Ballistic heating of holes in uniaxially deformed germanium

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It is shown that the maximum energy for ballistic heating of holes in the upper valence energy subband, which is split off by pressure, in germanium is the energy at which intersubband scattering accompanied by the emission of optical phonons starts. © *1995 American Institute of Physics.*

Heating of charge carriers under the conditions of strong threshold scattering by optical phonons results in a strongly anisotropic carrier momentum distribution, which is extended in the direction of the electric field. If the condition

$$\tau \gg \tau_E = p_0/eE \gg \tau_0 \qquad (1)$$

(here τ is the mean free time for carrier energy $\epsilon < \epsilon_0$, ϵ_0 is the energy of an optical phonon, $p_0 = (2m\epsilon_0)^{1/2}$, m is the effective mass, e is the elementary charge, and τ_0 is the emission time of an optical phonon) is satisfied, the carriers will execute a shuttle motion: They are accelerated by the electric field to energy ϵ_0 in a time τ_E, without having enough time to scatter by acoustic phonons or impurities [left-hand side of the inequality (1)]. They then lose their energy virtually instantaneously, emitting an optical phonon [right-hand side of Eq. (1)]. The process is then repeated (see the left inset in Fig. 1). This motion of carriers under conditions of ballistic heating is called streaming.[1,2]

We have investigated spontaneous far-IR radiation produced as a result of optical transitions of holes between the valence subbands of germanium; this is a convenient method for studying the ballistic heating of carriers.[3] The experimental conditions and the samples are the same as those in our preceding studies:[4,5] liquid-helium temperature, electric field applied in the direction of compression, and radiation measured with a Ge ⟨Ga⟩ detector. In undeformed germanium a maximum is observed in the field dependence of the spontaneous far-IR radiation. This maximum is attributed to the onset of ballistic heating of light holes. The decay of the radiation intensity (curve 1 in Fig. 1; see also Ref. 3) is attributed to the streaming-induced "needle-like" shape of the distribution function in the momentum space, as a result of which the concentration of light holes which contribute to the emission in the sensitivity band of the detector decreases, or to a change in the carrier lifetime on ballistic trajectories.[3] Under the conditions of streaming the lifetime of the holes in the "light" subband is τ_E — their ballistic acceleration time up to optical-phonon energies. In the range of fields where streaming exists for light holes but not for heavy holes, the concentration of the light holes decreases with increasing electric field as a result of the decrease in τ_E.

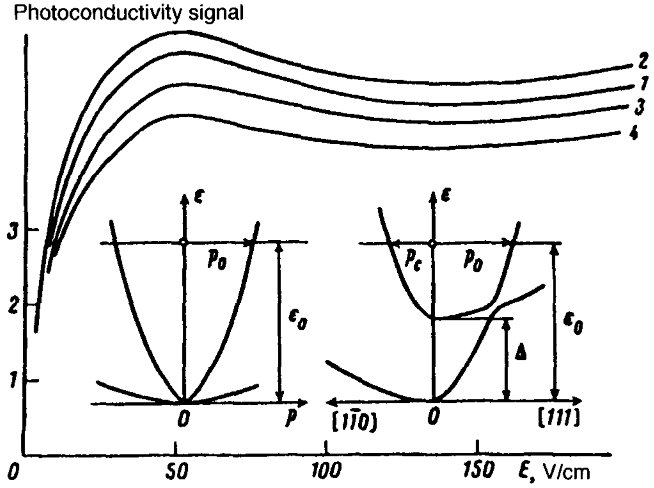

FIG. 1. Photodetector signal versus the electric field for different pressures P (kbar): 1 — 0; 2 — 1.3; 3 — 2.7; 4 — 3.5. $P \parallel [111]$. Insets: Band schemes of undeformed (on the left) and deformed (on the right) p-Ge; for convenience the hole subbands are shown here as for electrons.

Uniaxial deformation removes the degeneracy of the valence band of germanium for $k=0$ and splits the band into two subbands separated by an energy gap Δ proportional to the pressure. In this case the conditions of ballistic heating must change radically. In unaxially compressed germanium the "ceiling" for ballistic acceleration of holes in the upper split-off energy subband (see right inset in Fig. 1) should be the energy of an optical phonon measured from the bottom of the lower subband, since at this energy intense intersubband transitions of holes with emission of an optical phonon start. The critical field E_c, at which ballistic heating of the holes in the upper subband starts, is determined by the condition

$$eE_c\tau = p_0, \tag{2}$$

where $p_0=(2m_1\epsilon_0)^{1/2}$, and m_1 is the effective mass in the direction of the field. As one can see from the inset in Fig. 1, the quantity p_0 does not change with pressure; therefore, E_c should not change, which has been confirmed experimentally. As one can see from the curves in Fig. 1 (see also Ref. 6), the maximum radiation intensity measured with a Ge ⟨Ga⟩ detector is observed for the same field at different pressures. Therefore, ballistic heating of holes in the upper subband starts when the holes acquire, without colliding with acoustic phonons, in an electric field a momentum p_0, here their kinetic energy remains less than the energy of an optical phonon. Their distribution function cannot be a streaming function in the ordinary sense. In the case of streaming in one subband, the "needle-shaped" distribution function is formed because after an optical phonon is emitted, a hole returns periodically into a state with zero momentum and energy in the same subband. In uniaxially deformed germanium this cyclic process is interrupted: After an optical phonon is emitted, a hole is transferred from the upper band into the lower band. Since a hole returns into the upper subband as a result of intersubband exchange with the

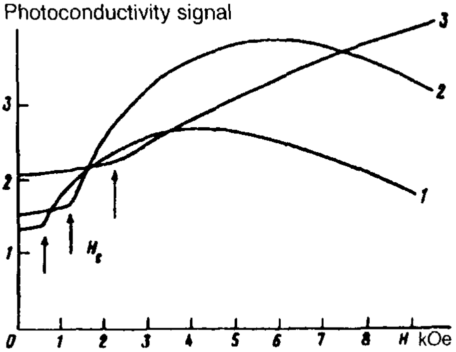

FIG. 2. Photodetector signal versus the magnetic field for different electric fields E (V/cm): 1 — 210; 2 — 440; 3 — 800. $P = 4$ kbar. The arrows indicate the critical magnetic fields at which rapid growth of emission begins.

participation of acoustic phonons (or impurities), the range of initial values of the momentum and energy of holes in the upper subband must be substantially broadened. The anisotropy of the distribution function should therefore be much smaller than in undeformed germanium. Under the conditions of streaming in the lower band, when the hole momenta are uniformly "smeared" in the direction of the field, the distribution function in the upper band should not be anisotropic. The decay of the radiation for $E > E_c$ with nonzero pressure can therefore be associated only with the decrease in their lifetime τ_E. We note that if ordinary streaming, in which after the emission of an optical phonon a hole returns to the bottom of the upper subband, existed in the upper band, then the corresponding momentum would depend on the pressure and the critical field would increase with the pressure.

The maximum energy $\epsilon_0 - \Delta$ for ballistic heating of holes in the upper subband should also be manifested upon application of a transverse magnetic field. Figure 2 shows the intensity of intersubband radiation versus the magnetic field for different electric fields. The sharp growth of the radiation starting in a threshold magnetic field H_c indicates that a magnetic trap is formed in the upper subband.[7] The quantity H_c and its pressure dependence are determined by the maximum energy to which holes in the upper band can be ballistically accelerated. It can be shown that the equation for the ballistic trajectory of a hole moving in crossed fields has the form

$$d\epsilon = dp_\perp cE/H, \qquad (3)$$

where $p_\perp$ is the momentum component in a direction pependicular to E and H, and c is the velocity of light. It is clear, therefore, that the threshold magnetic field for the formation of a magnetic trap (closed trajectories) in the passive energy range is determined by the the transverse momentum which corresponds to the maximum energy. For maximum energy $\epsilon_0 - \Delta$ and pressure applied parallel to the electric field we have

$$H_c = cEm_\perp / p_c = cE[m_\perp / 2(\epsilon_0 - \Delta)]^{1/2}, \qquad (4)$$

where $m_\perp$ is the effective mass in the direction $p_\perp$, and p_c is the value of $p_\perp$ corresponding to the maximum energy. Figure 3 shows curves of the threshold magnetic field versus

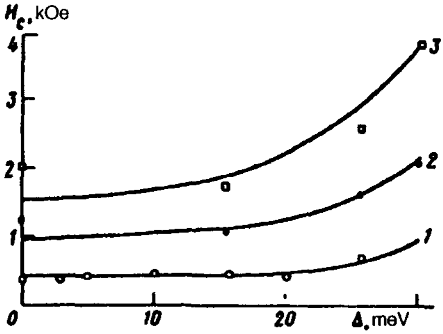

FIG. 3. Computed curves of the critical magnetic field versus the intersubband energy gap for different electric fields E (V/cm): 1 — 210; 2 — 440; 3 — 800. The circles and squares represent the experimental values.

the pressure which were obtained with the help of this expression and which were measured experimentally. These curves agree well with one another. We see that in the case of streaming in the upper subband only, H_c should not change with pressure, since in this case $p_c=(2m_\perp \epsilon_0)^{1/2}$ does not depend on the pressure.

It thus follows from the experiments performed in electric and crossed electric and magnetic fields that in uniaxially deformed p-Ge the maximum energy to which holes in the upper subband split off by pressure can be heated ballistically is the energy at which intersubband scattering by optical phonons appears. The ballistic motion of the holes in the upper subband is not streaming in the ordinary sense, since the distribution function is not "needle-like."

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