Interband emission of hot holes during uniaxial compression of Ge

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(Submitted 10 August 1987; resubmitted 10 November 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 3, 136–138 (10 February 1988)

A far-IR emission of hot holes in Ge has been observed as a result of optical transitions from the heavy-hole band into the light-hole band, split by uniaxial compression. At the threshold values of the electric field and the pressure, an emission of a stimulated nature is observed to arise, with an intensity as much as 10^3 times that of the spontaneous emission.

Radiative transitions between different branches of the valence band in *p*-Ge have recently been studied in many laboratories. The motivation for this research is the observed stimulated emission in a strong electric field and a strong magnetic field.[1] In this letter we are reporting data on the emission of hot holes in *p*-Ge during uniaxial compression in the absence of a magnetic field.

We studied crystals of dislocation-free *p*-Ge with a Ga concentration $\sim 2\times 10^{14}$ cm^{-3}. The samples were cut in the form of thin prisms of square cross section, with a transverse dimension of 0.7–1.25 mm and a length between 5 and 10 mm along the [111] direction. The faces were parallel within 4′. The deformation was applied along the axis of the prism. In order to be able to vary the pressure continuously, we used a water-filled vessel as a load.[2] This approach made it possible to record a signal at pressures up to ~12 kbar. The emission was detected by a cooled Ge:Ga detector with a sensitivity band from 80 to 120 μm. The photodetector, the sample, and filters between them were immersed in liquid helium. The filters were made of quartz, a substance equivalent to Teflon, and InSb; they served to restrict the spectral interval reaching the detector. The InSb filter, with a concentration $\sim 10^{14}$ cm^{-3}, also made it possible to eliminate electrical stray pickup from the detector circuit. Voltage pulses 0.2–1 μs long were applied to annular contacts of In, positioned along the perimeter of the narrow cross section of the sample. The distance between contacts was 3–7 mm. Measurements were taken in fields above the threshold for impurity breakdown, so the hole concentration, determined by the total impurity concentration, was constant, and the voltage dependence of the current resulted from the field dependence of the effective hole mobility. As the pressure was raised, the current through the sample always increased, but never by more than a factor of 1.5. In strong fields, this growth was substantially weaker.

Figure 1 shows the intensity of the spontaneous emission from the sample, plotted versus the magnitude of the uniaxial compression, for various values of the applied voltage. In an electric field $E < 1$ kV/cm the emission intensity decreases at large deformation levels. In field $E \geqslant 1$ kV/cm, we observe a growth of the signal, beginning at a pressure of 4–5 kbar. We attribute this growth to an increase in the filling of the heavy-hole band in the electric field.

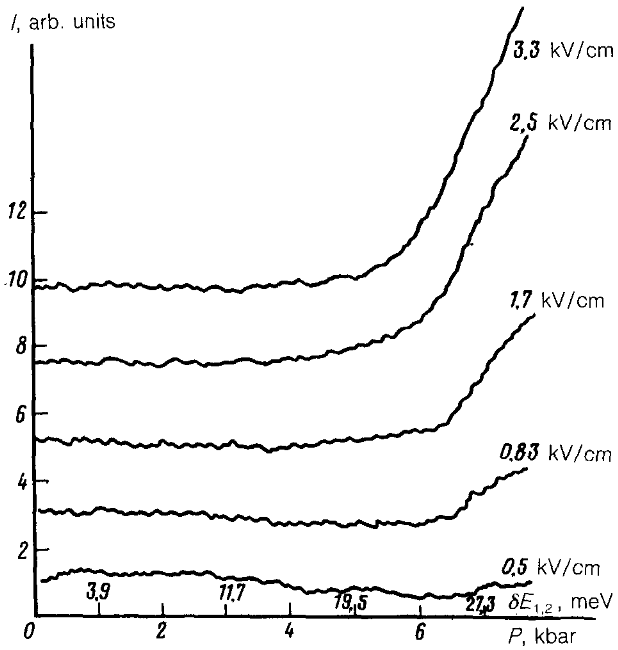

FIG. 1. Emission intensity versus the pressure for various voltages across the sample.

The uniaxial deformation lifts the degeneracy of the Ge valence band at $k=0$, and most of the hole concentration is in the band of lower energy, where the holes have a lower effective mass. The effective masses in the case of the compression of p-Ge along the [111] direction (low energies) are $m_{\parallel}^{(1)}/m_0=0.041$, $m_{\perp}^{(1)}/m_0=0.13$, $m_{\parallel}^{(2)}/m_0=0.483$, $m_{\perp}^{(2)}/m_0=0.053$. We used the following parameter values for the Ge valence band (expressed in units of electron volts): $A=-13.27$, $B=-8.63$, $D=-19.4$ (Ref. 3). When an electric field is applied, the light holes, rising in temperature, undergo transitions into the higher-lying band, with the larger mass. At fields as low as ~ 50 V/cm (Ref. 1), a ballistic heating of the light holes begins. This heating proceeds up to energies on the order of the energy of an optical phonon ($\hbar\omega_0=37$ meV in Ge). In other words, the light holes have enough energy to undergo transitions to the upper subband. Figure 2 shows possible optical transitions between branches of the valence band during uniaxial deformation. The dispersion curves were calculated for $P=3$ kbar from Eq. (30.5) of Ref. 3. We used the following values for the strain-energy constants: $a=-2.09$ eV and $d=-4.5$ eV. We used the value $S_{44}=1.5\times10^{-11}$ N/m^2 for the elastic constant. In the absence of a deformation, we can observe only transitions of type I (Ref. 1). Their intensity should fall off with increasing pressure because of the decrease in the concentration of light holes at energies near the energy of the photons which fall in the sensitivity band of the photodetector. Another mechanism might be intraband scattering of hot holes,[1] which should also decrease in a strong electric field as the pressure is raised. Consequently, the increase in the intensity of the emission with increasing pressure, which is observed in strong fields (Fig. 1), seems to be a consequence of the onset of optical transitions of type II.

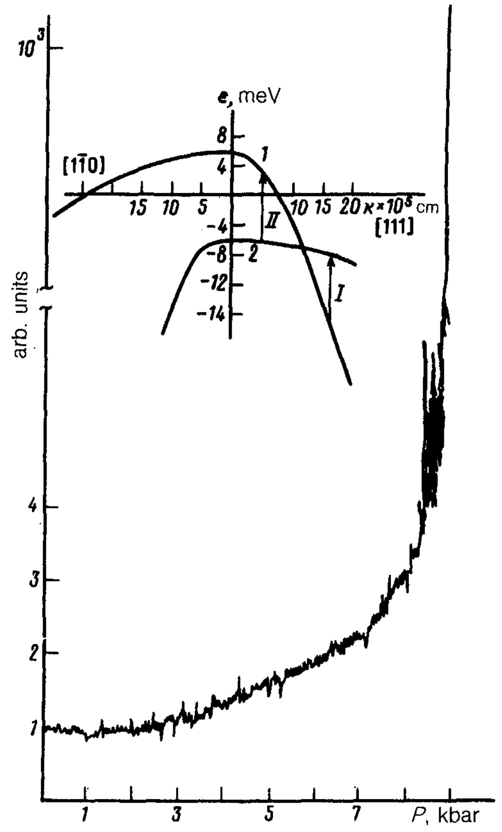

FIG. 2. Appearance of intense emission; diagram of optical transitions.

Clearly, these transitions can be observed only at a sufficiently high pressure, where the energy splitting of the bands falls in the sensitive interval of the detector, and at fields strong enough to provide the necessary accumulation of heavy holes. The splitting energy is $\delta E_{1,2} = (d/\sqrt{3})S_{44}P$, in the case $P \parallel [111]$; from this figure we find a coefficient of 3.9 meV/kbar. Accordingly, at pressures $P > 2.5$ kbar the value of $\delta E_{1,2}$ is already larger than the energy of the photons which fall in the sensitivity band of the photodetector.

To check these arguments, we studied the spontaneous emission from the same samples, again applying the pressure in the [111] direction, but with an electric field $E \perp [111]$. In this case the effective mass for the conductivity (in the field direction) in the light-hole band is larger than that for the heavy holes,[3] and the conditions for the heating of the holes of the lower band are seriously degraded. Consequently, the accumulation of holes in the upper band is reduced. In the case $E \perp P \parallel [111]$, the emission intensity falls off with the pressure up to $P = 5.5$ kbar in fields up to 5 kV/cm.

In several of the crystals, at fields above a certain threshold (1.5–3 kV/cm, depending on the particular sample), we observed a jump in the emission as the pressure was increased above 7.5 kbar (Fig. 2). The intensity of this jump could exceed the intensity of the spontaneous emission by three orders of magnitude. This jump in the emission was always accompanied by a sharp increase in the current (by a factor of several units), which was apparently caused by an increase in the concentration of light holes. Samples which exhibited no jump in the emission also exhibited no jump in the current. In two samples of the several studied, in which the faces were parallel within something on the order of 20″, the jump in the emission (and in the current) was observed at a field ~50 V/cm and at a pressure of 4–5 kbar. An intense emission occurred only in samples which were sufficiently long (with a distance $\geqslant 5$ mm between the current contacts). It may be that the observed jump in the emission is of a stimulated nature. This suggestion is supported by the fact that this emission occurs when a threshold is reached in both the electric field and the pressure. The increase in the spontaneous emission before the generation threshold and the jump in the current at the threshold are evidence that the reason for the stimulated emission is a population inversion between the heavy-hole and light-hole bands. Further research will of course be required in order to definitely prove that this emission is of a stimulated nature.

We wish to thank N. G. Zhdanova, S. N. Ivanov, and Ya. E. Pokrovskiĭ for a discussion of these results.

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Translated by Dave Parsons