DRAGGING OF ELECTRONS BY PHOTONS IN INTRABAND ABSORPTION OF LIGHT BY FREE CARRIERS IN SEMICONDUCTORS

P. M. VALOV, A. M. DANISHEVSKIĬ, A. A. KASTAL'SKIĬ, B. S. RYVKIN, S. M. RYVKIN, and I. D. YAROSHETSKIĬ

A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences; Institute of Semiconductors USSR Academy of Sciences

Submitted June 12, 1970

Zh. Eksp. Teor. Fiz. 59, 1919–1925 (December, 1970)

The effect of dragging of electrons by photons was observed experimentally in indirect intraband absorption of light in semiconductors. This effect is due to the asymmetry arising in the distribution function as a result of the momentum of the incident photon flux. The effect was registered in absorption of CO_2-laser radiation in n-Ge. The experimental results are in satisfactory agreement with the theory developed in[3].

WHEN light is absorbed by free carriers, the photon momentum is absorbed in addition to the photon energy, and as a result the electron system should acquire translational motion relative to the lattice, in the form of a current or a voltage. Two variants of the manifestation of this effect were discussed in[1], namely; a) the case of direct optical transitions of the electrons between the energy bands, when the absorption is possible without the intermediacy of a third body, and b) the case of indirect transitions, when a phonon or an impurity center must take part in the absorption act.

The first of these variants was effected in[1] by using a system of valence subbands in p-Ge. The theory for this case was developed by Grinberg[2]. Grinberg[2] and Baltenkov et al.[3] also carried out a theoretical study of the effect of dragging of electrons by photons in indirect intraband optical transitions. The case $\hbar\omega > k_BT$ was considered. The phenomenological theory of the photo-emf produced by the momentum transferred from an electromagnetic wave to the system of electrons and the lattice during the course of an indirect intraband absorption was developed by Barlow[4] and also by L. É. Gurevich and Rumyantsev[5] as applied to the case $\hbar\omega < k_BT$.

In this communication we present the results of experiments undertaken for the purpose of investigating the effect of dragging in intraband absorption of light by electrons of the conduction band. The object of the investigations was n-Ge.

1. ANALYSIS OF THE MODEL

In the case considered here, important roles in the formation of the dragging current are played both by the mechanism of abosorption of the photon current by the free carriers and by the mechanism of the carrier relaxation. We consider below the roles of these two factors in the creation of the dragging effect.

The absorption of light by free carriers in the case when $\hbar\omega > k_BT$ was investigated by many workers, and in particular in[6-8]. Since participation of a third body is necessary to satisfy the laws of energy and momentum conservation in the elementary act of the optical transition of an electron inside the conduction band, it is customary to consider the absorption due to the scattering of electrons by acoustical or optical phonons, and also by charged impurity centers[1)].

Naturally, under different experimental conditions (temperature, impurity concentration, energy of optical quantum) the role of the indicated factors may change considerably.

It is easy to see that since the crystal lattice also takes part in the absorption act itself, the law of conservation of the total momentum is

$$\Pi = \mathbf{P}_e + \mathbf{P}_i, \qquad (1)$$

where Π is the momentum transferred by the electromagnetic wave to the crystal, $\mathbf{P}_e$ is the momentum transferred to the assembly of electrons, and $\mathbf{P}_i$ is the momentum acquired or imparted by the crystal lattice.

It is seen from (1) that the momentum $\mathbf{P}_e$ obtained by the electron subsystem can turn out to be larger than $\mathbf{P}$ or may even have an opposite sign.

Allowance for the translational momentum of the photons in the process of optical intraband transitions leads to the appearance of an asymmetrical part in the equilibrium distribution function of the electrons with respect to the quasimomentum, and accordingly to the formation of an electron current. The appearance of this asymmetry in the absorption act itself, including the electron-phonon and electron-photon interactions, can be qualitatively explained by using one electron as an example. Figure 1, which contains the $E(k)$ dependence for one of the valleys in a plane parallel to the light propagation, shows the possible transitions of an electron with $\mathbf{k} = 0$.

After absorbing phonons[2)] with positive or negative momentum, the electron enters the intermediate state $2'$ or $1'$, with an energy smaller or larger, respectively, than the energy of the final state, depending on whether the signs of the photon and phonon momentum are equal or opposite. Since the energy of the inter-

[1)]Scattering by neutral center is as a rule ineffective.

[2)]We consider here for simplicity only interaction with acoustic phonons whose energy can be neglected.

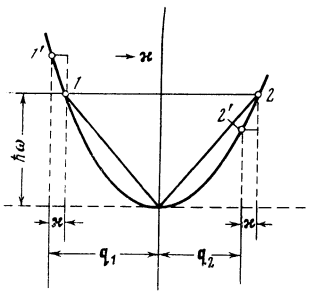

FIG. 1. Model explaining the occurrence of asymmetry in the probabilities of the electron transitions. 0–initial state of the electron; 1 and 2–states into which the electron goes over upon absorption of a photon and a phonon; 1′ and 2′–the intermediate states of the electron after it absorbs phonon momenta q_1 and q_2, respectively; κ–wave vector of the photon; $\hbar\omega$–quantum energy of the employed monochromatic radiation.

mediate state is smaller to the right of the ordinate axis (2′) (see Fig. 1) than to the left (1′), the lifetime of the excited electron in this state, by virtue of the uncertainty relation, turns out to be larger, and consequently the probability of the transition of the electron into the right-hand final state 2 as a result of the interaction with the phonon and photon should also be larger.

A similar picture is also obtained in photon absorption by an electron, with scattering by an impurity center. In this case, however, the occurrence of the asymmetry in the transition probabilities to the left and to the right is affected also by the dependence of this probability on the total momentum acquired by the electron from the photon and from the charged center.

As is well known, the cross section for the scattering of an electron by a Coulomb center is inversely proportional to the fourth power of the momentum acquired by the electron, and thus the asymmetry in the probabilities of the electron transitions to the left and to the right in Fig. 1 increases even more.

For convenience in the analysis of the model and to reveal the causes of the asymmetry in the electron distribution function, we can consider a situation in which two electrons on the two sides of the ordinate axis have equal probabilities of absorbing photons with a given energy. It is easy to show that these states have unequal energies in the band. Thus, when the electrons are excited from these states, two carrier systems with unequal momenta are produced: a) excited electrons, and b) electrons symmetrical about the ordinate axis, which remain unexcited. For both systems, a consequence of the inequality of the energies of the "left" and "right" electron states is inequality of their populations at a given temperature, and also inequality of the velocities and relaxation times.

All the indicated circumstances lead to the appearance of a current, which is the sum of the currents of the "cold" and "hot" electrons, the directions of which are opposite.

It should be noted that since the time of translational motion of the electrons responsible for the dragging current coincides with the time of relaxation of their momentum, differences in the contributions of various scattering mechanisms can also significantly alter the characteristic dependences of the dragging current. Just as in the case of absorption in different temperature and concentration regions, and also for different electron energies (excited and unexcited), the contributions of scattering by acoustic and optical phonons, and also by ionized impurity centers, can differ significantly. With increasing doping of the material, the change in the relaxation time as a result of the carrier scattering by the ionized centers becomes appreciable at ionized-center concentrations much smaller than required for an effective contribution of this process to the absorption by the free carriers.

In connection with the foregoing, and also in view of the computational difficulties, it is advantageous to consider an expression for the dragging current in the case of relatively small impurity-center concentrations (before they make a noticeable contribution to the absorption), and to analyze separately the increment resulting from absorption in which the ionized impurities take part.

The general expression for the dragging current in intraband transitions with participation of phonons was obtained in[3]. In writing out the explicit expression for the dragging current in this case (formula (14) of[3]), it was assumed that $\hbar\omega/2k_BT \gg 1$ and no account was taken of the change of the relaxation time as a result of scattering by charged impurities. Additional allowance for these circumstances leads to the following formula for the dragging current in the case when the absorption of the light takes place with participation of acoustic and optical phonons:

$$j_{dr} = 0{,}8(\alpha_{ac}+\alpha_{opt})\frac{e\hbar\varkappa\sqrt{\pi}(k_BT)^{1/2}\tau_{tot}(\hbar\omega)J_0}{(\hbar\omega)^{1/2}e^{z}k_2(z)m_n^*}$$
$$-1{,}6(\alpha_{ac}+\alpha_{opt})\frac{e\hbar\varkappa(k_BT)^{1/2}\tau_{ac}(k_BT)J_0}{(\hbar\omega)^{1/2}e^{z}k_2(z)m_n^*}\left(\frac{k_BT}{\hbar\omega}\right)^2$$
$$\times[2-\beta+\beta^{3/2}(ci\sqrt{\beta}\sin\sqrt{\beta}-si\sqrt{\beta}\cos\sqrt{\beta})]. \quad (2)$$

Here $\tau(\hbar\omega)$ is the total relaxation time of electrons of energy $\hbar\omega$, with account taken of all types of scattering, $\beta = \tau_{ac}(k_BT)/\tau_{imp}(k_BT)$, $\tau_{ac}(k_BT)$ and $\tau_{imp}(k_BT)$ are the relaxation times of electrons with energy k_BT, due to scattering by acoustic phonons and by charged impurities, respectively, m_n^* is the effective conduction mass, α_{ac} and α_{opt} are the coefficients of absorption of light by free carriers with scattering by acoustic or optical phonons

$$\alpha_{ac}=\frac{4e^2(2m_e^*)^{1/2}E_{ak}^2n}{3c_0\bar{n}\rho S^2\hbar^2(\hbar\omega)^{3/2}}k_BT\left[\left(\frac{2}{\pi}\right)^{1/2}e^{z}z^{1/2}(1-e^{-2z})k_2(z)\right], \quad (3)$$

$$\alpha_{opt}=\frac{8e^2(2m_e^*)^{1/2}E_{opt}^2(\hbar\omega_0)}{3\sqrt{\pi}\bar{n}c_0\rho S^2(\hbar\omega)^3\hbar^2}k_BT\frac{e^{z_+}}{\exp(\hbar\omega_0/k_BT)-1}$$
$$[(z_-)^2k_2(z)+z_+^2k_2(z_+)], \quad (4)$$

ρ is the density of the material, S is the velocity of sound, m_e^* is the longitudinal effective mass, $\bar{n}$ is the refractive index, c_0 is the velocity of light in vacuum, n is the electron density, E_{ac} and E_{opt} are the constants of the deformation potential for acoustic and optical phonons, respectively, $z = \hbar\omega/2k_BT$, $z_\pm = (\hbar\omega \pm \hbar\omega_0)/2k_BT$, $\hbar\omega_0$ is the energy of the optical phonon, and $k_2(z)$ is a modified Bessel function.

As seen from the foregoing formula, the total dragging current consists of two currents flowing in opposite directions. The current of the electrons absorbing a photon and having an energy $E_K > h\omega$ (first term of (2)) flows in the direction of light propagation, whereas the current of the lower group of carriers with energy

$\sim k_BT$ (second term in (2)) flows against the direction of the light.

A numerical calculation shows that in the investigated temperature range (77–300°K) the current of the cold electrons amounts in our case to only a small correction, and the main contribution to the dragging current is made by the "hot" electrons. This is particularly manifest in the case when there is an appreciable scattering of the thermalized carriers by the impurity centers. In the case when the absorption coefficient is determined mainly by the lattice vibrations, expression (2) in principle, can become positive at high temperatures corresponding to an electron-dragging current in a direction opposite to the direction of the light propagation.

At free-carrier densities on the order of 10^{16} cm^{-3} and higher, it is necessary to take into account, in the indicated temperature region, the contribution made to the dragging current by the absorption with participation of ionized impurities. In this case the expression for j_{dr}, as shown by Kramer, practically coincides with (2), if the total absorption coefficient, $\alpha = \alpha_{ac} + \alpha_{opt} + \alpha_{imp}$, is inserted in the latter. The absorption coefficient α_{imp} in best agreement with the experimental data is given by Donovan[8]. At $z = -\hbar\omega/2k_BT \gg 1$ the expression for α_{imp} is

$$\alpha_{imp} = 1.42\cdot 10^{-28}\frac{nN_i m^*}{\hbar^2\omega^3(k_BT)^{3/2}}(1-e^{-2z})\left(1+\frac{1}{6z}-\frac{1}{15z^2}+\cdots\right),$$

where n and N_i are the concentrations of the free carriers and of the ionized impurities, respectively.

It is easy to see that the contribution of α_{imp} to the total absorption coefficient and accordingly to the dragging current increases rapidly with increasing carrier density. This is particularly important at low temperatures, since the absorption due to scattering of lattice vibrations under these conditions decreases noticeably, whereas α_{imp} increases.

EXPERIMENTAL RESULTS AND DISCUSSION

Experiments aimed at observing and investigating the dragging effect in intraband transitions were made on n-Ge samples doped with antimony in a concentration range 6×10^{14}–7×10^{16} cm^{-3}.

As expected, we were indeed able to observe the dragging current due to intraband transitions. It turned out that, in accordance with the predictions of the theory, the dragging current is directed in this case opposite to the light propagation, i.e., the electrons were dragged along the light beam. The experimental procedure, the shapes of the samples, and the control experiments were perfectly analogous to those described earlier[1]. We plotted the temperature dependences of the dragging current in unpolarized light in the temperature range 77–300°K.

Figure 2 shows plots of the dragging current for three samples with carrier densities 6×10^{14}, 7×10^{15}, and 7×10^{16} cm^{-3}. Attention is called to the presence of a weak temperature dependence of the dragging current in the case of relatively lightly doped samples (Fig. 2a) and the appearance of a noticeable temperature variation with increasing free-carrier density (Figs. 2b and 2c). The same figures show the

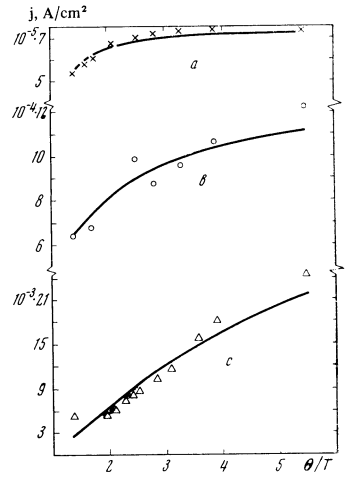

FIG. 2. Temperature dependences of the dragging current: a–$n = 6\times10^{14}$ cm^{-3}, b–$n = 7\times10^{15}$ cm^{-3} c–$n = 7\times10^{-16}$ cm^{-3}; points–experiment, solid curves–theoretical, $J_0 = 2\times10^{25}$ kV/cm² sec–intensity of light incident on the sample, Θ–Debye temperature for Ge.

corresponding theoretical plots. The agreement between theory and experiment is satisfactory[3].

It should be noted that in plotting the theoretical curve for the first sample we took into account transitions in which collisions with acoustic and optical phonons take part (transitions in which impurities take part are insignificant here), whereas the relaxation time was assumed to depend both on the scattering by phonons and on the scattering by charged impurities[4]. In this case the theory involves a constant β, equal to the ratio of the squares of the optical and acoustic deformation potentials. The best agreement in the temperature variation of the dragging current was obtained for the sample of Fig. 2a at $\beta^* = 0.7$. This value can be reconciled with the data of Conwell[9], who obtained a value $\beta^* = 0.4$ from measurements of the temperature dependence of the mobility in n-Ge. Allowing for the approximations made in the derivation of the corresponding theoretical expressions, the value of β^* obtained by us should be regarded as satisfactory. The weak temperature dependence of the dragging current for samples with relatively low free-carrier concentration is due to the presence of two mutually-cancelling factors that determine the dragging current. Indeed, when the temperature is lowered, the relaxation time of the electrons increases, but the absorption coefficient connected with the scattering by the lattice vibrations decreases, and the total dragging current changes insignificantly.

The increased concentration of the impurity centers (Fig. 2c) causes the absorption coefficient due to scattering by the impurity centers, α_{imp}, to increase and reach, at $n = 10^{17}$ (77°K) the approximate value of the absorption coefficient connected with the lattice scattering. Since $\alpha_{imp} \sim T^{1/2}$, the total absorption coefficient decreases much less with decreasing tempera-

[3]The theoretical curves in Fig. 2 reflect only the temperature dependence of the dragging current. The absolute values of the experimental and the theoretical values of the dragging current differ by a factor 2–3.

[4]It should be noted that at high carrier densities an important role is assumed by the decrease of the intensity of the exciting light in the sample, due to absorption by the free carriers. The corresponding corrections were introduced into the theoretical curves for the samples represented in Figs. 2a and 2c.

ture at high concentrations of the charged impurities, causing a rather strong increase in the dragging current with decreasing temperature.

In conclusion we note that the dragging effect can be used to investigate the coefficient α for the absorption of light by free carriers in the case of relatively low carrier density, and to observe the contribution made to α by scattering by phonons as well as by impurity centers. Thus, in particular, in our measurements at T = 77°K it turned out that the dependence of the dragging current on the impurity concentration, starting with a free carrier density $\sim 10^{16}$ cm^{-3}, becomes superlinear, this being due to the appreciable contribution made at these concentrations to the total absorption coefficient by scattering by impurities. We note that at a concentration $n \sim 7 \times 10^{16}$ cm^{-3} the contribution of scattering by ionized impurities to the absorption coefficient becomes commensurate with the contribution due to scattering by lattice vibrations.

The authors are grateful to A. A. Grinberg and N. P. Kramer for useful discussions, and also to Ya. T. Dashevskiĭ and V. S. Aliev for help with the experiment.

[1] A. M. Danishevskiĭ, A. A. Kastal'skiĭ, S. M. Ryvkin, and I. D. Yaroshetskiĭ, Zh. Eksp. Teor. Fiz. 58, 544 (1970) [Sov. Phys.-JETP 31, 292 (1970)].

[2] A. A. Grinberg, ibid. 58, 989 (1970) [31, 531 (1970)].

[3] A. S. Baltenkov, N. A. Brynskikh, V. B. Gilerson, and N. P. Kramer, Fiz. Tekh. Poluprov. 4, No. 12 (1970) [Sov. Phys.-Semiconductors 4, No. 12 (1971)].

[4] H. E. M. Barlow, Proc. IRE 46, 1411 (1958).

[5] L. É. Gurevich and A. A. Rumyantsev, Fiz. Tverd. Tela 9, 75 (1967) [Sov. Phys.-Solid State 9, 55 (1967)].

[6] H. J. G. Meyer, Phys. Rev., 120, 298 (1958).

[7] R. Rosenberg and M. Lax, Phys. Rev., 112, 843 (1958).

[8] B. Donovan, Proc. Phys. Soc., 76, 574 (1960).

[9] E. Conwell, J. Phys. Chem. Sol., 5, 234 (1959).

Translated by J. G. Adashko
217