Cyclotron resonance of hot holes heated by a SHF field in uniaxially deformed Ge

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Cyclotron resonance of holes heated by a SHF field to energies of the order of the deformation splitting of the valence band $\Delta_v \gg kT$ was observed in germanium crystals compressed along the $\langle 111 \rangle$ and $\langle 100 \rangle$ axes, in both (split) bands. The cyclotron mass m_c of the "hot" holes of the fundamental band measured in the direction of the magnetic field along the axis of compression coincides with m_c for heavy holes in nondeformed Ge.

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In the deformation of Ge crystals a quadruply degenerate valence band is split into two doubly degenerate bands with respect to spin. The parameters needed to describe the dispersion law for the valence band were obtained in Refs. 1–3 in a study of cyclotron resonance (CR). Because of the interaction of the split bands, the dispersion law $\epsilon(k)$ for holes in the range of energies of the order of the deformation splitting Δ_v differs strongly from the quadratic law.[4] In this energy range we can expect a nonlinear behavior of the response of a system of free carriers to a strong electromagnetic field at temperatures $T \ll \Delta_v / k$.

We studied the CR of holes in uniaxially compressed Ge crystals at different SHF intensities of the field and excitation densities of the nonequilibrium carriers ($n_{e,h}$). The experiment was carried out at $T = 1.27$ K; however, the picture did not change qualitatively even at $T = 4.2$ K. The observation of the CR was carried out in the 3-cm SHF range. A band cavity was used as the absorbing cell. The sample in the shape of a rectangular parallelpiped $0.5 \times 2 \times 8$ cm^3 was placed parallel to the band in the electric-field loop. The nonequilibrium carriers were excited in the center of the sample by using a yttrium aluminum garnet laser (1.06 μm). To obtain a deformation (along the greatest axis) the sample was held at room temperature in miniature capron clamps. On cooling down to the helium temperature, the crystal deformation increased greatly because of the different thermal expansion coefficients for Ge and capron. Control of the magnitude and uniformity of the deformation was accomplished according to the emission spectrum of excitons at $T = 4.2$ K. The splitting of the valence band in our experiments was 4–5 MeV.

The SHF absorption was measured according to the elapsed-time technique. In order to maintain a constant SHF signal input to the receiver, two attenuators (in front of and behind the cavity) were used in the SHF circuit. Under the experimental conditions the SHF electric field was perpendicular to the plane in which a constant magnetic field H was rotated. Thus, the probability of CR absorption was independent of the direction of H. The CR spectra for nondeformed and uniaxially compressed Ge in weak SHF fields for a low excitation density of $n_{e,h} \sim 10^{13}$ cm^{-3} were in good agree-

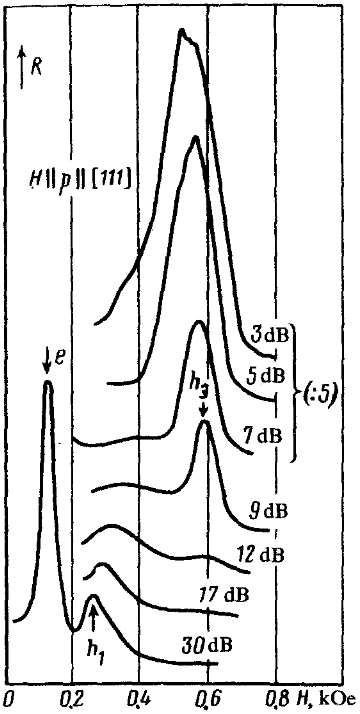

FIG. 1 The spectra of CR for Ge compressed along the ⟨111⟩ axis for a fixed laser excitation and different strengths of the SHF field. The maximum strength of the SHF field is ~30 mW, e are electrons, and h_1 and h_3 are holes.

ment with those in the literature.[3] The dependence of the CR spectra on SHF power was investigated for different $n_{e,h}$. The characteristics described below were most evident for $n_{e,h} \sim 10^{14} - 10^{15}$ cm^{-3}. The maximum SHF power in the cavity was 100 mW.

Figure 1 shows the evolution of the absorption line for holes in the CR spectrum as the SHF field intensity is increased. At first, the CR line for the holes h_1 is broadened greatly and its maximum is shifted in the direction of stronger fields. This result which agrees with the observations of Hensel and Feher,[3] is related to an increase in the cyclotron mass of the holes in proportion to the increase of their energy due to heating by the SHF field.[3] At a certain strength (~12 dB), however, when the position of the h_1 peak does not vary by more than 20%, a new absorption line h_3 is produced in a stronger field H, which corresponds to the CR position for holes with mass close to the cyclotron mass for heavy holes in nondeformed Ge crystals. As the strength of the SHF field is increased, the intensity of the h_3 line at first increases rapidly (Fig. 1), and then is broadened, basically in the direction of weaker fields, and the strong SHF absorption extends along the entire region $H < H(h_3)$. Since we are not concerned with studying the CR in the stronger SHF fields, the corresponding spectra are not shown.

Simultaneously with the h_3 line, the CR spectrum exhibits a resonance absorption near the CR of electrons (e) which appears at excitation density $n_{e,h} \sim 10^{14}$ cm^{-3} in the form of a separate narrow line h_2 (Fig. 2). We measured the angular dependence of

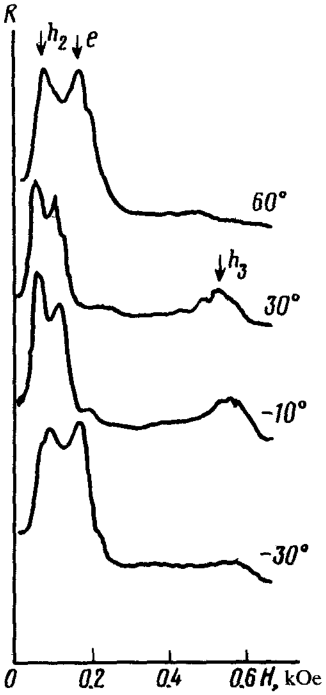

FIG. 2. Angular dependence of the CR spectra for Ge compressed along the ⟨111⟩ axis for $n_{e,h} \sim 10^{14}$ cm^{-3} and strength of the SHF field ~10 mW. The numbers near the curves denote angles between the **H** and **P**. **P** is the compression force.

the position of the lines h_1 and h_2 (Fig. 3). We find that for the h_2 line this dependence agrees with the one calculated for holes at the base of the detached band, if we use the

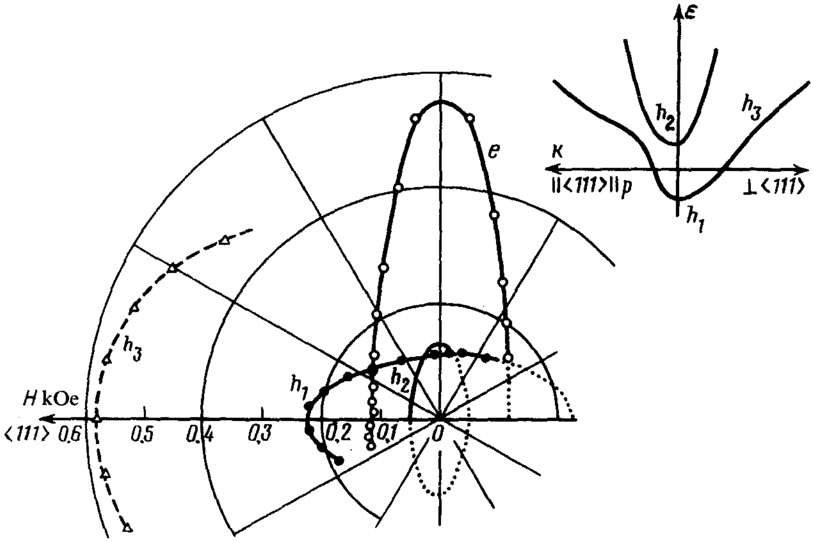

FIG. 3. Angular dependence of cyclotron masses of the electrons (e) and hole (h_1, h_2, and h_3) in Ge compressed along ⟨111⟩. The broken line denotes the angular dependence of the cyclotron mass of the heavy holes in nondeformed Ge. The inset shows the qualitative picture of the spectrum $\epsilon(k)$ of the valence band in compressed Ge.[4]

known band parameters $A = -13.38$, $D = -19.8$,[1] $m_{\perp}^{-1} = A + D/2\sqrt{3}$, and $m_{\parallel}^{-1} = A - D/\sqrt{3}$.[4] Thus, because of the heating of the holes by the SHF field it is possible to measure directly the effective masses for the holes not only in the main band but also in the detached band.

The appearance of the h_2 line in the CR spectrum indicates that the holes are heated by the SHF field to energies of the order of the deformation splitting of the valence band (in our case $\Delta_v \sim 5$ MeV). We can assume that the h_3 line is due to the CR of the "hot" holes with energies $\epsilon \gtrsim \Delta_v$ in the main hole band. A similar line can also be seen in crystals compressed along the $\langle 100 \rangle$ axis for $\mathbf{H} \| \mathbf{P}$. In both cases $[\mathbf{P} \| \langle 111 \rangle$ (Fig. 2) and $\mathbf{P} \| \langle 100 \rangle]$ for a fixed strength of the SHF field the intensity of the h_3 line decreased rapidly as the angle ϕ between **H** and **P** increases to greater than 30°. For small ϕ the position of the h_3 line is close to the cyclotron mass of heavy holes in the nondeformed Ge (Fig. 3). The disappearance of the h_3 line at angles $\phi > 30°$ at first sight appeared unexpected, since it is difficult to assume that by varying the angle ϕ the relaxation time of the holes will vary greatly or the absorption of the SHF energy will decrease under the experimental conditions when $\mathbf{E} \perp \mathbf{H}, \mathbf{P}$. However, such behavior of the CR spectrum can be explained qualitatively within the framework of the existing concepts concerning the behavior of a system of "hot" carriers. We note that under the experimental conditions the CR for holes in the detached band corresponds to the "cold" holes at its base. This means that the average energy of the holes in the fundamental band does not greatly exceed the splitting Δ_v. When $\mathbf{H} \| \mathbf{P}$, the hole orbit lies in the plane perpendicular to the compression axis, where the distortion of the dispersion law for the hole band is much less than in the direction of the compression axis (see inset in Fig. 3). Thus, even for holes with $\epsilon \sim \Delta_v$, for $\mathbf{H} \| \mathbf{P}$ the cyclotron mass is close to the cyclotron mass for the heavy holes. In the geometry $\mathbf{H} \perp \mathbf{P}$, this can be obtained only for a much greater heating of the carriers. However, on further heating of the carriers the CR lines are broadened sharply.

Therefore, the characteristics observed in the CR spectra are attributable to the special features of the density of states of the valence band.

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