Linear photogalvanic effect in *p*-type GaAs at classical frequencies

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A linear photogalvanic effect was observed in the classical and transition frequency ranges of exciting radiation ($\lambda = 90$–$385\ \mu$m). The photocurrent and the absorption coefficient were independent of the wavelength. A study was made of the carrier-density and temperature dependences of the photocurrent and the mechanisms of photogalvanic effects were analyzed. The appearance of the linear photogalvanic effect in the classical frequency range was equivalent to a quadratic electrical conductivity in the case of noncentrosymmetric crystals in a static electric field.

The linear photogalvanic effect in noncentrosymmetric crystals has been investigated extensively in the range of exciting radiation frequencies obeying the inequalities $\hbar\omega \gg kT$ and $\omega\tau \gg 1$ (τ is the carrier momentum relaxation time).

We shall report the discovery and investigation of the linear photogalvanic effect in the classical frequency range, where the opposite inequalities apply, and in the transition range between the quantum and classical frequencies. The appearance of the photogalvanic effect in the classical range is practically equivalent to the appearance of a quadratic electrical conductivity of noncentrosymmetric crystals in a static electric field.

We investigated p-type GaAs crystals with impurity (Zn) concentrations in the range $5\cdot10^{15}$-$5\cdot10^{17}$ cm^{-3} at temperatures 300-500 K. Our samples were cut to form plates and two ohmic contacts were deposited on the end faces along the $[1\bar{1}0]$ direction. The radiation was incident along [110] normally to the surface of a sample. We used linearly polarized radiation generated by a pulsed NH_3 (D_2O) laser which was optically pumped[1] and emitted at frequencies $\omega_1 = 2.0\cdot10^{13}$, $\omega_2 = 1.2\cdot10^{13}$, and $\omega_3 = 0.47\cdot10^{13}$ s^{-1} (corresponding to wavelenghts λ = 90.55, 152, and 385 μm).

The observed photocurrent depended on the angle θ between the polarization vector **e** and the $[1\bar{1}0]$ direction, proportionally to $\sin 2\theta$, and its sign was reversed when the sample was rotated by 180° about the $[1\bar{1}0]$ axis, in agreement with a phenomenological expression describing the linear photogalvanic effect in crystals of the T_d symmetry:

$$j_\alpha = I\chi\,|\delta_{\alpha\beta\gamma}|\,e_\beta e_\gamma, \qquad (1)$$

where I is the intensity of the incident radiation; χ is the only linearly independent component of the photogalvanic tensor; $\delta_{\alpha\beta\gamma}$ is a unit antisymmetric tensor.

Our measurements indicated that the constant χ was practically independent of the wavelength in the range 90-400 μm and that it increased with temperature. The carrier-density dependence of χ (Fig. 1) consisted of linear (in the range $p < 3\cdot10^{16}$ cm^{-3}) and quadratic ($p > 3\cdot10^{16}$ cm^{-3}) regions, and variation of the wavelength did not alter the nature of this dependence. Moreover, the absorption coefficient K was independent of the wavelength. At 300 K its value was $2\cdot10^{-15}p$ cm^{-1} and an increase in temperature increased the absorption coefficient.

We demonstrated in Ref. 2 that at $\omega_1 = 2\cdot10^{13}$ s^{-1} the main mechanism of the absorption of light and the formation of the photocurrent was the absorption by free carriers assisted by LO phonons. The nature of the temperature and carrier-density dependences of the absorption coefficient and of the linear photogalvanic current was retained also at other investigated frequencies, indicating that throughout the range under discussion the photocurrent was due to dissipation of the electromagnetic wave energy due to the absorption of LO phonons by free carriers. This assumption readily explained the observation that the magnitude of the effect was practically independent of the frequency of the radiation and showed no carrier-density dependence. When this problem is considered from the classical point of view, it is found that in the range of frequencies where the inequalities $\hbar\omega \ll kT$ and $\omega\tau \ll 1$ are satisfied (already at frequencies $\omega_1 > \omega_2 > \omega_3$ we have $\hbar\omega/kT = 0.55$ and $\omega\tau = 0.47$), both the absorption coefficient and the probability of hole scattering (governing of the photocurrent) are independent of the radiation frequency. The absence of a frequency dependence in the case of χ can be easily understood also from the quantum point of view, since the linear photogalvanic effect is governed by the energies and wave vectors of the initial and final states of carriers participating in the absorption of light irrespective of the mechanism of this effect. In the investigated frequency range these energies and wave vectors are independent of the wavelength, since the photon energy is much less than the optical phonon energy or the energy of the initial state of an optical transition.

We shall now discuss briefly the microscopic mechanisms of the investigated effect. There are two contributions to the linear photogalvanic effect: ballistic, associated with the directional velocity of carriers, and shift, associated with the displacement of carriers in real space.[3] In the classical range of frequencies[4] the ballistic current is due to the nonsphericity of the momentum distribution of electrons induced by the electric field of the optical wave and by the asymmetry of the subsequent scattering. In the quantum range of frequencies the ballistic current is due to, firstly, the asymmetry of the absorption events when electrons collide with scatterers and the optically induced asymmetry of the scattering processes (the relevant quantum transitions form a closed cycle) and, secondly, due to the asymmetry of the carrier scattering which are distributed anisotropically after the absorption of a photon.

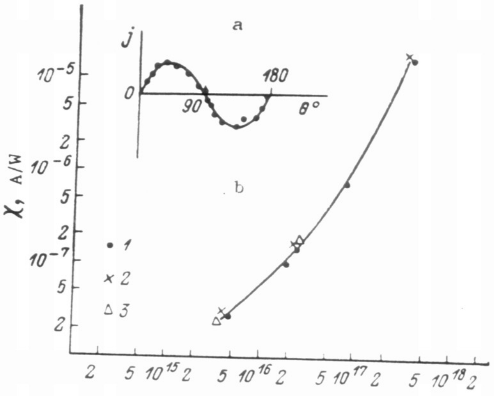

FIG. 1. Dependence of the photocurrent on the angle θ between the polarization vector of the incident radiation and the [$1\bar{1}0$] direction (a). The lower part of the figure (b) shows the carrier-density dependence of the constant χ at wavelengths Λ = 90.55 μm (1), 152 μm (2), and 385 μm (3).

Calculations of the ballistic contribution at quantum and classical frequencies[4] give the same result also for the transition range of frequencies.

The shift contribution to the current at frequencies $\hbar\omega > kT$ is due to the displacement of electrons in the course of the absorption of a photon and the displacement during the subsequent scattering.

In the classical range of frequencies the photocurrent due to the displacement of carriers in real space is determined by three components. Firstly, the current appears because of the displacement of carriers during scattering when these carriers are distributed nonspherically under the influence of the electric field of the optical wave. Secondly, the same displacement during scattering is responsible for the change in the carrier energy in an electric field, which in the final analysis makes the carrier distribution function asymmetric and similar to that discussed in Ref. 5. Thirdly, a change in the electric field imparts an additional velocity to an electron and this again results in a displacement in real space. The scattering of carriers and their motion in an electric field analyzed classically represent a closed cycle of transitions involving scatterers and photons. In the transition range of frequencies we can use both classical and quantum approaches.

The current can be estimated in the classical limit $\omega\tau \ll 1$ from the following expression describing the quadratic electrical conductivity[6]

$$|j| = \sigma E \frac{eEa_0}{kT}, \tag{2}$$

where σ is the conductivity; the quantity a_0 represents the average displacement of carriers in the case of the shift mechanisms or the distance in which carriers lose their directional velocity as a result of asymmetry of the elementary electron processes in the ballistic mechanism case.

When the hole density is $p < 3\cdot10^{16}$ cm^{-3} the formation of the current is related to the scattering by optical phonons, which leads to a linear dependence of the current on p (Ref. 2). The quantity a_0, determined from the experimental results in accordance with Eq. (2) amounts to $3\cdot10^{-11}$ cm. According to Ref. 6, the order of magnitude of a_0 is in this case governed by the ratio of the constants representing the deformation and polar mechanisms of interaction of carriers with LO phonons, which is $d_0/C = 4.6\cdot10^{-8}$ cm. The difference between this estimate and the experimental value shows that the various contributions to the linear photogalvanic current in p-type GaAs largely balance out at classical frequencies. A strong compensation of the contributions occurs also in the $\hbar\omega > kT$ case (Ref. 7).

If $p > 3\cdot10^{16}$ cm^{-3} the appearance of the average velocity on displacement of carriers is associated with the scattering by impurities and the photocurrent is a quadratic function of p. The asymmetry of the scattering by impurities may be related to the octupole moment of impurities or the dipole moment of impurity centers oriented along equivalent crystallographic directions when impurity complexes are present. The experimentally determined value of a_0 then amounts to $3\cdot10^{-10}$ cm for $p = 3.4\cdot10^{17}$ cm^{-3} and rises linearly on increase in the hole density.

[1] S. D. Ganichev, S. A. Emel'yanov, and I. D. Yaroshetskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. 35, 297 (1982) [JETP Lett. 35, 368 (1982)].

[2] E. V. Beregulin, S. D. Ganichev, K. Yu. Glukh, Yu. B. Lyanda-Geller, and I. D. Yaroshetskiĭ, Fiz. Tverd. Tela (Leningrad) 30, 730 (1988) [Sov. Phys. Solid State 30, 418 (1988)].

[3] V. I. Belinicher, E. L. Ivchenko, and B. I. Sturman, Zh. Eksp. Teor. Fiz. 83, 649 (1982) [Sov. Phys. JETP 56, 359 (1982)].

[4] V. I. Belinicher, Author's Abstract of Doctoral Thesis [in Russian], Novosibirsk (1982).

[5] Yu. B. Lyanda-Geller, Pis'ma Zh. Eksp. Teor. Fiz. 46, 388 (1987) [JETP Lett. 46, 489 (1987)].

[6] E. L. Ivchenko and G. E. Pikus, Pis'ma Zh. Eksp. Teor. Fiz. 39, 268 (1984) [JETP Lett. 39, 320 (1984)].

[7] Yu. B. Lyanda-Geller and R. Ya. Rasulov, Fiz. Tverd. Tela (Leningrad) 27, 945 (1985) [Sov. Phys. Solid State 27, 577 (1985)].

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