# DRAGGING OF FREE CARRIERS BY PHOTONS IN DIRECT INTERBAND TRANSITIONS IN SEMICONDUCTORS

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The dragging of free carriers by light in direct optical transitions is predicted and experimentally observed. The experiment was carried out in p-type germanium by means of a $CO_2$ Q-switched laser with a peak power of about 2 kW. Reversal of the sign of the drag current is observed with variation of the temperature from room to nitrogen temperature. The regularities observed are in good agreement with the theory developed in[4].

WHEN electrons interact with photons, the electron acquires not only energy but the photon momentum $\hbar\kappa$. This, in principle, should lead to ordered motion of the carriers relative to the lattice in the direction of light propagation. The resultant current should depend strongly both on the concrete energy band scheme and on the mechanism whereby the light interacts with the carriers. The effect of electron dragging by photons can have, in the main, two variants. In one of them the process occurs with a simultaneous participation of a third body (say a phonon or an impurity center) in addition to the electron and photon[1,2]. In the case of such indirect absorption of light, the photon momentum is partly transferred to the lattice in the very act of interaction.

The second variant calls for participation of only two particles in the primary interaction act, a photon and electron. An example of such a process is the appearance of recoil electrons in Compton scattering. In a solid, such a possibility is realized also in the direct transition between energy bands. Since the observation of the dragging effect in the case of direct interband transitions is made difficult by the strong absorption of the light (with the exception of the case of multiquantum absorption, which is not considered here), it is convenient from the experimental point of view to choose a system of subbands in the valence band, where a uniform distribution of light over the length of the sample can be easily realized because of the relatively small absorption coefficients.

In this investigation, undertaken for the purpose of observing the effect of carrier dragging by light in direct intraband transitions, we used p-Ge for this purpose, the light source being a $CO_2$ laser with wavelength 10.6 $\mu$.

## 1. ANALYSIS OF THE MODEL

Figure 1 shows the structure of the valence band of Ge in a plane passing through the point k = 0, and the possible optical transition[1)] ($\lambda$ = 10.6 $\mu$). For a given value of the photon energy, the energy and momentum conservation laws are satisfied in the given plane only for two holes in the band $V_h$, having momenta $\hbar\mathbf{k}_{1h}$ and $\hbar\mathbf{k}_{2h}$:

$$\frac{\hbar^2(\mathbf{k}_h)^2}{2m_h}+\hbar\omega=\frac{\hbar^2(\mathbf{k}_l)^2}{2m_l}, \tag{1}$$

$$\mathbf{k}_h+\varkappa=\mathbf{k}_l; \tag{2}$$

$\hbar\kappa$ is the photon momentum, $\hbar\mathbf{k}_l$ is the momentum of the hole going over to the band $V_l$ (the subscripts $l$ and h pertain to the systems of light and heavy holes). When these holes go over into the band $V_l$, the distribution of the carriers in the $V_h$ band turns out to be unbalanced with respect to the momentum, since $|\hbar\mathbf{k}_{1h}| \neq |\hbar\mathbf{k}_{2h}|$. For a similar reason, the system of non-equilibrium holes in the $V_l$ band will have at the initial instant of time likewise an uncompensated momentum $\hbar\mathbf{k}_l$. As a result, systems of holes, having oppositely directed momenta $\mathbf{k}_h$ and $\mathbf{k}_l$ are produced at the instant of the transition (the light propagates in the direction of the ensemble of holes in the $V_h$ band):

$$\mathbf{k}_h=\frac{2\varkappa}{1-m_l/m_h}, \quad \mathbf{k}_l=-\frac{2\varkappa(m_l/m_h)}{1-m_l/m_h} \tag{3}$$

Let us calculate the directional flux of carriers through the sample

$$\mathbf{j}=e(\Delta p_h\mathbf{v}_h+\Delta p_l\mathbf{v}_l)=eKI(\tau_h\mathbf{v}_h+\tau_l\mathbf{v}_l); \tag{4}$$

here I is the intensity of light in the sample, $\Delta p_h$ and $\Delta p_l$ are the concentrations of the systems of non-equilibrium holes with directed momentum in the bands $V_h$ and $V_l$, respectively, K is the absorption coefficient, $\tau_l$ and $\tau_h$ are the momentum relaxation times of the two systems of holes in question, $v_h$ and $v_l$ the drift velocities of the fluxes of non-equilibrium carriers in the bands $V_h$ and $V_l$, which are defined for the given cross section of the band scheme by

$$\mathbf{v}=\frac{\hbar\mathbf{k}_h}{m_h}=\frac{2\hbar\varkappa}{m_h-m_l} \qquad \mathbf{v}=\frac{\hbar\mathbf{k}_l}{m_l}=-\frac{2\hbar\varkappa}{m_h-m_l} \tag{5}$$

Obviously, in the case when the directed carriers in the bands $V_h$ and $V_l$ are equal (the $\tau$ are equal), no current

[1)]For clarity, Fig. 1 considers transitions only in one direction in k-space, whereas actually it is necessary to take into account the entire phase volume. This will be done when the theory is compared with experiment.

is produced, since the holes turn out to have equal and opposite velocities. Thus, in this model, the effect can be produced apparently only in the case when the momentum relaxation times in the bands $V_h$ and $V_l$ are different for the systems of holes considered above.

However, as shown by Grinberg[4], who developed a theory of the effect under consideration on the basis of experimental data, an important role is played, besides the inequality of the relaxation times, which indeed takes place, also by the asymmetry and intensity of the optical transitions of the "left" and "right" holes. The reason for this is the difference in the probabilities of excitation and in the concentrations of the "working" holes on the "left" and "right," which is due to the need for simultaneously satisfying the energy and momentum conservation laws. In turn, the difference in the concentrations is explained, first, by the fact that the states that are possible from the point of view of the optical transitions in question are distributed asymmetrically relative to the point $k = 0$ in the band $V_h$, and second, by the fact that the probabilities of filling these states are different, since the energies of the "working" holes on the "left" and "right" are unequal. Thus, for the light propagation direction shown in Fig. 1, the following situation is realized: 1) the number of states on the left, from which the transitions in question take place, is larger than on the right; 2) the transition probability for the "left" holes is also higher than for the "right" holes, owing to the large values of the quasimomentum; 3) since the energies of the "light" working holes are higher than the energies of the analogous "right" holes, the probability of occupying the corresponding states on the left is lower than on the right[2)].

Similar considerations can be advanced for the nonequilibrium carriers in the band $V_l$, the only difference being that the directional motion of the system of light holes, due to each of the causes considered above, turns out to be opposite to the motion of the heavy holes in the band $V_h$.

As seen from the foregoing picture, it is difficult to forecast in advance the polarity that the dragging current must have and how the current must change with temperature.

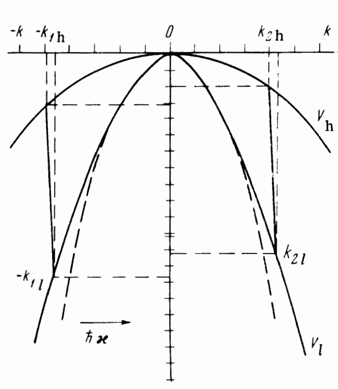


FIG. 1. Optical transitions ($\lambda = 10.6\ \mu$) between the subbands $V_h \rightarrow V_l$ in the valence band of germanium: dashed – $m_l = 0.043\ m_0$; $V_l$ is constructed in accordance with [3].

2)This circumst can cause the relative roles of the "left" and "right" holes to change with changing temperature.

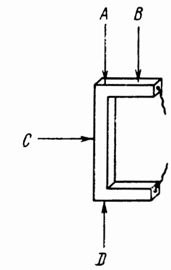


FIG. 2. Mutual positions of the sample and of the laser beam in the experiment.

These questions are considered in greater detail in Sec. 3, in the comparison of theory with experiment.

## 2. EXPERIMENTAL RESULTS

The source of unidirectional photons was a Q-switched $CO_2$ laser with frequency 250 Hz and pulse duration 0.5 $\mu$sec. The pulsed radiation power was $\approx$ 2 kW. The laser signal was monitored with the aid of a low-inertia ($\approx 10^{-7}$ sec) infrared-radiation receiver, constituting a photoresistor based on Ge : Zn (80°K).

The samples were cut from p-Ge of constant cross section $1.5 \times 1.5$ mm. To prevent light from falling on the contacts, the latter were constructed in the form shown in Fig. 2.

All the experiments were performed on samples of four concentrations, and several samples of each type were used. The sample length $l$ was varied in accordance with the concentration, in such a way that the number of absorbed photons in each of them was the same and amounted to not more than 15% of the intensity at the front face, thus ensuring approximately uniform distribution of the non-equilibrium hole over the length of the sample. The laser beam, focused with a long-focus lens into a spot of 1 mm$^2$ area, was incident on the sample. This produced a current pulse in the circuit made up of the sample and a load resistance. This pulse was amplified and registered on an oscilloscope. The load resistance was chosen as a rule such as to obtain the short-circuit current regime. For measurements at low temperatures, the laser beam was introduced from the top into a nitrogen Dewar, where the sample was placed. The signal/noise ratio in all the experiments was not less than 15–20. (This value was much higher when the measurements were made in the voltage regime.)

At room temperature and in the case when the laser beam was incident on the sample in the manner shown in Fig. 2 (variant A), a current pulse duplicating very accurately all the details of the laser pulse wave form, was observed. The direction of the current corresponded to the propagation direction of the light. When the sample was illuminated from the opposite side (variant D, Fig. 2), the current pulse, as expected, reversed polarity but retained the same amplitude. The signal increased linearly with decreasing laser light intensity.

In the case when the light propagation direction was that shown in variant C of Fig. 2, there was no signal. Rotation of the sample through a small angle in either direction relative to the beam, which was directed along the C axis in the plane of the figure, led to the occurrence of a current pulse whose polarity was correctly determined by the direction of rotation, and whose amplitude was determined by the magnitude of the angle.

In case B (Fig. 2), as expected, it was impossible to register a signal.

The dependence of the amplitude of the short-circuit current (variant A, Fig. 2) on the free-carrier concentration, shown in Fig. 3, has a linear character.

The temperature dependence of the described phenomenon was unique (Fig. 5). When the temperature decreased, the signal dropped to zero and then reversed polarity, rising to more than sixteen times room temperature at liquid-nitrogen temperature. The shape of the pulse at 77°K also duplicated exactly the waveform of the laser pulse. Experiments with rotation of the sample were repeated also at nitrogen temperature on all samples, and gave similar results, the only difference being that in this case the current direction was opposite to the photon-beam direction. The dependence of the short-circuit current on the hole concentration at 77°K (Fig. 3) and on the intensity of the incident light also remained linear.

All these facts show convincingly that the obtained effect, first, is connected with the directional action of the light and, second, is caused by the interaction between the photons and the free holes. Nonetheless, besides the dragging effect, we analyzed also other factors capable of producing the observed emf in the given experimental scheme: 1) the thermal emf due to nonuniform absorption of light; 2) the nonstationary photo emf on the surface[5]; 3) the emf due to the concentration gradient, which can occur when light is absorbed by deep impurity centers; 4) the hot-carrier thermal emf produced by the concentration gradient of the holes heated by the light along the sample.

In this connection, the following control experiments were performed.

A. Samples with larger cross section, 3 × 3 mm, were cut (in this case the light beam propagated along the sample without contact with the side walls), and the dependence of the resultant emf on the length of the sample was plotted. The dependence turned out to be linear, thus demonstrating the volume character of the effect; lowering the temperature also led in this case to a reversal of the sign of the emf.

B. A mirror was placed behind the sample to reflect the transmitted radiation back into the crystal. This reduced the signal greatly, in spite of the increase of the total intensity of the light in the sample. This experiment was performed also at liquid-nitrogen temperature, with analogous results.

C. The photoconductivity was measured at temperatures 293 and 77°K in the samples of all concentrations used in the experiment. The photoconductivity turned out to be negative, since it was caused not by the excitation of impurity centers, but by the decrease of the carrier mobility in the valence band.

Thus, we can obviously state that the obtained effect is connected with the dragging of free holes by the light. However, as already indicated, the directed carrier flux can also be due to dragging in direct transitions in the bands $V_h$ and $V_l$. In terms of nonlinear optics, such a process was regarded[6,4] as "rectification of the light" as the result of the high-frequency Lorentz force in the presence of simultaneous absorption. It is known, however, that the cross section for indirect absorption of the radiation with wavelength $\lambda = 10.6\ \mu$ in p-Ge is smaller by 2–3 orders of magnitude than the analogous quantity in the direct transitions $V_h \to V_l$. To estimate the approximate magnitude of such an "intraband" effect, an experiment was performed on n-Ge samples. At identical free-carrier concentrations, the dragging current in n-Ge turned out to be smaller than in p-Ge by a factor of 200. This apparently indicates that the observed effect in p-Ge is indeed connected with the transitions $V_h \to V_l$.

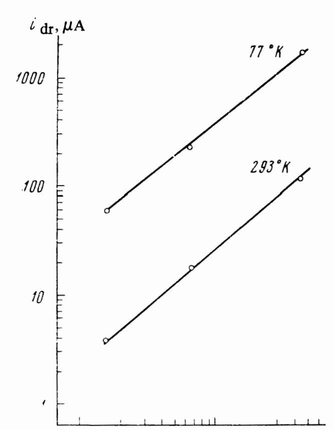

FIG. 3. Dependence of the dragging current (short-circuit regime) on the free-carrier concentration.

## 3. DISCUSSION OF RESULTS

As already indicated above, simple qualitative considerations concerning the relations between the relaxation times $\tau_l$ and $\tau_h$, and also concerning the number of "working" holes on the "left" and "right" can in principle lead to a reversal of the sign of the effect with changing temperature.

Let us consider the temperature dependence of the dragging current $j_{dr}$, confining ourselves to a quadratic dispersion law for the $V_h$ and $V_l$ bands. According to[4], in this case, when account is taken of the scattering of the holes by the optical and acoustical lattice vibrations, the expression for the total dragging current can be written in the form $j_{dr} = j_h + j_l$, where $j_h$ and $j_l$ are the dragging current of heavy and light holes, given by

$$j_h = A\tau_h(\varepsilon_h)\left\{4\left(1-\frac{\varepsilon_T}{2kT}\right)+F(T,\varepsilon_h)\right\}, \tag{6}$$

$$j_l = A\tau_l(\varepsilon_l)\left\{2\left(1+\frac{m_T}{m_l}-\frac{\varepsilon_l}{kT}\right)-F(T,\varepsilon_l)\right\}; \tag{7}$$

here

$$F(T,\varepsilon)=\frac{(k\Theta/\varepsilon)C[(1+k\Theta/\varepsilon)^{-1/2}-e^{\Theta/h}(1-k\Theta/\varepsilon)^{-1/2}]}{1+C[(1+k\Theta/\varepsilon)^{1/2}+e^{\Theta/h}(1-k\Theta/\varepsilon)^{1/2}]};$$

$\epsilon_h = h\omega m_l/(m_h - m_l)$, $\epsilon_l = h\omega m_h/(m_h - m_l)$ are the energies of the working holes in the bands $V_h$ and $V_l$, corresponding to direct transitions without allowance for the photon momentum;

$$A = IK(\omega)\frac{en\hbar\omega}{3c_0(m_h - m_l)},$$

$$C = \frac{B}{A}\frac{\Theta}{T}\frac{1}{e^{\Theta/h}-1},$$

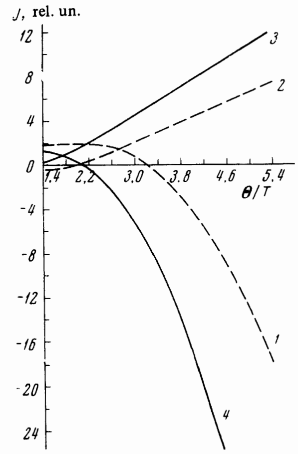


FIG. 4. Temperature dependences of $j_h$ and $j_l$, calculated from formulas (6) and (7): dashed – z = 0.17, 1 – $j_h$, 2 – $j_l$, solid lines – z = 0.24, 3 – $j_l$, 4 – $j_h$.

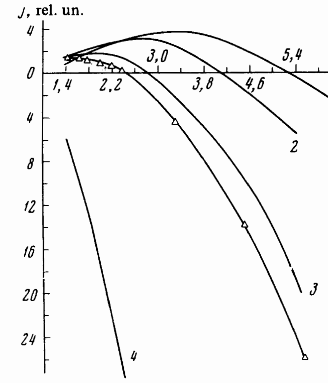


FIG. 5. Experimental temperature dependence of $j_{dr}$ (Δ) and analogous theoretical dependences plotted as functions of the parameter $z = m_l/m_h$: 1 – z = 0.123, 2 – z = 0.17, 3 – z = 0.24, 4 – z = 0.243.

where I is the intensity of the light in the sample, $K(\omega)$ is the absorption coefficient, n is the refractive index, $\hbar\omega$ is the quantum energy, $k\Theta$ is the energy of the optical phonon, $B/A = (1/2)(\mathscr{E}_{opt}/\mathscr{E}_{ac})^2$ is the ratio of the constants of the deformation potential for optic and acoustic phonons, $\tau_h$ and $\tau_l$ are the momentum relaxation times due to optic and acoustic phonons, for heavy and light "working" holes, $m_h$ and $m_l$ are the effective masses of the heavy and light holes in the parabolic-band approximation $V_h$ and $V_l$.

Numerical calculations by means of formulas (6) and (7) (curves on Fig. 4), using the known parameters for germanium, the dragging currents of the heavy and light holes turn out to have the same order of magnitude in the investigated temperature range, and have a distinctive temperature dependence. At high temperatures, the heavy-hole current flows in the direction of light propagation (positive direction). The current in the $V_l$ band is oppositely directed in this case. Then, with decreasing temperature, both currents $j_h$ and $j_l$ reverse polarity, but at different temperatures. It should be noted that the character of the temperature dependence of the total current $j_{dr}$ is determined mainly by the motion of the holes in the $V_h$ band (Fig. 4). The change in the direction of the current of heavy holes is due to the different temperature dependences of the probabilities of filling the working states from the left and from the right in the $V_h$ band. It is this circumstance, mentioned in Sec. 1, which determines mainly the reversal of the sign of the effect.

Figure 5 shows together with the experimental curve also the theoretical plots of $j_{dr} = f(\Theta/T)$, constructed for different values of $z = m_l/m_h$, where the regulated parameter is the effective mass of the holes in the $V_l$ band.

Figure 5 shows that the calculated and experimental relations are in qualitative agreement, which improves with increasing z.[3)] Nevertheless, exact equality of the theoretical curves and the experimental ones cannot be obtained, principally because the employed approximation of quadratic dispersion of the $V_l$ band is insufficient. It must be emphasized, however, that in spite of this, expressions (6) and (7) not only yield the temperature dependence of $j_{dr}$ (Fig. 5), but give also the absolute value of the dragging current accurate to within a factor of 2.

In conclusion we note that the effect described above, and particularly the position of the temperature-inversion point, can be used, in the presence of suitable theoretical expressions, to determine the degree of nonparabolicity of the light-hole band.

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[3)] It should be noted that at z = 0.243 the employed approximation leads to a qualitatively new temperature dependence of the dragging current (curve 4 of Fig. 5), one in which there is no inversion temperature in the temperature interval in question. This is due to the fact that at such values of z the energy of the "working" holes on the left in band $V_h$ reaches a value equal to the energy of the optical phonon, and thus generation of such holes becomes possible, leading to a sharp asymmetry of the relaxation times of the "left" and "right" "working" holes.

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