Detection of overpopulation of the subband of light holes in *p*-Ge in strong crossed E and H fields

V. A. Valov, V. A. Kozlov, L. S. Mazov, and I. M. Nefedov
Institute of Applied Physics, Academy of Sciences of the USSR

(Submitted 28 April 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 11, 608–611 (5 June 1981)

The galvanomagnetic characteristics of *p*-Ge in strong crossed **E** and **H** fields were investigated experimentally at 4 K. The relative density of light holes was found to be substantially higher than the equilibrium value. This indicates that the radiative transition between the subbands of light and heavy holes is inverted.

PACS numbers: 72.20.My, 72.80.Cw

The hot current carriers in semiconductors can produce inverted distributions under conditions of inelastic scattering by optical phonons.[1-3] The subband of light holes can become overpopulated in *p*-Ge, and in semiconductors similar to it, with degenerate subbands of heavy and light holes in strong crossed **E** and **H** fields[3-5]—the relative density of light holes increases, as compared with the equilibrium value equal to $(m_l/m_h)^{3/2}$, where m_l and m_h are the effective masses of light and heavy holes. This overpopulation gives rise to a number of curious effects, the most important of which is the generation or amplification of far infrared radiation due to inversion of the radiative transition between the subbands of light and heavy holes.[5] We have detected a considerable increase (approximately fourfold) of the relative density of light holes in *p*-Ge in strong $\mathbf{E}\perp\mathbf{H}$ fields. We have drawn this conclusion on the basis of an experimental investigation of galvanomagnetic characteristics of *p*-Ge and by comparing them with the results of calculations using the Monte Carlo method. The effect of light holes on the current-voltage characteristics of pure *p*-Ge samples in $\mathbf{E}\perp\mathbf{H}$ fields was noticed for the first time in Ref. 6. Similar peculiarities in the behavior of a Hall field have been reported recently.[7]

The subband of light holes becomes overpopulated because of accumulation of light holes in the spindle-shaped K_l region of closed momentum-space trajectories,[1,8] in which the energy of the holes is insufficient for radiation of an optical phonon and

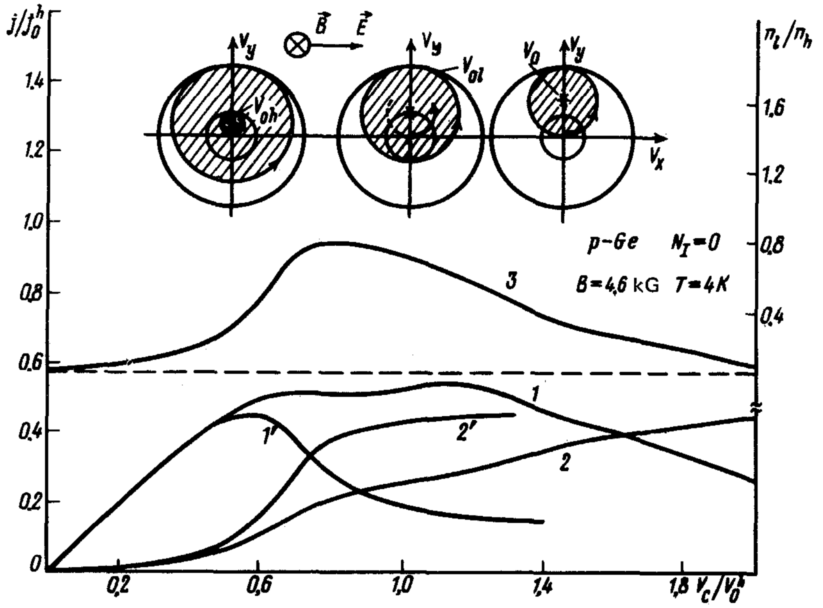

FIG. 1. Results of a calculation using the Monte Carlo method. (1, 1') $-j_H/j_0^h$; (2, 2') $-j_D/j_0^h$; (3) $-n_l/n_h$. (1', 2')–single-band model. $j_0^h = en_{\text{tot}}/v_0^h$; $n_{\text{tot}} = n_h + n_l$; n_l is the density of light holes, n_h is the density of heavy holes; the dashed line represents the equilibrium value of $n_l/n_h = (m_l/m_h)^{3/2}$; the K_l and K_h regions are denoted by hatched lines.

the time between the collisions is large. If the spindle-shaped K_h region in the subband of heavy holes is missing and the K_l region exists, which occurs when $v_0^h < v_c < v_0^l$, then there is an accumulation only in the light subband, which increases n_l/n_h. Here $v_c = cE/H$ is the drift velocity in $\mathbf{E} \perp \mathbf{H}$ fields, v_0^h and v_0^l are the velocities at the boundaries of passive energy regions ($\epsilon < \hbar\omega_0$) for heavy and light holes, and $m_h (v_0^h)^2/2 = m_l (v_0^l)^2/2 = \hbar\omega_0$ is the energy of the optical phonon (see Fig. 1).

Figure 1 shows the results of a calculation of the Hall j_H and the dissipative j_D currents (see Fig. 2) using the Monte Carlo method as well as n_l/n_h plotted as a function of v_c/v_0^h at a constant magnetic field $B = 4.6$ kG. We have used a spherically symmetric model of the band structure, $m_h = 0.35\, m_0$, $m_l = 0.043\, m_0$: Scattering by optical and acoustic phonons was taken into account. For comparison, we present the results of a calculation of j_H and j_D using a single-band model and ignoring the light holes. The overpopulated subband of light holes has characteristically much larger values of j_H than the single-band model at $v_c/v_0^h \approx 1$, where the K_h region vanishes (Fig. 1). This is attributable to the fact that the light holes accumulated in the K_l region contribute significantly to j_H.

Figure 2 shows the results of measurements of j_h and j_D at $T = 77$ K and 4 K in a magnetic field $B = 9.2$ kG. The measurements were conducted in a pulsed regime ($\tau_p \sim 1$ μsec) using a method with a large off-duty factor which is described in Ref. 9. We have used p-Ge samples with a hole density $N_A - N_D \approx 2 \times 10^{13}$ cm^{-3} and mobility $\mu_{77} \approx 40\,000$ cm^2/V · sec in nitrogen. The shape and orientation of the sample

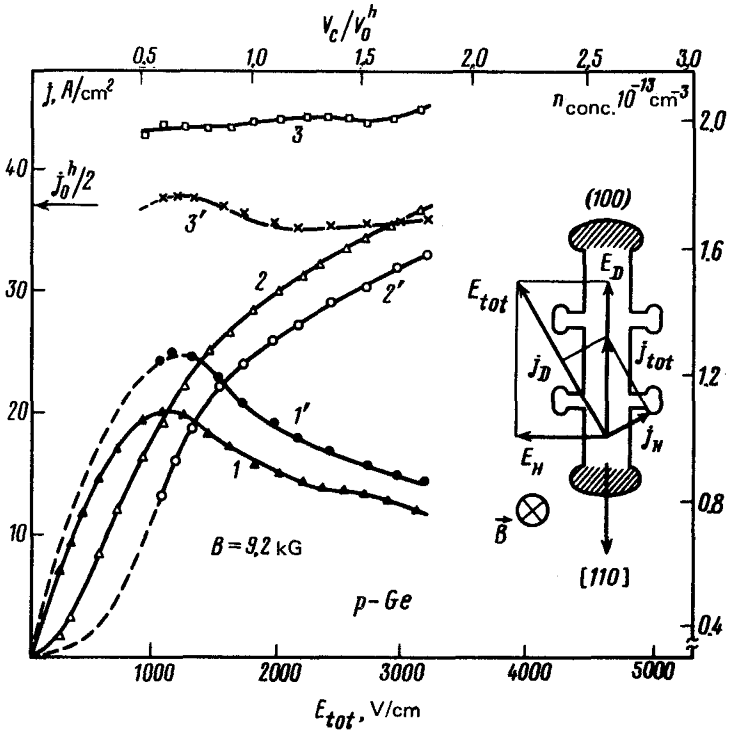

FIG. 2. Results of the experiment. (1, 1′) -j_H; (2, 2′) -j_D; (3, 3′) - Hall density $n_{\rm Hall} = Bj_{\rm tot}/eE_H$; (1′, 2′, 3′) - T = 4 K; (1, 2, 3) - T = 77 K.

are illustrated in Fig. 2. The results of measurements at 4 K are given for fields in which the carrier density remained the same with increasing field. The $n_{\rm Hall}$ dependence ($E_{\rm tot}$) in Fig. 2 is associated with the variation of the Hall factor; the difference in $n_{\rm Hall}$ at T = 4.2 K and 77 K is apparently attributable to an incomplete ionization

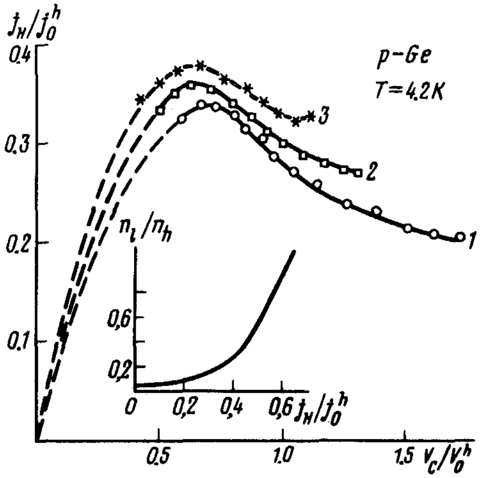

FIG. 3. Results of measurements of j_H/j_0^h as a function of v_c/v_0^h in different magnetic fields. (1) - B = 9.2 kG; (2) - B = 13.8 kG; (3) - B = 18.4 kG; (4) - dependence of n_l/n_h on j_H/j_0^h.

of impurities.

The results of calculation using the Monte Carlo method for different temperatures and magnetic fields show that at $\nu_c/\nu_0^h = 1$, when the K_h region has vanished and n_l/n_h has a maximum value, j_H/j_0^h corresponds to n_l/n_h, as roughly illustrated by curve 4 in Fig. 3. This allowed us to estimate the value of n_l/n_h from the experimental measurements of j_H and j_D in the E_{tot} field. As the cyclotron frequency increases at a specified value of ν_c/ν_0^h, the value of n_l/n_h must increase because the transit time of a heavy hole through the passive region decreases. Figure 3 shows the j_H/j_0^h and ν_c/ν_0^h dependences for several values of the magnetic field. It can be seen in these plots that the following values of n_l/n_h are obtained when $\nu_c/\nu_0^h \approx 1$: $B = 9.2$ kG, $n_l/n_h = 0.12 = 2.8\,(m_l/m_h)^{3/2}$; $B = 13.8$ kG, $n_l/n_h = 0.13 = 3.1\,(m_l/m_h)^{3/2}$; $B = 18.4$ kG; $n_l/n_h = 0.17 = 4\,(m_l/m_h)^{3/2}$. A relatively small overpopulation also occurs at 77 K because of an increase in acoustic scattering in the passive region: $B = 9.2$ kG, $n_l/n_h = 0.08 = 1.9\,(m_l/m_h)^{3/2}$.

The observed increase in the density of light holes indicates that the radiative transition between the subbands of light and heavy holes is inverted, since a rough criterion of overpopulation of this transition is the fact that the relative density n_l/n_h is higher than the value of $(m_l/m_h)^{3/2}$ (see Refs. 3 and 5).

In conclusion, the authors thank A. A. Andronov for his supervision over this work, V. N. Murzin for a discussion and interest in this work, and S. Komiyama for giving us the opportunity to read his article[7] before its publication.

1. H. Maeda and T. Kurosawa, J. Phys. Soc. Japan 33, 562 (1972).
2. S. Komiyama, T. Masumi, and K. Kajita, Phys. Rev. B 20, 5192 (1979).
3. A. A. Andronov, V. A. Valov, V. A. Kozlov, and L. S. Mazov, Solid State Commun. 36, 603 (1980).
4. I. I. Vosilyus, Fiz. Tverd. Tela 11, 924 (1969) [Sov. Phys. Solid State 11, 755 (1969)].
5. A. A. Andronov, V. A. Kozlov, L. S. Mazov, and V. N. Shastin, Pis'ma Zh. Eksp. Teor. Fiz. 30, 585 (1979) [JETP Lett. 30, 551 (1979)].
6. L. K. Gvardzhaladze and Yu. L. Ivanov, Fiz. Tekh. Poluprovodn. 7, 1328 (1973) [Sov. Phys. Semicond. 7, 890 (1973)].
7. S. Komiyama (submitted to Phys. Rev. Lett.).
8. I. I. Vosilyus and I. B. Levinson, Zh. Eksp. Teor. Fiz. 52, 1013 (1967) [Sov. Phys. JETP 25, 672 (1967)].
9. A. A. Andronov, V. A. Kozlov, L. S. Mazov, and V. A. Valov, J. Phys. C: Solid State Phys. 13, 6287 (1980).

Translated by S. J. Amoretty
Edited by Robert T. Beyer