon_1)$ and $f(\epsilon_2)$ from Ref. 1. We see that at relatively low hole concentrations the emission condition in (1) can be satisfied easily. The emission conditions are satisfied better in the long-wave region ($\lambda > 200$ µm).

We are indebted to I. B. Levinson for some useful comments.

1. L. E. Vorob'ev, F. I. Osokin, V. I. Stafeev, and V. N. Tulupenko, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 125 (1981) [JETP Lett. **34**, 118 (1981)].
2. I. I. Vosilyus and I. B. Levinson, Zh. Eksp. Teor. Fiz. **50**, 1660 (1966) [Sov. Phys. JETP **23**, 1104 (1966)]; **52**, 1013 (1967) [**25**, 672 (1967)]; I. I. Vosilyus, Fiz. Tverd. Tela (Leningrad) **11**, 924 (1969) [Sov. Phys. Solid State **11**, 775 (1969)].
3. A. A. Andronov, V. A. Kozlov, L. S. Mazov, and V. I. Shastin, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 585 (1979) [JETP Lett. **30**, 551 (1979)].
4. Yu. L. Ivanov, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 539 (1981) [JETP Lett. **34**, 515 (1981)].
5. S. Komiyama, Phys. Rev. Lett. **48**, 271 (1982).
6. V. I. Gavrilenko, V. N. Murzin, S. A. Stoklitskiĭ, and A. P. Chebotarev, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 81 (1982) [JETP Lett. **35**, 97 (1982)].
7. E. V. Loewenstein, D. R. Smith, and R. L. Morgan, Appl. Opt. **12**, 398 (1973).
8. E. O. Kane, J. Phys. Chem. Solids **1**, 82 (1956).

Translated by Dave Parsons
Edited by S. J. Amoretty