Drag of carriers by photons in semiconductors in the far infrared and submillimeter spectral ranges

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An investigation was made of the drag of carriers in *n*- and *p*-type germanium by photons of far infrared and submillimeter wavelengths. Multiple spectral inversion of the sign of the drag emf in *p*-type Ge at 300 and 78 K, and impurity-concentration-dependent inversion in *p*-type Ge at 300 K were observed for the first time and explained. Such inversion was attributed to the competition between four elementary drag currents in the light and heavy valence subbands of Ge and also to the drag currents due to indirect transitions in the valence and conduction bands. Each of these currents could predominate under certain conditions. Spectral inversion was not observed in the case of *n*-type Ge. The experimental results were in satisfactory agreement with the theory.

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INTRODUCTION

The phenomenon of drag of carriers by photons was observed experimentally and analyzed theoretically.[1–4] The drag was due to the transfer of the photon momentum to electrons and holes in the case of "direct" transitions between the valence subbands of Ge (Refs. 1 and 3) and "indirect" transitions within one band.[2–4] The radiation source was a CO_2 laser emitting at wavelengths from 9.2 to 10.6 μ. The drag at far infrared and submillimeter wavelengths would be particularly interesting because variation of the photon energy in this range should alter considerably the conditions for the formation of the drag current and should give rise to several new effects. Investigations of this kind have become recently possible because of the development of high-power optically pumped pulsed lasers.[5] An experimental technique of this kind was used by Kimmitt et al.[6] but the authors simply reported the occurrence of the drag emf at the wavelengths of 337 and 385 μ. The interest in the drag phenomena in the far infrared and submillimeter spectral ranges is also due to the possibility of constructing uncooled fast-response detectors of pulsed laser radiation emitting at these wavelengths. In view of this, we decided to investigate the phenomenon of drag in the far infrared and submillimeter parts of the spectrum. The results of an investigation of the drag in n- and p-type germanium are presented below.

EXPERIMENTAL METHOD AND RESULTS

Our radiation source was a laser system comprising a high-power pulsed tunable heavy water and NH_3 vapor laser, which was optically pumped. Pumping was in the form of radiation from a CO_2 TEA laser and ultraviolet preionization was employed. The CO_2 laser parameters are as follows: The energy per line was ~10 J and the tuning range was from 9.2 to 10.6 μ. The energy, duration, and shape of the pulses were determined with an FP-5 photodetector.[7,8] The CO_2 laser resonator was formed by a mirror with a radius of curvature 10 m and an echelette with 100 lines/mm, which made it possible to tune the CO_2 laser output. A submillimeter cell was similar to that described in Ref. 9. Radiation was injected through an aperture 4 mm in diameter. The exit aperture had a diameter of 6 or 8 mm. The exit mirror was made of Teflon. The duration and shape of the submillimeter pulses were determined using a detector made of n-type Ge which operated on the principle of the drag of carriers by photons.[1,10] The energy of the submillimeter pulses was recorded with an IMO-2 calorimeter. The wavelength was measured with a Michelson interferometer. The radiation was linearly polarized and the polarization was determined using wire grids. This laser system emitted lines in the range from 9.2 to 385 μ in the form of pulses with typical durations $(1-2)\cdot 10^{-7}$ sec and an output power of up to 2 MW per pulse.

The drag effect was investigated in p-type Ge samples cut parallel to the (111) plane and characterized by hole densities p from 10^{11} to $3\cdot 10^{15}$ cm^{-3}, and also in n-type Ge samples with $n = 3.5\cdot 10^{14}$ cm^{-3}. The block diagram of the apparatus used to study the effect in the infrared and submillimeter spectral ranges was similar to that described by us earlier.[11] The dependences of the drag signal (in the emf regime) on the wavelength and carrier density were determined at various temperatures.

The experimental results are presented in Figs. 1–3. It is clear from Figs. 1 and 2 that p-type Ge exhibited spectral inversion of the sign of the drag current and that the number of such inversions depended also on temperature. For example, at 300 K there was a double spectral inversion (Fig. 1a), whereas at 78 K there was a triple inversion (Fig. 2). In the case of n-type germanium (Fig. 1b) there was no spectral inversion of the drag current.

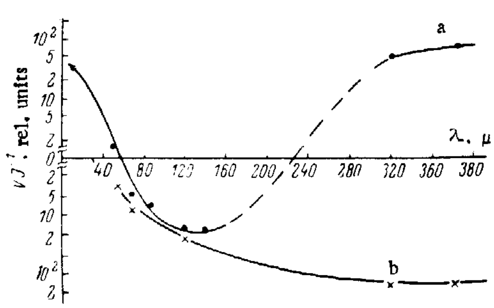

FIG. 1. Spectral dependence of the drag emf developed by Ge: a) $T = 300$ K, $p = 3\cdot 10^{14}$ cm^{-3}; b) $T = 300$ K, $n = 3.5\cdot 10^{14}$ cm^{-3}.

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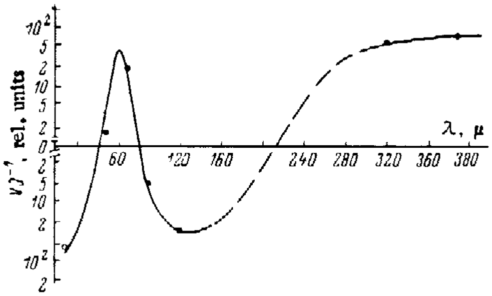

FIG. 2. Spectral dependence of the drag emf developed in p-type Ge. $T = 78$ K, $p = 3 \cdot 10^{14}$ cm^{-3}.

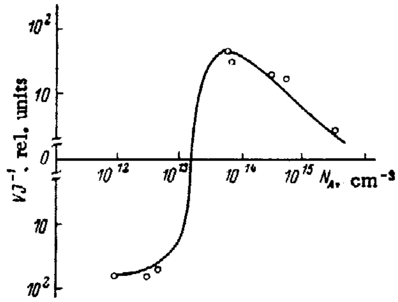

FIG. 3. Dependence of the drag emf on the acceptor impurity concentration in p-type Ge at 300 K on excitation with light of the wavelength $\lambda = 385\ \mu$. The points are the experimental values and the curve is theoretical.

Consequently, such inversion was associated with the complex structure of the valence band of Ge. It was interesting to note also that in the case of p-type Ge at 300 K excited at the wavelength of $\lambda = 385\ \mu$ the sign of the drag current also exhibited inversion as a function of the impurity concentration (Fig. 3). This effect was not observed at 78 K.

DISCUSSION OF EXPERIMENTAL RESULTS

Qualitative understanding of the drag effect can be gained by examining Fig. 4, which shows the structure of the valence band of Ge in a plane parallel to the direction of propagation of light and passing through the point $k = 0$. This figure demonstrates all possible optical transitions due to the absorption of a photon of energy $\hbar\omega$ and momentum $\hbar\varkappa$. In accordance with a model proposed in Refs. 1 and 12, the drag current in p-type Ge due to direct transitions between the heavy V_1 and light V_2 valence subbands is a sum of four elementary currents due to indirect transitions in the light and heavy subbands.

According to Ref. 12, the elementary currents due to the direct transitions can be written in the form

$$j_h = j_{1'} + j_{1''} = B\frac{m_2}{m_1 - m_2}\left(\tau_1(k_{1'})\,k_{1'}^4 \exp\left(-\frac{\hbar^2 k_{1'}^2}{2m_1 k_B T}\right)\right. \quad (1)$$

$$\left. - \tau_1(k_{1''})\,k_{1''}^4 \exp\left(-\frac{\hbar^2 k_{1''}^2}{2m_1 k_B T}\right)\right),$$

$$j_l = j_{2'} + j_{2''} = -B\frac{m_1}{m_1 - m_2}\left(\tau_2(k_{1'} - \varkappa)\,k_{1'}^3 (k_{1'} - \varkappa) \exp\left(-\frac{\hbar^2 k_{1'}^2}{2m_1 k_B T}\right)\right.$$

$$\left. - \tau_2(k_{1''} + \varkappa)\,k_{1''}^3 (k_{1''} + \varkappa) \exp\left(-\frac{\hbar^2 k_{1''}^2}{2m_1 k_B T}\right)\right), \quad (2)$$

$$j_f = j_h + j_l, \quad (3)$$

Here,

$$B = \frac{e^3 \hbar^4 A_{1-2}\, p_1 J_0 \Delta\Omega}{\bar{n}\,\omega m_0^2 c_0 (2\pi)^{5/2} m_1^{1/2} (k_B T)^{3/2}},$$

where A_{1-2} is a coefficient that determines the interband dipole moment; $\bar{n}$ is the refractive index; ω is the frequency of the exciting radiation; m_0 is the mass of a free electron; m_1 and m_2 are the effective masses of a hole in the heavy and light valence subbands; $\tau(k)$ is the momentum relaxation time; p_1 is the carrier (hole) density; J_0 is the intensity of the incident radiation; $\Delta\Omega$ is the solid angle; $k_{1'}$ and $k_{1''}$ are the initial wave vectors of the excited carriers (Fig. 4); $\varkappa$ is the photon wave vector; c_0 is the velocity of light.

In Eqs. (1) and (2) the factor k^4 represents the dependences of the density of states, transition probabilities, and carrier velocities on the wave vector, and the exponential factor determines the equilibrium population of the initial states.

Changes in the sign of the drag current on lowering of temperature from 300 to 78 K were observed earlier[1] on excitation with light of the wavelength $\lambda = 10.6\ \mu$ when the energy of photoholes was higher than the optical phonon energy $\hbar\omega_0$. Such temperature inversion is entirely due to the competition between the currents $j_{1'}$ and $j_{1''}$ because the currents within the light hole subband are then considerably less than the currents in the heavy subband due to the short quantum relaxation times of carriers in the light subband. Under these conditions ($T = 78$ K) the current $j_{1''}$ predominates in the heavy subband because the equilibrium population of the state $1''$ is greater than that of the state $1'$.

When the energy of the exciting photons is reduced, a situation occurs when the energies of the initial states $1'$ and $1''$ approach the thermal energy $k_B T$. According to Eq. (1), in the case of the currents $j_{1'}$ and $j_{1''}$ with the factor k^4 this should result in a mutual compensation of the two currents $j_{1'}$ and $j_{1''}$ so that the net drag current under these conditions is dominated by $j_{2''}$, which is greater than the current $j_{2'}$ and has the same direction as the incident electromagnetic wave. This produces the first inversion of the sign of the net drag current.

Further reduction in the photon energy makes the current $j_{1'}$ predominate in the heavy subband and the current $j_{2'}$ in the light subband. The current in the heavy

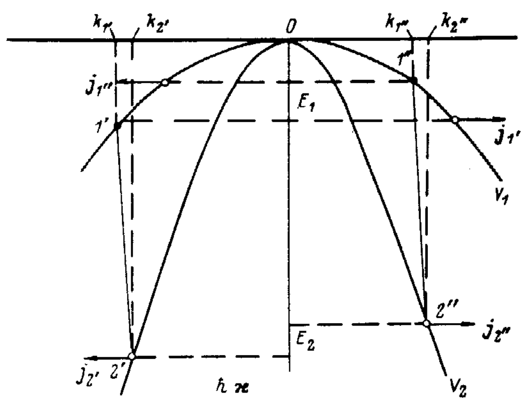

FIG. 4. Optical V_1 V_2 transitions between the valence subbands of germanium.

subband predominates as long as the energies of the states 2' and 2" are different from the energy of an optical phonon $\hbar\omega_0$. When the energies of the final states 2' and 2" become less than $\hbar\omega_0$, the momentum relaxation times of excited carriers in the heavy and light subbands become comparable, since the light holes in the V_2 subbands can then no longer emit optical phonons. Consequently, in view of the smaller effective mass, the light hole drag current becomes greater than the drag current due to the heavy holes, and the dominant contribution comes from the current $j_{2'}$ directed opposite (in respect of the momentum) to the electromagnetic wave. It follows that in this situation we can expect a second inversion of the sign of the net drag current.

A further increase in the radiation wavelength (reduction in the photon energy) results in a rapid rise of the contribution of the drag current due to the indirect transitions. This causes a third inversion of the sign of the net drag current. It should be pointed out that spectral inversion of the drag current p-type Ge at 300 K was given by us in Ref. 11.

Figure 5 shows the calculated spectral dependence of the net drag current due to the direct transitions in p-type Ge, as well as the separate contributions made to this current at 78 K for $p = 3 \cdot 10^{14}$ cm^{-3}. These calculations were carried out using Eq. (15) of Ref. 3. Similar dependences for 300 K were given in Ref. 11. The expression for the drag current due to the indirect transitions within one subband[4] is

$$j = -\frac{3}{5}\frac{4\pi e^3 \hbar n_0}{m^2 c_0^2 \omega} j_0, \quad (4)$$

where n_0 is the electron density. A comparison of these theoretical dependences with the corresponding experimental data (Figs. 1 and 2) shows that the theory and experiment are in qualitative agreement. However, a rigorous quantitative comparison is at present difficult because of the following circumstances. Firstly, the existing theories of the drag of electrons by photons in p-type Ge ignore the nonsphericity of the heavy-hole band and the nonparabolicity of the light-hole band. Secondly, no reliable data are yet available on the absorption coefficients for the direct and indirect intraband transitions in the investigated range of wavelengths. Nevertheless, the most interesting experimental results – the existence of double and triple spectral inversion at 300 and 78 K, respectively – is manifested clearly by the theoretical dependences.

As pointed out earlier, we observed also impurity-concentration-dependent inversion of the sign of the drag current in p-type Ge at 300 K when a sample was excited with light of the wavelength 385 μ (Fig. 3). This effect is due to the fact that at low acceptor concentrations N_A ($N_A < 10^{13}$ cm^{-3}) the process of thermal generation of electron–hole pairs makes the number of free carriers in the conduction band (electrons) comparable with the number of free carriers in the valence band (holes). Under these conditions the smaller effective mass of the carriers in the conduction band makes the drag current of the minority carriers participating in the indirect transitions within the conduction band (this current is directed opposite to the photon wave vector) the dominant contribution to the net drag current at low concentrations N_A. When the acceptor concentration is increased, a considerable rise in the number of the majority carriers in the valence band of Ge results in predominance of the drag current due to these carriers. This current is formed as a result of the indirect transitions of heavy and light holes in the relevant subbands and its direction is the same as that of the light wave. This is the cause of the observed concentration inversion of the sign of the net drag current.

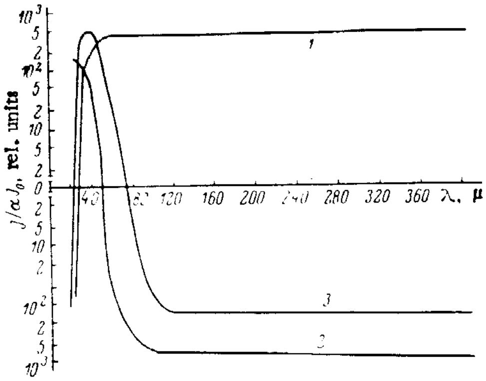

FIG. 5. Calculated dependences of the drag current $j/\alpha J_0$ (T = 78 K, p = $3 \cdot 10^{14}$ cm^{-3}): 1) drag current of heavy holes in the case of the direct transitions; 2) drag current of light holes; 3) net drag current due to the direct transitions.

All these features are shown in Fig. 3, where the continuous curve is the theoretical dependence of the drag emf on the acceptor impurity concentration, calculated allowing for the indirect electron transitions within the conduction band and also for the indirect transitions of heavy and light holes in the V_1 and V_2 bands, respectively. This dependence is constructed employing the following expression:

$$V = \left(-\frac{3}{5}\frac{4\pi e^3 \hbar 2 n_i^2}{m_c^2 c_0^2 \omega N_A}\left(1 + \sqrt{1 + \frac{4n_i^2}{N_A^2}}\right)^{-1} + \frac{3}{5}\frac{4\pi e^3 \hbar N_A}{2 c_0 \omega}\left(1 + \sqrt{1 + \frac{4n_i^2}{N_A^2}}\right)\left(\frac{1 - \left(\frac{m_2}{m_1}\right)^{3/2}}{m_1^2} + \frac{\left(\frac{m_2}{m_1}\right)^{3/2}}{m_2^2}\right)\right) \times \frac{1 - \exp(-\alpha d)}{\alpha} \rho J_0, \quad (5)$$

where $n_i = 2 \cdot 10^{13}$ cm^{-3} is the intrinsic density of carriers in Ge at 300 K; m_c is the effective mass of carriers in the conduction band; ρ is the resistivity of a sample; α is the total absorption coefficient; d is the length of the sample; N_A is the acceptor impurity concentration. It must be stressed that the contribution of the indirect drag current of light holes is several times greater than the contribution of the indirect current of heavy holes in spite of the fact that the density of equilibrium light holes represents only 4.0% of the total density of holes. We can see in Fig. 3 that the experimental and theoretical dependences agree well.

CONCLUSIONS

Our investigations revealed multiple spectral inversion of the sign of the drag current in p-type Ge at 300 and 78 K at far infrared and submillimeter wavelengths. We were able to observe for the first time the dominant contribution of each of the four elementary currents formed as a result of direct transitions between the valence subbands in Ge. Concentration inversion of the sign of the drag current in p-type Ge was observed in the long-wavelength part of the spectrum at 300 K and it was attributed to the contribution of the minority carriers to the drag current. The experimental results obtained demonstrated that the drag of carriers by photons in semiconductors with a simple band structure could be used in constructing uncooled fast-response detectors of high-power pulsed laser radiation in the infrared and submillimeter spectral ranges.

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