# Hot-hole far-IR emission from uniaxially compressed germanium

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Stimulated and spontaneous hot-hole far-IR emission from uniaxially deformed germanium in the absence of a magnetic field was investigated. A possible mechanism for population inversion in the magnetic subbands is discussed.

In Ref. 1 we reported the observation of intense stimulated far-IR emission in uniaxially deformed germanium in warming electric fields, but in the absence of a magnetic field (in contrast to stimulated emission observed in the same material in the presence of both strong electric and magnetic fields simultaneously[2]). In this paper we present the results of an investigation of spontaneous and stimulated hot-hole emission from deformed germanium and we discuss a possible mechanism for the population inversion of hot holes on different branches of the Ge valence band split by uniaxial compression.

We employed *p*-Ge crystals with Ga density of $3\cdot10^{13}$–$10^{15}$ cm$^{-3}$. The specimens were 5–10 mm long in the direction of compression and their cross section was 0.5–1 mm$^2$. The pressure $P$ and the electric field $E$ were applied in one of two crystallographic directions: [111] or [100]. Voltage pulses, having a width of 0.2–1 $\mu$s, were applied to In contacts deposited on the narrow faces of the specimen and separated by a distance of 3–9 mm. The measurements were performed at the temperature of liquid helium. The required carrier density was produced by electric breakdown of a shallow impurity (Ga). For this reason, the hole density in fields significantly stronger than the breakdown field does not depend on the voltage, and the form of the current-voltage characteristic is determined by the distribution of holes between the branches of the valence band and by the field dependence of the corresponding mobilities. As the pressure increases the current flowing through the specimen always increases: by a factor of 1.5–2 in moderate fields and by several percent in strong fields (see Figs. 3 and 7b below).

The radiation from the specimen was recorded with a Ge:Ga detector which is sensitive at 100 $\mu$m. Filters made of quartz, InSb, and teflon were placed between the specimen and the photodetector (Fig. 1a) to limit the spectral range of the radiation reaching the detector.

For specimens whose lateral (long) faces were parallel to within 20″ the emission was observed to jump at the threshold values of the pressure and field (1.5–3 kV/cm for different specimens) (Fig. 1). The intensity of the emission could exceed by three orders of magnitude the intensity of the spontaneous emission. The threshold pressure was equal to 8–11 kbar for specimens with **P**‖[111] (Fig. 1) and to 6–7 kbar for **P**‖[100]. The jump in the emission was always accompanied by a jump in the current by several (2–6) times. In those specimens where no emission jump was observed, there was also no current jump. The current jump is probably caused by an increase of the light-hole density.

The existence of threshold values of the field $E$ and pressure $P$ for the appearance of intense emission indicates that the emission is stimulated. This is also confirmed by the fact that the parallelism of the faces and the quality of the surface of the crystal play a decisive role. The jump in both the emission and the current vanished when one of the side boundaries of the generating specimen was rough-ground (curve 2 in Fig. 1). After repeated polishing the effect reappeared (curve 3).

The stimulated emission is evidently caused by an inversion in the energy distribution of the carriers. To determine the reason for the inversion we investigated spontaneous far-IR emission. Figure 2 shows the pressure dependence of the radiation intensity for **P**‖[100] in electric fields which are not too strong. A characteristic feature of these curves is that the signal decreases exponentially in some pressure range. The slope of the curves remains approximately constant in fields of 6–20 V/cm and decreases in stronger fields. The maxima on the curves in Fig. 2 are associated with the increase in the free-hole density caused by the fact that for fields $E < 40$ V/cm the impurity is still not

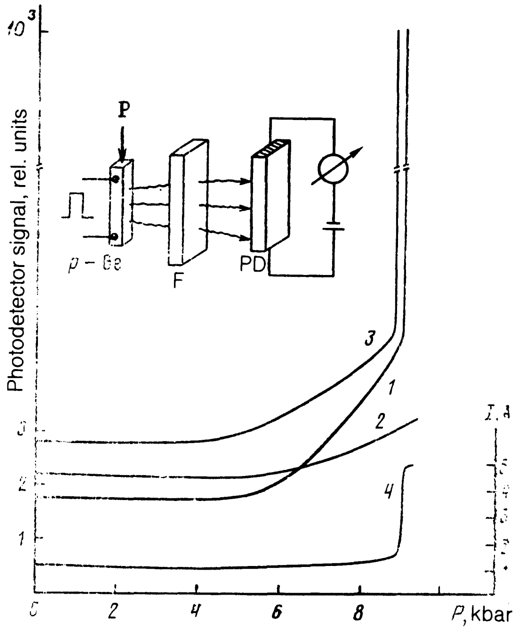


FIG. 1. Arrangement of the experiment (a) and dependence of the emission (1–3) and current (4) on the pressure **P**‖[111]: 1, 4) initial specimen; 2) after rough grinding; 3) after repeated polishing; F—filter; PD—photodetector.

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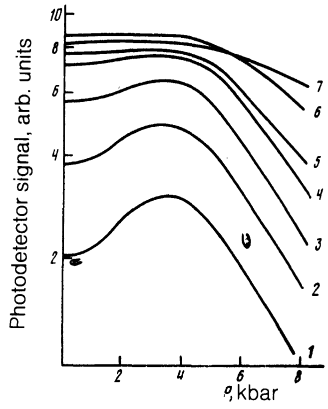


FIG. 2. The pressure dependence of the emission intensity for pressure $P \| [100]$ in intermediate electric fields ($E$, V/cm): 6 (1), 10 (2), 15 (3), 20 (4), 40 (5), 60 (6), and 100 (7).

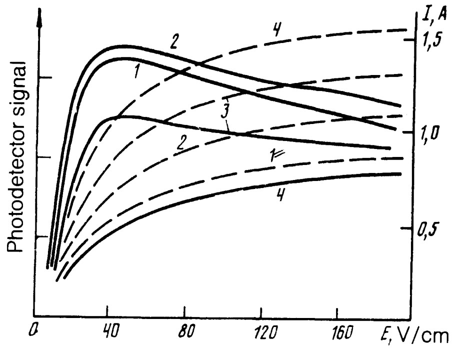


FIG. 3. The photodetector signal (solid lines) and the current flowing through the specimen (dashed lines) as a function of the electric field for different pressures $\mathbf{P} \| [111]$: 0 (1), 1.8 (2), 3.6 (3), and 5.0 (4) kbar.

completely depleted. Indeed, since the pressure lowers the impact-ionization threshold, the hole density increases when the pressure is increased in a fixed field. Figure 3 shows the signal from the photodetector and the current flowing through the specimen as a function of the electric field. One can see that the radiation maximum, observed in the absence of compression in a field of the order of 40 V/cm and explained by streaming of light holes (Ref. 2), vanishes at pressures $P > 5$ kbar. This shows that the dynamics of hole heating in deformed germanium differs substantially from that in the undeformed crystal.

Uniaxial strain removes the degeneracy of the valence band of germanium and splits the valence band into two elliptic subbands, separated at $\mathbf{k} = 0$ by an energy gap $\Delta = \alpha P$. The values of $\alpha$ and the corresponding effective masses are presented in Table I. The point $Q$ of intersection of the branches of $\varepsilon(\mathbf{k})$, shown in Fig. 4, is the point of tangency of the two $\varepsilon(\mathbf{k})$ surfaces in $\mathbf{k}$ space. The complicated character of the dispersion curves $\varepsilon(\mathbf{k})$ in the case of strain should substantially increase the complexity of the dynamics of heating of the carriers. In weak fields virtually all holes are in the bottom energy band with a smaller effective mass in the compression direction. In strong fields an appreciable fraction of the holes can populate states with energy $\varepsilon > \Delta$. Only holes with energy $\varepsilon > \Delta$ from the "tail" of the distribution function can participate in direct optical transitions between different valence subbands, and for this reason the detected radiation should be determined by the character of the heating of the holes and by the distribution of the hole density between the subbands.

Strain introduces another important factor: The shape of the energy surfaces, corresponding to the energy of the emitted photon detected by the detector, depends on the pressure.[4] At zero pressure the surface $\varepsilon_2(\mathbf{k}) - \varepsilon_1(\mathbf{k}) = h\nu = \text{const}$ is almost spherical. At high pressures it is divided into two almost elliptic surfaces, displaced in the direction of compression toward large $k$. Figure 4 shows the dispersion curves $\varepsilon(\mathbf{k})$ (a) for $\mathbf{k} \| \mathbf{P} \| [111]$ ($k_\|$) and $\mathbf{k} \perp \mathbf{P}$ ($k_\perp$) as well as the projections, calculated using Eq. (30.5) in Ref. 3, of the surface $\varepsilon_2(\mathbf{k}) - \varepsilon_1(\mathbf{k}) = h\nu$ on the plane $k_\| k_\perp$ (b) for $h\nu = 10$ meV. The arrows indicate the possible optical transitions at the boundary values of $k_\|$. Strain can thus affect the intensity of optical transitions for several reasons: hole redistribution between pressure-split bands; change in the character of hole heating in different sections of the energy spectrum; and, change in the shape of the momentum-space surfaces between which a transition with given photon energy occurs.

We shall now examine the plots shown in Fig. 2. The exponential decay of the emission with increasing strain can be attributed, in principle, to a decrease of the hole density in the tail of the distribution function with increasing $\Delta$. If the distribution function is assumed to be Maxwellian, the corresponding temperature $T_l$ in the "light" band can be determined from the slopes of the curves in Fig. 2. The electric-field dependences of $T_l$ are presented in Fig. 5 for two crystallographic directions. One can see that there exists a range of fields where $T_l = \text{const}$. On the other hand, at a fixed pressure the signal increases with the field in the same range (see Fig. 3). This indicates that the number of holes with energy $\varepsilon > \Delta$ increases; this corresponds to an increase

TABLE I. Parameters of the valence band of germanium under uniaxial compression.[3]

| Crystallographic direction | $\alpha$, meV/kbar | light holes | | heavy holes | |
|---|---|---|---|---|---|
| | | $m_\| / m_0$ | $m_\perp / m_0$ | $m_\| / m_0$ | $m_\perp / m_0$ |
| [111] | 4 | 0,04 | 0,13 | 0,5 | 0,05 |
| [100] | 6 | 0,05 | 0,12 | 0,22 | 0,06 |

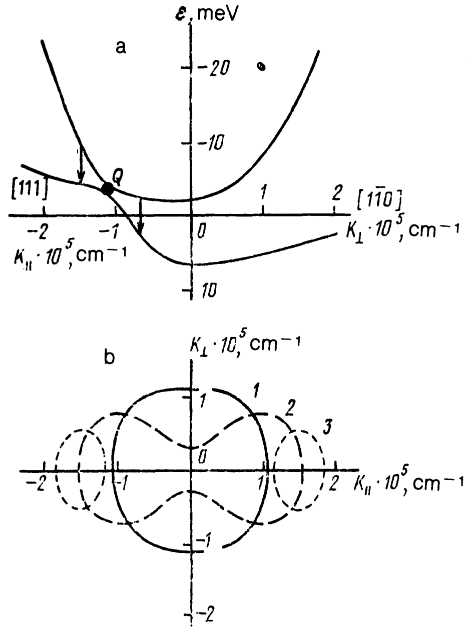


FIG. 4. The dispersion curves (a) for *p*-Ge with $P = 3$ kbar and projections of the surface $\varepsilon_2(\mathbf{k}) - \varepsilon_1(\mathbf{k}) = h\nu = 10$ meV (b) with $\mathbf{P}\|[111]$ on the plane $k_\| k_\perp$ for $P = 0$ (1), 2.5 (2), and 5 kbar (3).

of $T_l$. This contradiction shows that even in moderate fields the distribution function is significantly different from Maxwellian. Figure 5 also shows that for $\mathbf{P}\|[111]$ the temperature $T_l$ is lower than for $\mathbf{P}\|[100]$ and the electric field in which $T_l$ starts to increase is weaker than for $\mathbf{P}\|[100]$. Since the light-hole mass is somewhat larger in the case of compression in the [100] direction than in the [111] direction (see Table I), one would think that the reverse should be true—it should be easier to heat light holes in the [111] direction. This shows that even in moderate fields the pressure-split heavy-hole band plays a significant role in the heating of the holes.

In the absence of strain the distribution function is non-Maxwellian because of streaming,[2] when holes are accelerated by the electric field up to the energy of the optical phonon $\varepsilon_0$ in a time shorter than the acoustic scattering time of the holes. The distribution function in momentum space is strongly elongated in the direction of hole drift up to momentum values $p_0 = (2m\varepsilon_0)^{1/2}$ ($m$ is the hole effective mass). In strained germanium the maximum energy for collisionless acceleration of light holes can be the energy $\Delta$ corresponding to the edge of the pressure-split heavy-hole band (if $\Delta < \varepsilon_0$). At this energy additional acoustic scattering of light holes occurs as a result of transfer of light holes into the heavy band (Fig. 6). If the probability of such transitions is significantly higher than that of intraband scattering of light holes, then the electric field will transfer virtually all holes into the heavy band. Inversion could be caused by the runaway of light holes up to energy $\Delta$ in an electric field.

The necessary condition for this runaway is that the flight time of a hole $t_{fl}$ up to energy $\Delta$ must be shorter than the acoustic scattering time $\tau$ in the "light" band. Obviously, there always exists an energy band $\delta\varepsilon$ near $\Delta$ (see Fig. 6) where this condition is certainly satisfied:

$$t_{fl} = \frac{1}{eE}\{(2m_1\Delta)^{1/2} - [2m_1(\Delta - \delta\varepsilon)]^{1/2}\} < \tau. \quad (1)$$

Here $m_1$ is some average effective mass of light holes in the direction of the field and $\tau$ is the acoustic scattering time of light holes with energy of the order of $\Delta$. The competing process limiting the transfer of light holes is the reverse transition of holes from the "heavy" band into the "light" band. If the characteristic energy $\delta\varepsilon_0$ given up by a hole in such a transition is less than $\delta\varepsilon$, then the field removes virtually all holes from the "light" band. For estimates, we shall use the maximum value of the energy $\delta\varepsilon_0 \approx (2m_\perp s^2\Delta)^{1/2}$, where $s$ is the velocity of sound. Assuming that $\delta\varepsilon_0 \ll \Delta$ (this corresponds to pressures that are not too low, when $\Delta \gg 2m_\perp s^2$), we find from the condition $\delta\varepsilon_0 < \delta\varepsilon$, with the help of Eq. (1), that $e\tau E(m_1 m_\perp)^{-1/2} > s$. Estimating $\tau$ from the expression $\tau^{-1} = 1.455T\Delta^{1/2}$ s$^{-1}$ (Refs. 5 and 6; $T$ and $\Delta$ are given in degrees Kelvin) we get $\tau \approx 10^{-10}$ s for the limiting values $\Delta \approx \varepsilon_0$ at $T = 4$ K. Then we obtain $E \geqslant 0.2$ V/cm, even for $m_1 \approx m_\perp = 0.13m_0$ ($\mathbf{P}\|[111]$).

The rough estimate presented above shows that the removal of light holes by the electric field and their accumulation in the "heavy" band can occur in comparatively weak fields. The "sticky wall" approximation, i.e., the assumption

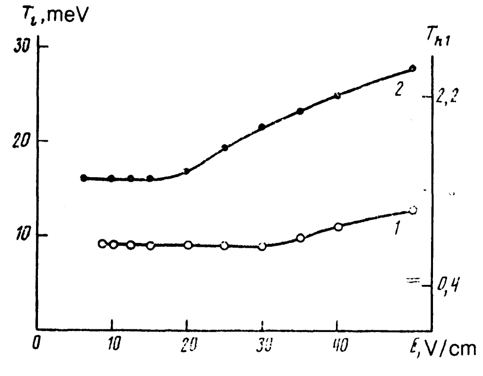


FIG. 5. Temperatures of light holes ($T_l$) and heavy holes ($T_h$) for different crystallographic directions: [111] (1) and [100] (2).

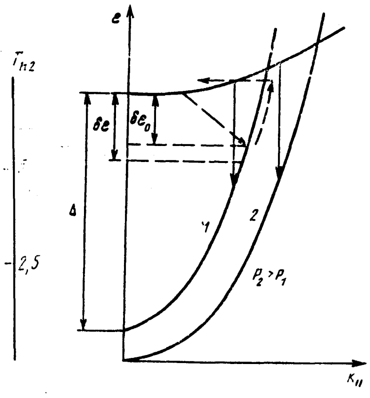


FIG. 6. Scheme of the hole transitions.

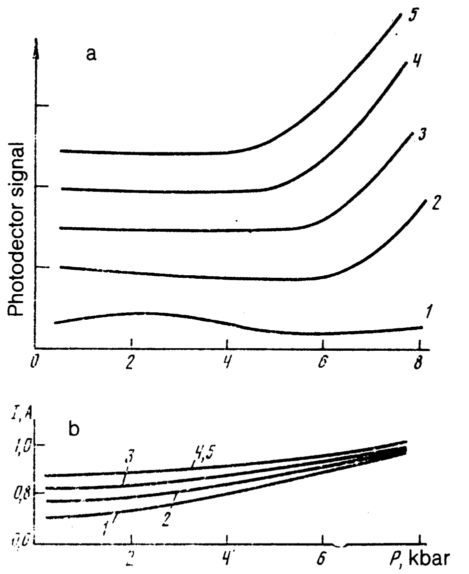


FIG. 7. Pressure dependence (**P**||[111]) of the intensity of spontaneous emission (a) and of the current flowing through the specimen (b) for different electric fields $E$ (in kV/cm): 0.6 (1), 1.0 (2), 2.0 (3), 3.0 (4), and 4.0 (5).

that the intersubband scattering time of the holes is significantly shorter than the intraband scattering time of light holes, is most important in the above arguments. If virtually all holes end up in the top energy band as a result of field-induced runaway, then, as before, for fixed photon energy (within the sensitivity band of the detector) the radiation should decrease exponentially with increasing pressure, but the slope is determined by the hole temperature $T_h$ in the top band. It is easy to verify that $T_h$ is related with the quantity $T_l$, presented in Fig. 5, by the relation

$$T_h = T_l (m_{\|h}/m_{\|l} - 1)^{-1}$$

(see the right-hand scale in Fig. 5). This makes it possible to understand the results obtained for different crystallographic orientations. Since the effective mass $m_{\|}$ of the holes in the top band is smaller for the [100] direction than for the [111] direction, the temperature $T_h$ is higher for [100]. As long as the electric field is too weak to heat the heavy holes, their temperature is determined only by intersubband scattering and does not depend on $E$. Starting with some field the heavy holes become heated, and their temperature increases (see Fig. 5). It is obvious that for the [100] direction, in which the mass of the heavy holes is smaller, the heating starts in weaker fields.

As the heavy holes are heated their energy distribution becomes smeared, so that population inversion of the valence subbands can exist only in fields which are not too strong. In the experiment, stimulated emission was observed, as a rule, in strong electric fields. However, in three of the specimens from among those studied stimulated emission was observed in comparatively weak fields immediately after impurity breakdown.

The dependence of the intensity of spontaneous emission on the pressure (**P**||[111]) for strong electric fields is shown in Fig. 7a. For $E < 0.5$ kV/cm the signal decreases slightly at pressures $P > 3$ kbar. For $E > 0.5$ kV/cm the signal is observed to increase at pressures of the order of 6 kbar. In this case, however, the current flowing through the specimen has no singularities (Fig. 7b). The intensification of the signal indicates another redistribution of the holes among the subbands; this could be attributed to heavy-hole streaming which is significant precisely in fields $E > 0.5$ kV/cm.[2] Under streaming conditions the hole distribution function is bounded by the optical phonon energy $\varepsilon_0$. Since hole transitions to the bottom of the light-hole band are possible in strained germanium, this limiting energy for heavy holes is equal to $\varepsilon_0 - \Delta$ (Fig. 8). After an optical phonon is emitted the holes occupy the bottom energy band, wherefrom they are rapidly transferred by the electric field into the top band.

Thus virtually all holes occupy the energy band $\varepsilon_0 - \Delta$. As the pressure increases this band decreases, and at $\Delta \approx \varepsilon_0$ virtually all holes are located at the bottom of the heavy subband. In this case we have strong inversion. Band splitting on the order of the energy of an optical phonon in Ge ($\approx 36$ meV) is achieved at pressures $\approx 9$ kbar in the [111] direction and $\approx 6$ kbar in the [100] direction. Stimulated emission arises precisely at these pressures (see Fig. 1). We note that in the [100] direction, due to the lower threshold pressure, stimulated emission could be observed at pressures for which the splitting was greater than $\varepsilon_0$, but in this case the intensity of the radiation decreased strongly with increasing pressure and, in addition, the threshold value of the electric field increased.

It should be noted that an emission jump could also be

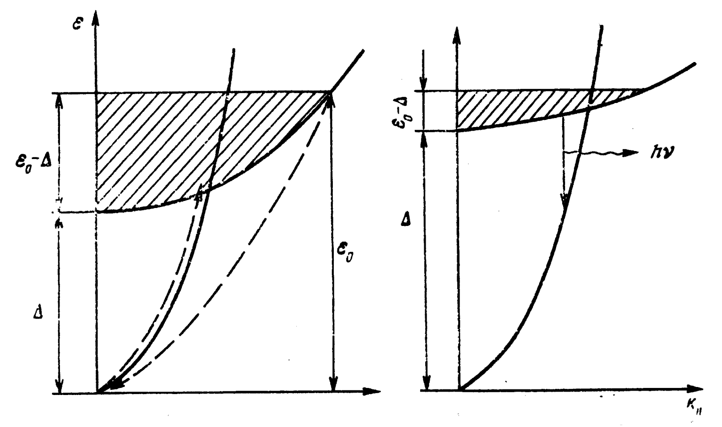


FIG. 8. Diagram illustrating the onset of strong inversion with band splitting by an amount of the order of the energy of an optical phonon.

observed at pressures lower than presented above.[1] It was found, however, that the threshold pressure $P_c$ depended on both the width of the voltage pulse and the material of the plungers through which the pressure was transmitted to the specimen. The reason is Joule heating of the specimen by the current and, as a consequence, additional compression of the sample by the plungers owing to the thermal expansion of the crystal. In the case of copper dies and pulse widths of $\approx 10\ \mu s$ it was possible to observe a jump of emission with virtually no external pressure. $P_c$ increased when the pulse width decreased the threshold value. For pulse widths less than $\approx 1\ \mu s$ the value of $P_c$ no longer changed and corresponded to the splitting of the valence band by an amount equal to the energy of the optical phonon.

Thus in uniaxially strained germanium stimulated hot-hole emission can appear in the absence of a magnetic field. The results presented here show that the population inversion in the valence subbands could be caused by the depletion of the light-hole band due to runaway of light holes up to energies corresponding to the higher-lying heavy-hole band split off by the pressure. The inversion is significantly intensified when the valence subbands are split by an energy of the order of the energy of an optical phonon, since in this case the maximum energy up to which the holes can be heated by the field is close to the bottom of the heavy-hole band.


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