Linear–circular dichroism of drag current due to nonlinear intersubband absorption of light in p-type Ge

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(Submitted September 15, 1992)

Fiz. Tverd. Tela (St. Petersburg) **35**, 198–207 (January 1993)

A study has been made of the effect of the polarization state on linear absorption of radiation in the submillimeter range ($\lambda = 90\ \mu$m) in p-type Ge crystals. The dependence of the current due to electron drag by photons on the intensity I of linearly and circularly polarized light has been measured. In both cases, it is observed that inversion of the photocurrent takes place with increasing intensity at $I = 114$ kW/cm^2 and $I = 80$ kW/cm^2 (at $T = 300$ K). The polarization dependences of the drag currents corresponding to two-photon transitions and the nonlinear current due to saturation of one-photon transitions are calculated. The theoretical results are then compared with experimental data, which makes it possible to identify the two contributions.

The linear–circular two-photon dichroism that was predicted in Ref. 1 and discovered in III-V, II-VI, III-VI, and II-V compounds (see, e.g., Refs. 2 and 3 and the references cited therein) has so far been observed only for interband transitions of electrons from the valence band to the conduction band in semiconductors. We report the first observation of this effect in the case of nonlinear intraband absorption of radiation accompanied by one-photon and two-photon transitions of free carriers between the heavy- and light-hole subbands of the degenerate valence band in germanium. The effect of the polarization state on the absorption of strong submillimeter radiation in p-type Ge was studied in terms of the drag of carriers by photons. It was shown earlier that the current due to drag of holes by linearly polarized photons changes sign as the intensity of light I increases.[4,5] The inversion of the current was explained in Refs. 4 and 5 by the fact that the one-photon and two-photon contributions to the drag photocurrent have different signs and compensate one another at some intensity I_i. The calculations of Ref. 6 show that the absorption coefficients K^2 for direct two-photon intersubband transitions for circular and linear polarizations of light differ by a factor of 1.5 ($K_{\rm circ}^{(2)} > K_{\rm lin}^{(2)}$). It could thus be expected that the inversion point I_i shifts toward lower intensities when the polarization changes from linear to circular.

In Sec. 1, we explain briefly the experimental method and present the results of our measurements of the drag photoelectric power for the two polarizations of the radiation. In Sec. 2 we derive formulas for the two-photon drag currents $j_{\rm lin}^{(2)}$ and $j_{\rm circ}^{(2)}$. Since the expressions for $j^{(2)}$ and $K^{(2)}$ have different structure, the ratio of currents $j_{\rm circ}^{(2)}/j_{\rm lin}^{(2)}$ is not in general equal to the ratio of the absorption coefficients $K_{\rm circ}^{(2)}/K_{\rm lin}^{(2)}$. We show in Sec. 3 that resonance saturation of one-photon transitions, which influences the drag current, also depends on polarization, which modifies the value of the intensity corresponding to inversion of the drag current. The theoretical and experimental results are compared in Sec. 4.

1. EXPERIMENTAL METHOD AND RESULTS

The experiments were carried out on n-type and p-type germanium samples at $T = 300$ K for carrier concentrations in the range 10^{14}-10^{16} cm^{-3}. Samples were cut out in the form of cylinders of diameter 5 mm and length 20 mm with thin ring ohmic contacts fused in on the sides. This geometry was dictated by the need to obtain the maximum possible photoresponse per unit intensity when investigating the drag emf for low intensities of light. The strong absorption condition $K_s d > 1$, where K_s is the total absorption coefficient, was satisfied for all carrier densities.

We measured the dependence of the longitudinal drag emf on the intensity and polarization of the radiation. We used as a source of radiation a pulsed NH_3 laser with optical pumping by TEA CO_2 laser. The wavelength and the duration of a pulse were, respectively, 90.5 μm and 40 ns. Linearly polarized laser radiation was transmitted through a quartz $\lambda/4$ plate (Fig. 1). As the angle θ between the quartz optical axis and the polarization vector **e** of light varied from 0 to 45°, linear polarization changed to circular polarization. The intensity of radiation incident on the sample was varied with calibrated Teflon-based filters. During the measurements, the intensity of radiation was monitored by diverting part of the beam with a Mylar plate and it was detected with a fast-response photodetector. The light was focused onto the sample by means of a TPX lens with focal length of 100 mm. The time resolution of the measuring system was 5 ns.

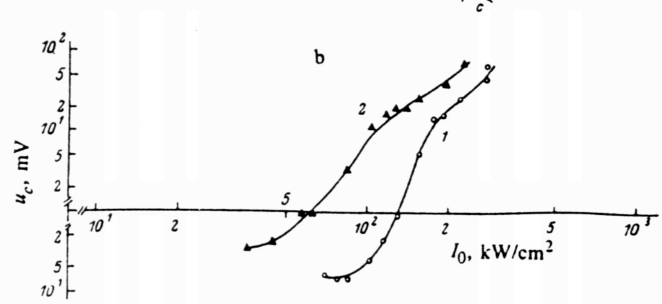

FIG. 1. a) Experimental geometry: 1) $\lambda/4$ plate; 2) condensing lens; 3) attenuators; 4) sample. b) Dependence of the longitudinal drag emf on the intensity of radiation in p-type Ge at $T = 300$ K and for hole concentration $p = 1.5 \times 10^{14}$ cm^{-3}: 1) linear polarization; 2) circular polarization.

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The experimental results obtained for p-type Ge with $p = 1.5 \times 10^{14}$ cm^{-3} for the two polarization states are shown in Fig. 1. It can be seen that the drag emf U_c changes sign as the intensity increases for both linearly and circularly polarized radiation. For relatively low intensities, the drag current flows in the direction opposite to the direction of propagation of radiation whereas the directions of the photocurrent and the exciting beam are the same for high intensities. When the illumination goes to circular polarization the curve $U_c(I)$ is shifted considerably to the left (Fig. 1). Experiments carried out on a series of samples showed that the inversion point I_i does not depend on the carrier concentration. In n-type Ge samples where there are no direct transitions, the drag is associated with indirect transitions and the ratio of the drag emf to the intensity was found to be independent of the polarization state in the range of intensities under study.

2. THEORY. TWO-PHOTON DRAG CURRENT FOR LINEAR AND CIRCULAR POLARIZATIONS

When calculating the two-photon drag current $j_{\rm circ}^{(2)}$ for circularly polarized radiation, we use the procedure developed in Ref. 5 for linearly polarized radiation. We state here only the final formulas for $j_{\rm circ}^{(2)}$ and $j_{\rm lin}^{(2)}$, explain the notation, and discuss the expected differences between the two photocurrents. Using notation similar to that employed in Ref. 5, we can write the two-photon drag current in the form

$$j_l^{(2)} = e\frac{\hbar q}{m_1 - m_2}\tau_l^{(2)}(-1)^{1+l}\frac{K^{(2)}I}{\hbar\omega}(u_{2,l} + u'_{2,l}), \tag{1}$$

$$u_{2,l} = a_2\left(b_2 + \frac{2}{7}\nu_l(E_l^{(2)})\right),$$

$$\nu_l(E) = \frac{\partial \ln \tau_l(E)}{\partial \ln E} - \beta E, \tag{2}$$

$$u'_{2,l} = -\frac{1}{35}\left(c_2 + d_2\frac{m_l^-}{m_l} + h_2\frac{m_l^-}{m_0}g\right). \tag{3}$$

Here we have for linearly polarized radiation $a_2 = 21/20$, $b_2 = 53/49$, $c_2 = 110$, $d_2 = 21$, and $h_2 = -56$ and, for the circular polarization, $a_2 = 28/15$, $b_2 = 51/49$, $c_2 = 87$, $d_2 = 21$, and $h_2 = -182/3$; e is the elementary charge ($e > 0$); l labels the heavy- ($l = 1$) and light- ($l = 2$) hole subbands; m_0 is the free electron mass; m_l is the effective mass of a hole in the subband l; $m_l^- = m_2$ for $l = 1$ and $m_l^- = m_1$ for $l = 2$; g is the g factor of a Γ_8 hole; I is the intensity; $\mathbf{q}$ is the wave vector of the radiation in the crystal; $q = n_\omega \omega/c$, n_ω is the refractive index of light of frequency ω; $\beta = (k_BT)^{-1}$; $E_l^2 = 2h\omega\mu/m_l$; the reduced mass is $\mu = m_1m_2/(m_1 - m_2)$; and $\tau_l^{(2)} \equiv \tau_l(E_l^{(2)})$ is the momentum relaxation time of a hole from the subband l in a state with energy $E_l^{(2)}$. The two-photon and one-photon absorption coefficients for direct inter-subband transitions are mutually related by

$$K^{(2)}/K^{(1)} = \frac{I}{I_0}e^{-\beta E_1^{(1)}}(1 + e^{-\beta\hbar\omega})\,4\sqrt{2}\,(2 + P^2_{\rm circ}), \tag{4}$$

$$K^{(1)} = \alpha\frac{k^{(1)}}{n_\omega}f(E_1^{(1)})(1 - e^{-\beta\hbar\omega}), \tag{5}$$

where $P_{\rm circ}$ is the degree of circular polarization of light; α is the fine structure constant $e^2/c\hbar$; $K^{(1)} = (2\mu\omega/h)^{1/2}$; $E_l^{(1)} = h\omega\mu/m_l$; $f(E)$ is the equilibrium energy distribution function of the holes; and we have introduced the characteristic intensity

$$\bar{I}_0 = \frac{2n_\omega}{\pi\alpha}\mu\omega^3. \tag{6}$$

We have eliminated in our equations (2) and (3) the error in Eqs. (40) and (42) of Ref. 5 derived for linearly polarized radiation. In particular, a_2 was reduced by a factor of two.

When calculating $j^{(2)}$, we need to evaluate the averages

$$\xi_i = \langle \varphi_i \sin\theta\cos\theta \rangle, \tag{7}$$

where angular brackets denote averaging over all directions of the hole wave vector $\mathbf{k}$,

$$\varphi_1 = |e'_-|^2 e'_- e^*_{z'}, \quad \varphi_2 = |e_{z'}|^2 e'_- e^*_{z'},$$

$$\varphi_3 = (e'_- e_{z'})^*(e^2_{x'} + e^2_{y'}), \quad \varphi_4 = -i|e'_-|^2 e^*_{z'} e_{y'},$$

$e_-' = e_{x'} - ie_{y'}$; and $e_{\alpha'}$ denotes a projection of the polarization vector on the x', y', and z' axes that are related to the vector $\mathbf{k}$ as follows: $\mathbf{k} \parallel z'$, x' lies in the $(\mathbf{q}, \mathbf{k})$ plane, and θ is the angle between $\mathbf{k}$ and the wave vector $\mathbf{q}$ of the radiation.

For linearly polarized radiation we have

$$\xi_1 = 4/105, \ \xi_2 = 1/35, \ \xi_3 = 4/105, \ \xi_4 = 0$$

and for circular polarization,

$$\xi_1 = 4/35, \ \xi_2 = 2/105, \ \xi_3 = -2/105, \ \xi_4 = 1/15.$$

As in Ref. (5), we have calculated $j^{(2)}$ and $K^{(2)}$ in the approximation of spherical bands, where the polarization dependence of the two-photon absorption coefficient is described by the factor $(1 + P_{\rm circ}^2)$ in Eq. (4), the component of the drag current perpendicular to $\mathbf{q}$ is zero, and the longitudinal components is characterized by the polarization dependence

$$j^{(2)} = j^{(2)}_{\rm lin}(1 - P^2_{\rm circ}) + j^{(2)}_{\rm circ}P^2_{\rm circ}. \tag{8}$$

We note that the cubic anisotropy of the hole subbands must lead to a dependence of $j^{(2)}$ on the direction of linear polarization. In particular, for $\mathbf{q} \parallel 001$ we must add to the right-hand side of Eq. (8) an anisotropy term proportional to $(|e_x|^4 + |e_y|^4)$, where $x \parallel [100]$ and $y \parallel [010]$. It follows from the structure of expressions (1)-(4) that the ratio of the absorption coefficients $K_{\rm circ}^{(2)}/K_{\rm lin}^{(2)} = 1.5$ is fixed, whereas the ratio of the two-photon currents $j_{\rm circ}^{(2)}/j_{\rm lin}^{(2)}$ depends both on the frequency of the radiation and on the band structure parameters m_1, m_2, g, and the relaxation times $\tau_l^{(2)}$, which means that this ratio may be either greater or smaller than 1.5.

Before we compare the theoretical and experimental results quantitatively, we should discuss yet another possible contribution to nonlinear absorption of radiation and nonlinear drag current associated with resonance saturation of one-photon transitions. As the intensity of the radiation increases, the steady-state populations of resonance states of heavy holes with energy close to $E_1^{(1)}$ begins to decrease rapidly and the population of light holes with $E \approx E_2^{(1)}$ increases, which must alter the one-photon drag current and result in an additional shift of the inversion point I_i. Moreover, we shall show in the next section that the saturation effect and, hence, also the corresponding correction to the drag current depend on the polarization state. We note that the saturation effect was ignored in Ref. 5.

3. THEORY. SATURATION OF ONE-PHOTON DRAG CURRENT FOR LINEAR AND CIRCULAR POLARIZATIONS

The rate of one-photon intersubband transitions per unit volume for an arbitrary radiation intensity I can be written in the form

$$W^{(1)} = \frac{2\pi}{\hbar} f(E_1^{(1)})(1 - e^{-\beta\hbar\omega}) \sum_{\mathbf{k},\, s=\pm} \frac{R^{(s)}(\mathbf{k}, \mathbf{e})}{[1 + 4T_1T_2\hbar^{-2}R^{(s)}(\mathbf{k}, \mathbf{e})]^{1/2}} \times \delta(E_{2\mathbf{k}} - E_{1\mathbf{k}} - \hbar\omega), \tag{9}$$

where

$$R^{(\pm)}(\mathbf{k}, \mathbf{e}) = |M^{(1)}_{\pm 1/2;\, \pm 3/2}(\mathbf{k}, \mathbf{e})|^2,$$

$M_{m',m}{}^{(1)}(\mathbf{k}, \mathbf{e})$ is the one-photon transition matrix element [see Eqs. (7) and (9) in Ref. 5]; we neglect the wave vector $\mathbf{q}$ of the radiation; and T_l is the lifetime of a hole in the subband l near the resonance energy $E = E_l^{(1)}$, which is in general much shorter than the momentum relaxation time $\tau_l^{(1)} \equiv \tau_l(E_l^{(1)})$ (see Ref. 7).

Substituting in Eq. (9) the expression for the matrix element $M_{m',m}{}^{(1)}$ and carrying out summation over $\mathbf{k}$, we obtain for the linear and circular polarizations

$$W^{(1)}_{\rm lin} = W_0^{(1)}\xi_{\rm lin}(I/I_s), \tag{10a}$$

$$W^{(1)}_{\rm circ} = W_0^{(1)}\xi_{\rm circ}(2I/I_s), \tag{10b}$$

where $W_0^{(1)} = K^{(1)}I/\hbar\omega$; the coefficient $K^{(1)}$ was introduced in Eq. (5); the intensity I_s is defined by $I_s = (3\omega^2T_1T_2)^{-1}I_0$; and

$$\xi_{\rm lin}(x) = \frac{3}{4x}\left[1 + \frac{x-1}{\sqrt{x}}\arcsin\left(\frac{x}{x+1}\right)^{1/2}\right], \tag{11a}$$

$$\xi_{\rm circ}(y) = \frac{3}{2}\left(\frac{\sqrt{1+y}}{y} - \frac{1}{2y\sqrt{y}}\ln\frac{\sqrt{y+1}+\sqrt{y}}{\sqrt{y+1}-\sqrt{y}}\right). \tag{11b}$$

The function $\xi_{\rm lin}(x)$ is identical with the function $\xi(x)$ obtained in Ref. 7 in the investigation of the nonlinear absorption of linearly polarized light.

The asymptotic behavior of the functions (11) for small and large values of their argument is given by

$$\xi_{\rm lin}(x) = \begin{cases} 1 & \text{for } x \ll 1, \\ \dfrac{3\pi}{8\sqrt{x}} & \text{for } x \gg 1, \end{cases} \tag{12a}$$

$$\xi_{\rm circ}(y) = \begin{cases} 1 & \text{for } y \ll 1, \\ \dfrac{3}{2\sqrt{y}} & \text{for } y \gg 1. \end{cases} \tag{12b}$$

Let us clarify the causes of the linear–circular dichroism in the case of saturation of one-photon absorption. For simplicity, we shall consider the transitions $3/2, \mathbf{k} \to 1/2, \mathbf{k}$ and $-3/2, \mathbf{k} \to -1/2, \mathbf{k}$ of a hole with $\mathbf{k} \parallel \mathbf{q}$. For linear polarization, the squares of such transition matrix elements $R_{\rm lin}{}^{(\pm)} \equiv R^{\pm}(\mathbf{k} \parallel \mathbf{q})$ are the same. For circularly polarized radiation, say with right-hand circular polarization, the transition $3/2 \to 1/2$ is forbidden and [sic]. For low intensity of radiation, where the optically induced changes in the hole distribution function can be neglected, the total probabilities of these transitions do not depend on the polarization state. In the saturation case, these probabilities must be multiplied, respectively, by $[1 + 4T_1T_2\hbar^{-2}R_{\rm lin}{}^{(\pm)}]^{-1/2}$ and $[1 + 4T_1T_2\hbar^{-2}R_{\rm circ}{}^{(\pm)}]^{-1/2}$. The mechanism of the linear–circular dichroism for two-photon absorption is similar. The only difference is that, in contrast to the saturation of one-photon absorption, the intermediate states in the two-photon processes are virtual and the lifetime T_l is now replaced by the energy denominator $h/(E_l - E_{l'} - h\omega)$. It follows that one cannot neglect the interference of the contributions of different virtual states n' to the two-quantum process $n \to n' \to n''$; i.e., it is not enough to sum the squares $|M^{(2)}(n \to n' \to n'')|^2$ over n'; rather, one must first sum over n' all the matrix elements $M^{(2)}(n \to n' \to n'')$ of two-photon transitions and then take the modulus squared of the resultant sum.

It follows from the equality $R_{\rm circ}{}^{(-)} = 2R_{\rm lin}{}^{(\pm)}$ that the one-photon transitions with $\mathbf{k} \parallel \mathbf{q}$ should become saturated first for circular polarization. For high intensities, i.e., $I \gg I_s$, the corresponding transition rates cease to depend on I and their values for the linear and circular polarizations are in the ratio 2:1. For nonparallel $\mathbf{k}$ and $\mathbf{q}$, this difference is reduced. It follows that an exact calculation that involves summation over all possible directions of $\mathbf{k}$ (see Fig. 2) leads to a smaller value $\pi\sqrt{2}/4 \approx 1.1$ for the ratio of the transition rates. We have calculated the correction $\delta j^{(1)}$ quadratic in the intensity that is due to the saturation effect and which should be added to the component of the drag current liner in the radiation intensity.[5]

$$j_l^{(1)} = e\frac{\hbar q}{m_1 - m_2}\tau_l^{(1)}(-1)^{l+1}\frac{K^{(1)}I}{\hbar\omega}(u_{1,l} + u'_{1,l}), \tag{13}$$

$$u_{1,l} = 2 + \frac{4}{5}\nu_l(E_l^{(2)}), \tag{14}$$

$$u'_{1,l} = \frac{1}{10}\left(-3 + 7\frac{m_l^-}{m_l} + 10\frac{m_l^-}{m_0}g\right). \tag{15}$$

When calculating $\delta j^{(1)}$, it is necessary to take into account the linear term in $\mathbf{q}$ in the energy difference $E_{2,k+q} - E_{1,k}$ and the matrix element $M_{m'k+q;m,k}{}^{(1)}(\mathbf{e})$ and include in Eq. (9) the second-order correction in $R^{(s)}$. The final result is given by

$$\delta j_l^{(1)} = e\frac{\hbar q}{m_1 - m_2}\tau_l^{(1)}(-1)^{l+1}\frac{K^{(1)}I^2}{\hbar\omega I_s}(\nu_{1,l} + \nu'_{1,l}), \tag{16}$$

$$\nu_{1,l} = -\frac{36}{5}\tilde{a}\left(1 + \frac{2}{7}\nu_l(E_l^{(2)})\right), \tag{17}$$

$$\nu'_{1,l} = \frac{12}{35}\left(\tilde{c} + \tilde{d}\frac{m_l^-}{m_l} + \tilde{h}\frac{m_l^-}{m_0}g\right). \tag{18}$$

For linear polarization, we have $a = 1$, $\tilde{c} = 8$, $\tilde{d} = -9$, and $\tilde{h} = -14$, and for circular polarization, $a = 11/6$, $\tilde{c} = 8$, $\tilde{d} = -20$, and $\tilde{h} = -28$. We note that the quantities $u_{2,l}$, $u_{1,l}$, and $\nu_{1,l}$ describe the drag effect calculated with allowance for the dependence on $\mathbf{q}$ of the difference $E_{2,k+q}$

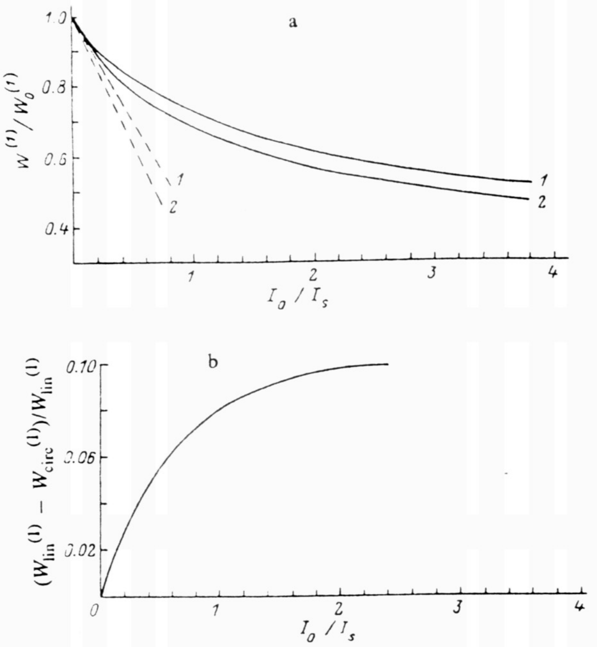

FIG. 2. Effect of polarization on the saturation of the one-photon intersubband absorption with increasing intensity of radiation: a) calculated dependences of the ratio [sic] on I_0 for linear (solid curve 1) and circular (solid curve 2) polarizations. Here, $W^{(1)}$ is the average number of one-photon transitions per unit volume and unit time for the intensity I_0; [sic] the same quantity but neglecting the effect of saturation. Broken curves represent the approximate dependence calculated in the second order in I_0. b) Relative difference between the transition probabilities $W^{(1)}$ for the linear and circular polarizations as a function of I_0. Here, I_s is the characteristic intensity introduced in Eq. (10).

$- E_{1,k}$ that enters the law of conservation of the energy but neglecting the dependence on **q** of the matrix element $M_{m',k+Nq;mk}^{(N)}$ of N-photon transitions, whereas the contributions proportional to $u_{2,l}'$, $u_{1,l}'$, and $v_{1,l}'$ appear solely as a result of the dependence of the matrix elements on **q**.

4. DISCUSSION

The nonlinearity leads to a relation between the emf and the drag current that is more complex than in the case of linear dependence of j on I. In fact, the measured emf is proportional to the photocurrent averaged over the sample length d

$$\bar{j} = \frac{1}{d} \int_0^d j(z)\, dz. \tag{19}$$

When the contributions $\delta j^{(1)}$ and $j^{(2)}$ quadratic in I are included, the dependence of the total density of drag current on z can be written in the form

$$j(z) = aI(z) + bI^2(z), \tag{20}$$

where $I(z)$ is the radiation intensity at a point z and the coefficients a and b do not depend on intensity. As was shown in Ref. 8, the absorption of radiation with wavelength $\lambda = 90$ μm in p-type Ge at room temperature is due mainly to indirect optical transitions with participation of phonons and to lattice absorption. We note that, in spite of the dominant role of direct transitions in the generation of drag current,[9] their relative contribution to the absorption amounts to less than 15%. As a result, it is possible in the interpretation of experimental data to neglect the dependence of the total absorption coefficient K_s on the intensity and substitute in Eq. (20) instead of $I(z)$ the exponential function $I_0\exp(-K_s z)$, where I_0 is the intensity of radiation entering the crystal. We then obtain for the average value of the photocurrent under the condition $K_s d > 1$ the expression

$$\bar{j} = \frac{1}{K_s d}\left(j^0_{\rm lin} + \frac{1}{2} j^0_q\right), \tag{21}$$

where $j_{\rm lin}^0 = aI_0$ and $j_q^0 = bI_0^2$ are, respectively, the linear and quadratic drag currents near the exterior surface of the sample. It thus follows that the measured intensity I_i corresponding to inversion of the drag current does not correspond to the point where $j_{\rm lin}^0$ becomes equal to $-j_q^0$ as is the case for $K_s d \ll 1$ but corresponds to the equality $j_{\rm lin}^0 = -j_q^0/2$, which was not taken realized in Ref. 5.

The experimental and theoretical dependences of the ratio $\chi = \bar{j}/pI_0$ on I_0 for linear and circular polarizations are shown in Fig. 3. In accordance with Eq. (21), the theoretical dependence was obtained by dividing the currents $\delta j^{(1)}(I_0)$ and $j^{(2)}(I_0)$ by a factor of two and adding to their sum the linear photocurrent.

We have calculated the relaxation times $\tau_l^{(N)}$ taking account of the scattering of holes by acoustic[10,11] and optical[12] phonons. Estimates indicate that the relative contribution to τ_l^{-1} due to scattering of holes by ionized impurities is small in the range of densities considered, which is in agreement with the observation that the measured ratio j/pI_0 does not depend on p (at room temperature).

We have used the following values of parameters for germanium: $m_2 = 0.045m_0$, $g = -6.8$, the acoustic length $l_0 = 4.3 \times 10^{-3}$ cm, the velocity of sound $v_s = 5.2 \times 10^5$ cm$\cdot$s^{-1}, the density $\rho = 5.3$ g$\cdot$cm^{-3}, the constant of interaction with optical phonons $E_{\rm opt} = 13$ eV, the energy of an optical phonon $\hbar\omega_{\rm opt} = 37$ meV, and the static permittivity $\varepsilon = 16$. In this case, we obtained $\tau_1^{(1)} = 4.5 \times 10^{-13}$ s, $\tau_2^{(1)} = 3.7 \times 10^{-13}$ s, $\tau_1^{(2)} = 4.3 \times 10^{-13}$ s, $\tau_2^{(2)} = 2.8 \times 10^{-13}$ s, and $\chi_{\rm theor}^{(1)} = 87 \times 10^{-24}$ A$\cdot$cm$^3\cdot$W^{-1} corresponding to the measured value $\chi_{\rm exp}^{(1)} = 80 \times 10^{-24}$ A$\cdot$cm$^3\cdot$W^{-1}. We note that the values of $\chi_{\rm theor}^{(1)}$ and $\chi_{\rm exp}^{(1)}$ for $E_{\rm opt} = 11.4$ eV differ by a factor of about two.

Then calculating $\delta j^{(1)}$, we should also specify the value of T_1T_2, which may be less than $\tau_1^{(1)}\tau_2^{(1)}$, as already mentioned. Calculations show that the substitution of $\tau_l^{(1)}$ for T_l yields $\omega^2 T_1T_2 = 97$ and the inversion points I_i obtained, respectively, for linear and circular polarizations are equal to 57.5 and 23.5 kW$\cdot$cm^{-2} and the corresponding ratio is I_i(lin)/I_i(circ) $\equiv \Lambda_i = 2.4$. If we neglect the saturation effect for the one-photon drag current, we obtain I_i(lin) = 682 and I_i(circ) = 428 kW$\cdot$cm^{-2} and $\Lambda_i = 1.6$.

Best agreement with the experimental values I_i(lin) = 114 and I_i(circ) = 80 kW$\cdot$cm^{-2} is obtained for $\omega^2 T_1T_2 = 24$, i.e., I_i(lin) = 138 and I_i(circ) = 70 kW$\cdot$cm^{-2}. In this case, the contribution of saturation to the one-photon drag current $\delta j^{(1)}$ is 2.7 times greater than that of the two-photon current $j^{(2)}$ and both terms have the same sign opposite to that of $j^{(1)}$. We recall that we have evaluated $\delta j^{(1)}$ in the second order in the radiation intensity. It can be seen from Fig. 2

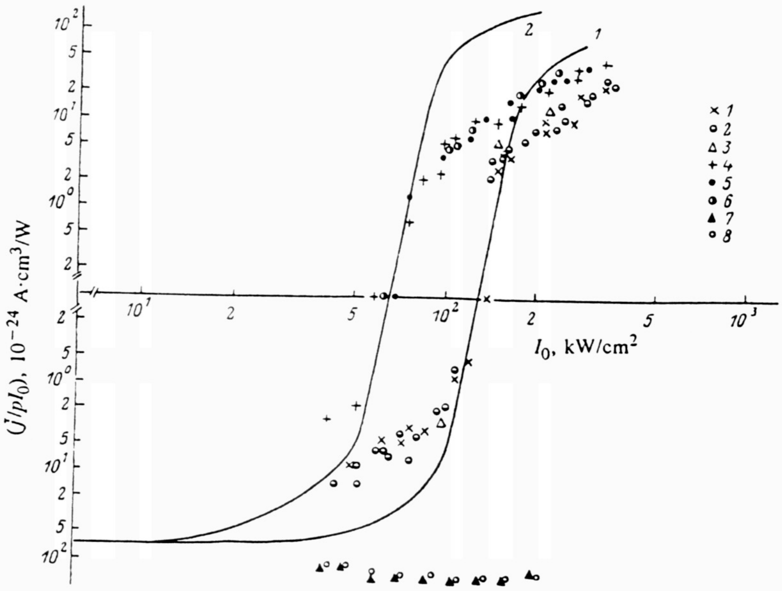

FIG. 3. Dependence of the average drag current j divided by the hole concentration p and by the intensity I_0 on the intensity of radiation for linear (1) and circular (2) polarizations. Solid curves are theoretical results including the effect of partial saturation of one-photon transitions; 1-3 experiments on p-type Ge, linear polarization; 4-6) experiments on p-type Ge, circular polarization; 7) experiment on n-type Ge, linear polarization; 8) experiment on n-type Ge, circular polarization; 1, 4) hole concentration $p = 1.5 \times 10^{14}$ cm^{-3}; 2, 5) $p = 3 \times 10^{14}$ cm^{-3}; 3, 6) $p = 3 \times 10^{15}$ cm^{-3}; 7, 8) electron concentration $n = 4 \times 10^{15}$ cm^{-3}.

that for $I_0 \approx I_i$, there is a considerable deviation of the ratio $W^{(1)}(I)/W_0^{(1)}(I)$ from linearity. It follows that our estimate for $\omega^2 T_1 T_2$ could be refine by calculating $\delta j^{(1)}$ with greater accuracy.

In conclusion, we have combined experimental and theoretical investigations of the dependences of the drag photocurrent on the intensity and polarization of exciting radiation so as to separate and compare the contributions to the linear absorption of radiation due to the saturation of one-photon transitions and to two-photon transitions.

One of the authors (S.D.G.) is grateful to The Humboldt Foundation for support of the present research.

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Translated by D. Mathon