

Drag of carriers by photons under conditions of multiphoton absorption of submillimeter radiation in *p*-type germanium

S. D. Ganichev, S. A. Emel'yanov, Ya. V. Terent'ev, and I. D. Yaroshetskii

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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An investigation was made of the drag of carriers by photons in *p*-type Ge subjected to high-power submillimeter radiation under conditions ensuring multiphoton absorption representing several simultaneous *n*-photon processes ($n \approx 10$) of comparable probability. It was found that variation of the illumination intensity caused inversion of the sign of the drag current.

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Nonlinear absorption in *p*-type Ge under the action of high-power submillimeter laser radiation was reported in Ref. 1. The nonlinearity of such absorption is associated with simultaneous (and comparable) processes of *n*-photon ($n = 1, 2, 3, \dots$) intraband absorption involving direct transitions between the heavy V_1 and light V_2 valence subbands of germanium,¹⁾ so that the total absorption coefficient is then $k(\omega) = \sum_n k_n(\omega)$. The coefficient $k_n(\omega)$ in-

cludes contributions not only of those processes as a result of which *n* photons are absorbed, but also higher-order processes in which virtual transitions involve absorption of (*n* + *m*) photons and emission of *m* photons. These different *n*-photon absorption channels interfere and partly suppress one another, so that the coefficient $k_n(\omega)$ is not proportional to the intensity of light *I* to the power (*n* - 1), in contrast to the situation in the lowest order of perturbation theory, but is a complex oscillatory

function of *I*. The number *N* of *n*-photon absorption processes making important contributions varies with the intensity of light.

Clearly, under the conditions favoring this process all the photoelectric phenomena associated with intraband absorption should change considerably. Therefore, we investigated the drag of carriers by photons under conditions of intraband multiphoton absorption.

EXPERIMENTAL METHOD AND RESULTS

Our radiation source was a high-power pulsed NH_3 laser pumped optically by a CO_2 laser. The emission wavelength was 90.55μ and the pulsed duration was 40 nsec. The intensity *I* of the radiation reaching a sample was 4 MW/cm^2 . We used the apparatus described in Refs. 1 and 2. Our *p*-type Ge samples had carrier densities from $p = 3 \cdot 10^{14}$ to $p = 10^{16} \text{ cm}^{-3}$ and *n*-type Ge samples had a

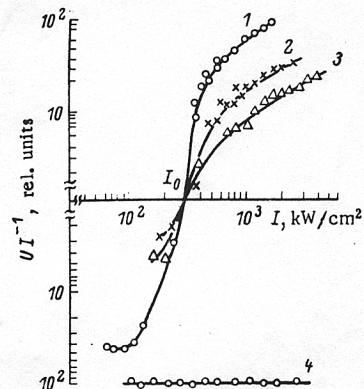


FIG. 1. Dependences of the normalized drag emf on the intensity of the radiation incident on a sample at 300 K: 1)-3) p-type Ge with hole densities $p = 3 \cdot 10^{14}$, $10 \cdot 10^{14}$ and $100 \cdot 10^{14} \text{ cm}^{-3}$ (1, 2, and 3, respectively); 4) n-type Ge with $5.5 \cdot 10^{15} \text{ cm}^{-3}$.

density of $n = 5.5 \cdot 10^{15} \text{ cm}^{-3}$ at 78 and 300 K. We investigated the dependence of the longitudinal drag emf on the intensity of the radiation reaching a sample.

The experimental results obtained for p-type Ge at 300 and 78 K are plotted in Figs. 1 and 2, respectively. At relatively low radiation intensities the drag current was opposite to the direction of propagation of light²⁾ and was a linear function of the radiation intensity. An increase in I altered the sign of the drag emf both at 300 and 78 K. At 300 K the characteristic intensity I_0 at which the drag emf vanished was independent of the carrier density and amounted to 0.3 MW/cm^2 (Figs. 1 and 3), whereas at 78 K the value of I_0 depended on the carrier density right up to $p \approx 10^{15} \text{ cm}^{-3}$ and then the dependence disappeared (Figs. 2 and 3). When the intensity was increased above I_0 , the dependence $U(I)$ was readily approximated by a quadratic function, but in the case of $T = 78 \text{ K}$ beginning from a certain intensity I_1 we found that the nature of the dependence changed from quadratic to nearly linear. The value of I_1 increased on increase in the carrier density. In the case of n-type Ge it was found that there was no change of the sign of the drag emf at 78 or 300 K and the effect was linear in respect to the radiation intensity.

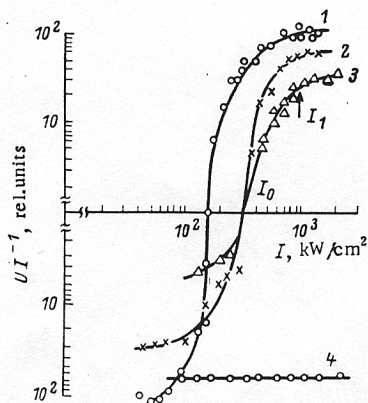


FIG. 2. Dependences of the normalized drag emf on the intensity of the radiation incident on a sample kept at 78 K. The notation is the same as in Fig. 1.

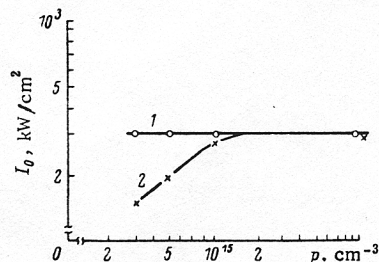


FIG. 3. Dependences of the characteristic intensity I_0 on the density of free carriers in p-type Ge. T (K): 1) 300; 2) 78.

DISCUSSION OF EXPERIMENTAL RESULTS

We shall base our qualitative analysis on Fig. 4, which shows the structure of the valence band of Ge in a plane parallel to the direction of propagation of the radiation and passing through the point $k = 0$. The same figure shows some of the possible direct n-photon optical transitions between the V_1 and V_2 valence subbands of Ge subjected to monochromatic radiation of photon energy $\hbar\omega$ (by way of example, the transitions with $n = 1, 2$, and 3 are shown). For each n-photon absorption process the energies of the initial states $\varepsilon_{11}^{(n)}$ and $\varepsilon_{1n}^{(n)}$ and the energies of the final states $\varepsilon_{21}^{(n)}$, $\varepsilon_{2n}^{(n)}$ of excited carriers are fixed and governed by the value of $n\hbar\omega$ in accordance with the laws of conservation of energy and momentum. As pointed out earlier, the number of n-photon absorption processes making a significant contribution to the total absorption depends on the intensity of the incident radiation. For example, according to Ref. 1, if $I = 2 \text{ MW/cm}^2$, then the contribution of n-photon processes with $n \leq 13$ is important.

It follows from Ref. 3 that the carrier drag current is related to the transfer of the photon momentum to carriers and is a sum of four elementary currents in the heavy and light valence subbands. These elementary currents are produced by optical transitions between the V_1 and V_2 subbands and they are both parallel and antiparallel to the direction of propagation of the incident radiation. In general, the values of these currents and, consequently, the value and direction of the total drag current in p-type Ge depend on the energies of the initial $\varepsilon_{11}^{(n)}$, $\varepsilon_{1n}^{(n)}$ and final $\varepsilon_{21}^{(n)}$, $\varepsilon_{2n}^{(n)}$ states of photocarriers and on the electron temperature T_e . It therefore follows that each multiphoton absorption process gives rise to four elementary drag currents $j_n^{(i)}$ and since the number of such processes is N , the

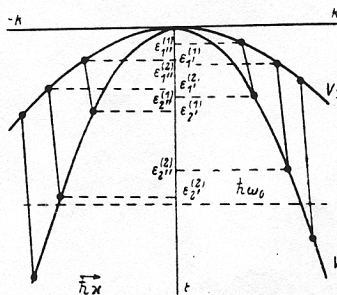


FIG. 4. Optical transitions ($\lambda = 90.55 \mu$) between the V_1 and V_2 valence subbands of germanium under conditions of multiphoton intraband absorption.

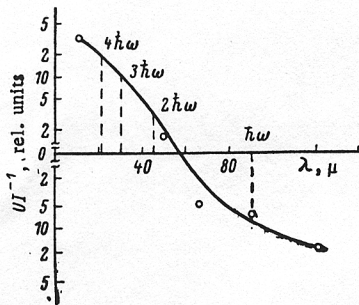


FIG. 5. Spectral dependence of the drag emf of p-type Ge at 300 K (Ref. 3). The dashed lines are the values of the drag emf at the wavelengths corresponding to n-photon absorption processes ($n = 1, 2, 3, \dots$).

total drag current is

$$j = \sum_{n=1}^{n=N} j_n, \text{ where } j_n = \sum_{i=1}^{i=n} j_n^{(i)}.$$

The magnitude and direction of each of the currents j_n can be estimated from the relevant spectral dependences of the drag emf, found experimentally in Ref. 4 at relatively low radiation intensities when the nonlinear processes are unimportant (Figs. 5 and 6). We shall assume that the conditions for the formation of the drag current j_n as a result of n-photon absorption of radiation with the photon energy $\hbar\omega$ are similar to the conditions for the formation of the drag current when monochromatic light of photon energy $n\hbar\omega$ is absorbed.

We shall now consider the experimental data obtained at $T = 300$ K (Fig. 1). At relatively low radiation intensities the resultant drag current is governed by the one-photon current and its direction is, in accordance with the spectral dependence shown in Fig. 5, opposite to the direction of propagation of the incident radiation. At sufficiently high intensities of this radiation the contribution made to the total absorption by n-photon processes with $n > 1$ becomes important. However, the sign of j_n for $n > 1$ is, in accordance with Fig. 5, opposite to the sign of j_1 and the probabilities of the n-photon absorption processes under these conditions are comparable. Consequently, the total drag current changes its sign. The characteristic intensity I_0 at which the drag emf vanishes is independent of the carrier density (Figs. 1 and 3) because of the linearity of the carrier-density dependences of all the components of the resultant drag current. The near-quadratic nature of the dependence $U(I)$ in the range $I > I_0$ is very reasonable because in the investigated range of intensities the total absorption coefficient can be approximated quite accurately¹ by the linear dependence on the radiation intensity, whereas $j_n \propto k_n(\omega)I$.

We shall now consider formation of the drag current at 78 K (Fig. 2). At relatively low radiation intensities the drag current is still governed by the one-photon absorption process: the current is a linear function of I and is directed opposite to the direction of propagation of the incident radiation. When I is increased, it is found that, as in the case of $T = 300$ K, that the processes of n-photon absorption with $n > 1$ become important and they make a positive contribution to the total drag current (Fig. 6); consequently, the sign of this current is reversed. However, it follows from Fig. 6 that the positive contribution is made only by the process with $n = 2$, whereas for $n = 3$,

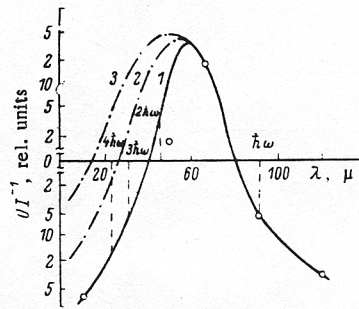


FIG. 6. Spectral dependence of the drag emf in p-type Ge at 78 K (Ref. 3). The chain curves represent schematically the change in the spectral dependence on increase in the temperature of the hole gas: $T_{e2} < T_e < T_{e3}$ (corresponding to curves 1, 2, and 3, respectively).

4, ..., the value of j_n is negative. This is true as long as we ignore the heating of the hole gas because of energy relaxation of photocarriers as a result of hole-hole collisions. An allowance for this process shifts the point of the first spectral inversion toward shorter wavelengths⁴ (chain curves in Fig. 6) and this, in turn, increases the number of n-photon processes making a positive contribution to the total drag current. A further increase in the intensity of the incident radiation ($I > I_1$) reduces rapidly the number of n-photon processes making a significant contribution to the total absorption¹ and, therefore, an increasing role is played by n-photon processes corresponding to the spectral range to the left of the first inversion point, i.e., those making a negative contribution to the total drag current. Clearly, this circumstance is the reason for the change in the nature of the dependence $U(I)$ in the range $I > I_1$ from quadratic to near-linear. We shall conclude by noting that, according to our estimates, "bleaching" of a one-photon transition because of depletion of the populations of the initial states occurs in p-type Ge at $\lambda = 90 \mu$ and $T = 78$ K already when the hole density is $p = 10^{15} \text{ cm}^{-3}$ and the radiation intensity is $I < I_0$ ($I_0 = 0.3 \text{ MW/cm}^2$). This process reduces the contribution of j_1 to the total drag current and, therefore, equalization of the oppositely directed one-photon and n-photon drag currents occurs at lower values of the radiation intensity I_0 . Therefore, the carrier-density dependence of I_0 is observed in the range $p < 10^{15} \text{ cm}^{-3}$ (Fig. 3).

In the case of n-type Ge the absorption observed in the investigated range of intensities at room and nitrogen temperatures is governed by "indirect" one-photon transitions so that there are no singularities in the dependence of the drag current on the intensity of the incident radiation (Figs. 1 and 2).

¹By the n-photon process we mean a direct optical transition of a hole from V_1 to V_2 , as a result of which its energy changes by $n\hbar\omega$.

²In our experiments this direction of the drag current corresponded to a negative drag emf.

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