Hot-hole cyclotron resonance in germanium in constant fields E⊥H

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The cyclotron-resonance spectra of hot holes in germanium have been measured at the wavelength $\lambda = 1.65$ mm in a constant electric field **E**⊥**H**|| [001]. These are the first reported measurements of this type. The results reveal an overpopulation, effects of a nonparabolic light-hole dispersion law, a cutoff of the light-hole cyclotron resonance at $\mathbf{E} > 500$ V/cm, and the appearance of even harmonics of the heavy-hole cyclotron frequency.

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1. Hot-hole effects in germanium[1-5] have attracted interest because of the associated possibility of arranging a negative differential conductivity at wavelengths 2 mm $\gtrsim \lambda \gtrsim 0.05$ mm. This negative conductivity would result from an inversion of heavy holes in terms of the cyclotron-revolution energy in fields[6,7] **E**⊥**H** and **E** || **H** (this is a classical analog of an inversion in terms of Landau levels) and from that inversion of direct optical transitions between heavy and light subbands which occurs in fields **E**⊥**H** and which is accompanied by an increase in the light-hole concentration to a point above its equilibrium value.[8] Extensive information on the properties of holes in strong electric and magnetic fields can be obtained by the cyclotron-resonance method, which can be used to study light and heavy holes separately, to determine their concentrations and relaxation times in a constant electric field,[9] to find effects resulting from the complex dispersion law, and, finally, to determine the absorption of germanium under conditions favoring a cyclotron-resonance negative differential conductivity.

In this letter we are reporting the first results of backward-wave-tube spectroscopy involving the cyclotron resonance of hot holes in Ge(Ga) at the wavelength $\lambda = 1.65$ mm, at $T \cong 10$-30 K, in electric fields up to 1 kV/cm.

2. In the experiments, the absorption of the millimeter-wave radiation from a backward-wave tube is measured in p-type germanium in a constant external magnetic field and a pulsed external electric field. The radiation propagates through a quasioptical system to a sample of square cross section, cut along [100] crystallographic axes. The sample is in a helium cryostat, at the center of a superconducting solenoid ($p \cong 4 \times 10^{13}$ cm^{-3}, $N_A + N_D \sim 10^{14}$ cm^{-3}). A plane face of the sample with an area of 4.7×4.7 mm^2 is oriented perpendicular to the magnetic field and to the wave vector of the millimeter-wave radiation. A voltage pulse ($\tau_p = 10$ μs, $f_{rep} = 3.3$ Hz) applied to opposite faces with areas of 4.7×0.7 mm^2 ionizes acceptors,[1)] giving rise to a modulation of the millimeter-wave radiation propagating through the sample. The output signal from an n-InSb detector below the sample is converted by a strobe integrator and recorded on a chart re-

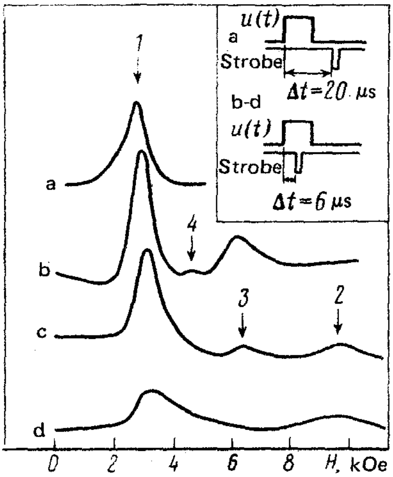

FIG. 1. The cyclotron-resonance spectra of p-Ge in crossed fields $\mathbf{E} \perp \mathbf{H}$. Arrow 1–Light holes; 2–4–second through fourth harmonics of the heavy-hole cyclotron resonance. u/l, V/cm; a–0 ($T = 30$ K); b–90; c–330; d–780.

corder. The signal is stored in the strobe integrator at the time of arrival of a strobe pulse, synchronized with the voltage pulse.

3. Figure 1 shows some typical cyclotron-resonance spectra. Spectrum *a* is that of equilibrium holes; it was obtained by applying the strobe pulse immediately after the voltage pulse, $u/l = 1300$ V/cm ($l = 0.47$ cm is the length of the sample). This voltage pulse heated the lattice to $T \cong 30$ K (according to an estimate for adiabatic heating), so that essentially all the acceptors were ionized[2)] (see the inset in Fig. 1). Spectra *b-d* correspond to coincident strobe and voltage pulses. In this case we can evaluate the ratio of the number of light holes at $u = 0$ ($p_{0,l}$) and $u \neq 0$ (p_l), taking the integrated intensity of the cyclotron-resonance line to be proportional to the hole concentration, $\int I(H)dH \sim p$.

The results show that the light-hole concentration begins to exceed its equilibrium value ($p_l/p_{0,l} > 1$) even at moderate electric fields, $u/l \sim 100$ V/cm (Fig. 2). Overpopulation effects in such fields have not been discussed or, apparently, observed previously. The overpopulation remains up to strong electric fields, at which $v_c \sim 0.3 v_l \sim v_h$ [here $v_c = cE/H$, $v_{l,h} = (2\hbar\omega_0/m_{l,h})^{1/2}$, $m_{l,h}$ are the effective masses of the light and heavy holes, and $\hbar\omega_0$ is the energy of the optical phonon]. In such fields the overpopulation results from the intense scattering of heavy holes by optical phonons, which increases the rate of transitions from heavy to light holes; the number of inverse transitions is small because of the magnetization of the light holes.[9]

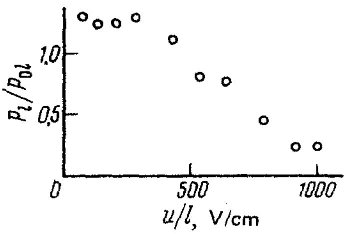

FIG. 2. Dependence of the concentration of "magnetized" light holes on the electric field. Here $p_{0,l}$ is the concentration of thermalized light holes at $T = 30$ K.

At fields $u/l > 500$ V/cm there is a decrease in the line intensity (a cutoff of the cyclotron resonance), because of an increase in the relative number of the holes which are "demagnetized," i.e., which reach an energy $\epsilon = \hbar\omega_0$ over a time shorter than the wave period, are scattered by a phonon, and thus do not participate in the cyclotron resonance. These events are accompanied by a decrease in the total number of light holes and by a disappearance of the overpopulation.[9]

4. With increasing electric field, the light-hole cyclotron-resonance line is observed to shift toward a stronger magnetic field: $\Delta \mathbf{H}/\mathbf{H} \sim 20\%$ at $v_c \sim 0.5 v_l$. Calculations show that this effect results from the deviation from a parabolic dispersion law for the light holes, which is manifested during the heating of the carriers. In a strong electric field some of the holes reach an energy $\epsilon \sim \hbar\omega_0$, at which their mass increases significantly, during the cyclotron-revolution period. At $v_c = 0.5 v_l$, the cyclotron frequency of such holes is 8% lower than that of the holes which are revolving at energies $\epsilon \sim 3/2\, kT = 0.1\, \hbar\omega_0$ with $T = 30$ K and $E = 0$. The shift of the cyclotron-resonance peak in the electric field is caused by both a decrease in the average value of ω_c and a change in the line shape[10] caused by the dependence of ω_c on the hole oscillation energy. Estimates show that both of these effects shift the peak by 15%, if it is assumed that at $\epsilon < \hbar\omega_0$ the holes are localized around a trajectory in momentum space which passes through $\epsilon = 0$ (a principal trajectory), as a result of inelastic scattering by optical phonons. The good agreement of this estimate with experiment may be regarded as indirect evidence for the occurrence, at $u/l > 500$ V/cm, of a localized distribution of this sort, which is a distribution with an inversion in terms of the cyclotron-revolution energy.[11]

5. The spectra in Fig. 1 reveal the appearance and intensification of the second and fourth harmonics of the heavy-hole cyclotron resonance, along with a decrease in the intensity of the third harmonic, with increasing electric field. We know that with $\mathbf{H} \parallel [001]$ and $E = 0$ the cyclotron-resonance spectrum of the heavy holes, with their anisotropic dispersion law, has only odd harmonics, because of the fourfold symmetry of the free-motion trajectories (Fig. 3). In an external electric field $\mathbf{E} \parallel [100]$ this symmetry is disrupted; the intensities of the odd harmonics of the cyclotron revolution change; even harmonics appear; and we see evidence that the cyclotron revolution of the holes is not isochronous.[7,12] Even harmonics appeared experimentally even at low drift velocities, $v_c \sim 0.1 v_h$ (Fig. 1). At $v_c > 0.5 v_h$, the nonisochronous revolution of the holes occurs: The second cyclotron harmonic of the heavy holes shifts 10% toward stronger magnetic fields at $v_c = 0.45\ v_h$.

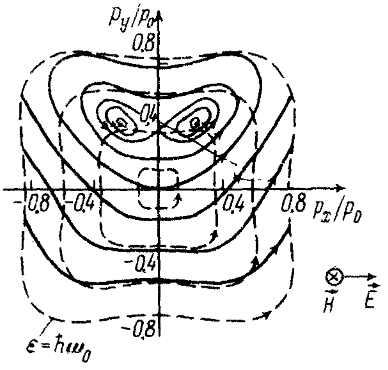

FIG. 3. Free-motion trajectories of heavy holes in the $p_z = 0$ plane in momentum space for energies $\epsilon < \hbar\omega_0$. $\mathbf{H} \parallel [001]$, $\mathbf{E} \parallel [100]$, $E/H = 0.1$ V/(cm · Oe). Dashed curves–$E = 0$. $p_0 = (2m_h \hbar\omega_0)^{1/2}$, where $m_h = 0.32 m_0$.

It would be very interesting to see a further study of the hot-hole cyclotron resonance in pure germanium samples. We may expect that when an inversion in terms of the cyclotron-revolution energy is reached, the nonisochronous revolution of the holes [due to the nonparabolic nature of $\epsilon(p)$ in the case of the light holes or due to the anisotropy of $\epsilon(p)$ in the case of the heavy holes] will give rise to a cyclotron-revolution, negative-differential conductivity in crossed fields $\mathbf{E} \perp \mathbf{H}$.

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[1)] It has been determined elsewhere that at $T = 4.2$ K there is essentially full ionization of the shallow impurities in p-Ge ($p \sim 10^{14}$ cm^{-3}) in fields $E \sim 20$–40 V/cm (see Ref. 1, for example).

[2)] The characteristic thermalization time for the holes at the end of the field pulse is $\lesssim 10^{-8}$ s. The subsequent cooling of the sample and the corresponding freezing of the holes occur in a time $\gtrsim 10^{-3}$ s. The hole concentration after the field pulse depends on the energy imparted to the sample by the electric field; for pulses 10 μs long, the hole concentration reaches saturation at $u/l > 900$ V/cm, as was verified from the cyclotron resonance.

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