Detection of light-hole accumulation in *p*-Ge in crossed electric and magnetic fields through far-IR measurements

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The onset of long-wave IR absorption and emission in strong electric fields has been observed in *p*-Ge. Direct optical measurements (at $\lambda = 80$–$130\ \mu$m) show that both the absorption and the emission result from transitions between upper branches of the valence band of Ge. An accumulation of light holes has been observed in crossed fields $\mathbf{E}\perp\mathbf{H}$. The dynamics of this accumulation has been studied.

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Theoretical results show that strong fields $\mathbf{E}\perp\mathbf{H}$ may change the carrier distribution in *p*-Ge significantly, to the extent that a hole population inversion occurs in a certain part of quasimomentum space.[1,2] An increase in the concentration of light holes in *p*-Ge has been observed in experiments on galvanomagnetic characteristics[3,4] and on the optical absorption in the near-IR region.[5]

In this letter we are reporting some direct optical measurements in the long-wave part of the IR range of *p*-Ge ($\lambda = 80$–$130\ \mu$m), which is the most interesting region from the standpoint of lasing and laser amplification. In electric fields above the impurity breakdown fields we observed the appearance of nonequilibrium absorption and emission of *p*-Ge in this wavelength region. It has been established experimentally that the two effects are of the same nature and result from 1-2 hole transitions between upper branches of the Ge valence band.

An intensification of the hole emission, implying the accumulation of light holes, was observed in crossed fields $\mathbf{E}\perp\mathbf{H}$. We studied the dynamics and other aspects of this phenomenon.

We studied Ge (Ga) crystals ($N_A - N_D = 5\times10^{13}$ and 4×10^{14} cm^{-3}) at $T = 1.5$–4.2 K in crossed fields $\mathbf{E}\perp\mathbf{H}$ with $E = 0$–1500 V/cm and $H = 0$–10 kOe. The optical measurements of the transmission and emission of *p*-Ge were carried out with a long-wave IR spectrometer in a helium lightguide cryostat[6] with a Ge (Sb) detector. The spectral interval of the measurements ($\lambda = 80$–$130\ \mu$m) was set by the red boundary of the detector and by the filters in the cryostat. The use of a pulsed modulation method eliminated secondary effects due to background emission and so forth.

In electric fields we observed the onset of long-wave IR absorption and emission in *p*-Ge; these effects behaved in similar ways as functions of E. Both effects set in at $E > 2E_0$, where E_0 is the impurity breakdown field. The absorption and emission intensities increase rapidly until saturation begins to set in at $E > 50$ V/cm (Fig. 1).

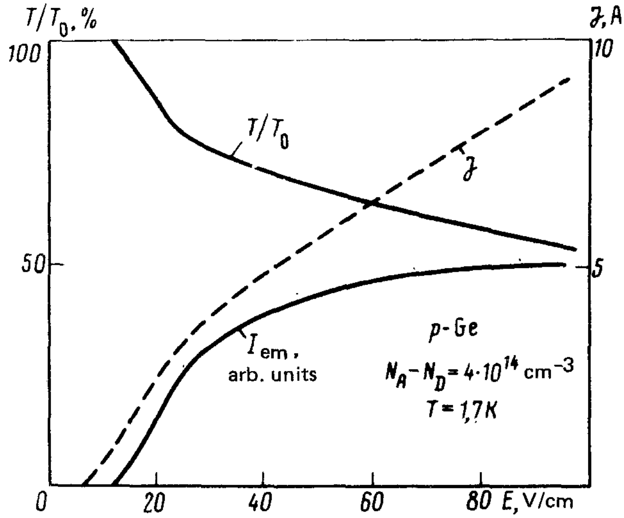

FIG. 1. Electric-field-induced long-wave IR emission and electric-field-induced change in the transmission of p-Ge. Shown for comparison is the voltage-current characteristic.

The observed decrease in the far-IR transmission of p-Ge cannot be attributed to impurity absorption (the impurities are essentially fully ionized). The Drude absorption by free carriers is also insignificant in the measurement region ($\sigma_{\text{fr}} \approx 2 \times 10^{-16}$ cm^2 for $\lambda = 100$ μm and $m_h = 0.33$ m_0). The lattice absorption due to the heating of the crystal occurs outside the spectral interval selected for the measurements. The phonon spectra of Ge nearest this interval are difference spectra and thus cannot make any appreciable contribution to the absorption. Direct measurements show that the absorption falls off as the repetition frequency of the pulses heating the sample is raised ($T \approx 50$–60 K, according to Ref. 7), and the samples become more transparent than the original samples ($E = 0$). These results are consistent with the conclusion that the observed absorption is due to 1-2 hole transitions in Ge. The absorption cross sections evaluated from the experimental data, $\sigma_{12} \approx 2 \times 10^{-14}$ cm^2, agree with data in the literature[9] and are significantly higher than those measured for Ge at 70-100 K (Ref. 8). A long-wave IR emission has been observed previously in n-Ge under impurity breakdown conditions[1)] and attributed to a radiative recombination of carriers at impurities.[10] A study of the spectrum of the emission observed in the present experiments and also several other experimental facts (in particular, the observed intensification of the emission, $I_{\text{em}} \sim N_{\text{imp}}$) lead to the conclusion that the long-wave IR emission of p-Ge is of the same nature as the absorption, i.e., a consequence of 1-2 hole transitions.

Figure 2 shows the dependence of the intensity of this emission on the electric field. In the absence of a magnetic field ($H = 0$) the emission intensifies with E, and at $E > 100$ V/cm it reaches saturation at a level corresponding to a concentration ratio $(n_2/n_1) \sim (m_2/m_1)^2$ of the light and heavy holes.[1,2] When a magnetic field is imposed we observe an increase in the 1-2 hole emission which is proportional to the concentration of the light holes in the region of **k** space under study (Figs. 2 and

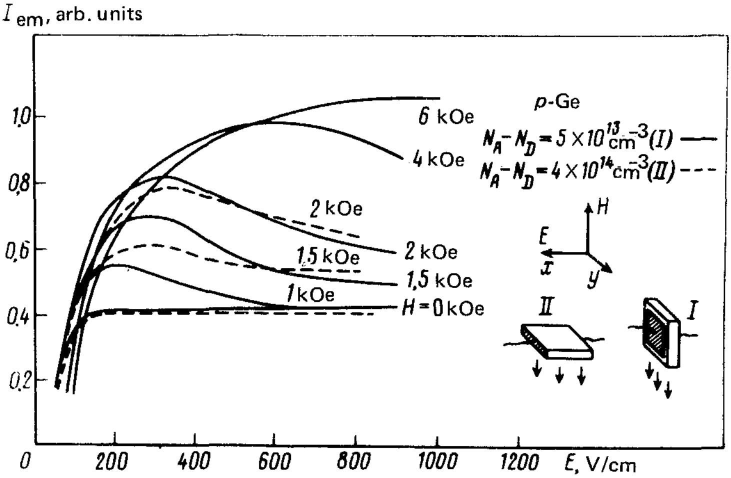

FIG. 2. Dynamics of the changes in the emission intensity in crossed fields $E \perp H$. The measurements of I_{em} for various samples are corrected to a common value at $H = 0$.

3). The curves of I_{em} (E, H) reveal a maximum, which shifts with increasing E toward a higher value of H. The position of this maximum conforms well to the theoretical straight line $c \cdot E/H = \sqrt{2\hbar\omega_{opt}/m_l}$ which corresponds to the theoretical conditions for the optimum accumulation of light holes,[2] as can be seen from the inset in Fig. 3. The picture in velocity space corresponding to these conditions is also shown in this figure. A rough estimate based on the experimental data shows that

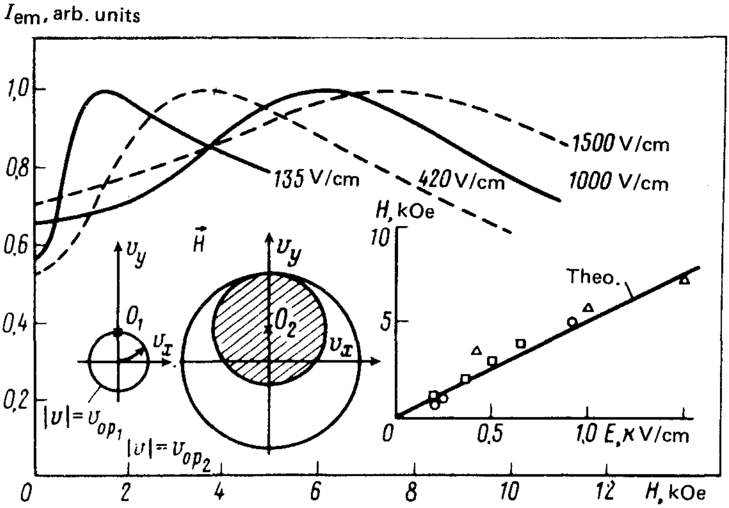

FIG. 3. Emission intensity as a function of H at various fields E. The curves are normalized to a unit value at the maximum. The points in the inset show experimental data on the position of the I_{em} (E, H) maximum. Δ and ○—Data on I_{em} (H) and I_{em} (E) for a sample with 5×10^{13} cm^{-3}; □—data on I_{em} (E) for a sample with 4×10^{14} cm^{-3}.

the accumulation of light holes reaches a value $n_2(H)/n_2(H=0)\approx 2$. The overall behavior of $I_{\text{em}}(E, H)$ is approximately the same in samples with $N_A - N_D = 5\times 10^{13}$ and 4×10^{14} cm^{-3}, whereas the emission intensity of the sample with the higher impurity concentration is substantially higher, as mentioned previously.

We see from Fig. 2 that the emission intensity measured at the maximum of the $I_{\text{em}}(E, H)$ curves increases with increasing E and H, but this growth slows substantially at $E>800$ V/cm. This fact contradicts the theory of Ref. 2, which predicts that the increase in the accumulation of light holes will continue up to fields $E\sim 4$ kV/cm. This slowing of the growth may have several causes, including an adiabatic overheating of the samples. It is clear, however, that a possible deviation from a perfectly perpendicular orientation of E and H should play an important role in this effect. At strong fields E, the existence of a longitudinal component of $\mathbf{E}$ (parallel to $\mathbf{H}$) can "extract" a substantial number of the light holes from the accumulation region.

According to the theory, the average hole energy in *p*-Ge in fields $E\geqslant 20$–30 V/cm corresponds to temperatures on the order of 100 K (Ref. 1). The value $\sigma_{12}\approx 2\times 10^{-14}$ cm^2 found in the present experiments is nearly an order of magnitude higher than the values measured in Ref. 8 for *p*-Ge at $T=70$–100 K. Using theoretical results[9] on the temperature dependence of σ_{12}, we may suggest that under the present experimental conditions at $E\approx 50$–100 V/cm ($N_A - N_D\approx 4\times 10^{14}$ cm^{-3}) an important role is being played by the scattering of holes by charged impurities. This scattering results in a decrease in the average energy of the carriers and in an increase in the relative number of low-energy holes. It is apparently this group of the carriers (with $T_{\text{eff}}\approx 10$–20 K) which dominates the 1-2 hole absorption in "subtransit" electric fields ($E\lesssim 50$–100 V/cm). This assertion is confirmed by measurements in electric-field-heated samples ($T\approx 50$–60 K), in which the induced absorption disappears almost completely.

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[1)] A long-wave IR emission has also been observed in purer *p*-Ge samples (Yu. L. Ivanov, private communication).

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