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LINEAR PHOTOVOLATIC EFFECT IN GALLIUM ARSENIDE IN SUBMILLIMETER WAVELENGTH REGION

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ABSTRACT The linear photovoltaic effect (LPVE) in semiconductors in FIR-submillimeter wavelength region (λ=90-385 μm) has been observed. It has been shown, that LPVE and light absorption are caused by nondirect intraband transitions with participation of the polar optical phonons. The frequency, density, polarization and the temperature dependences of the LPVE and the absorption coeffitient have been studied. The theory of the LPVE in submillimeter spectral range is presented.

The linear photovoltaic effect (LPVE) arises in the homogeneous semiconductors lacking a centre of symmetry under the excitation by linearly polarized homogeneous radiation. The effect results in the photocurrent, which caused by the asymmetry of elementary electron processes. Up to now LPVE have been observed under the excitation by the visible or infrared incident light wave. We report on the first experimental observation of the LPVE in the submillimeter spectral range, where the photocurrent and the light absorption mechanisms are not the same as in the earlier investigated wavelength region.

We have used the pulsed optically pumped NH_3 (D_2O) laser operating at λ=90.55, 152 and 385 μm with the pulse duration τ_p=40 ns. The LPVE have been stadied in p-type GaAs(Zn) samples with the impurities density from $5*10^{15}$ to $5*10^{17}$ cm^{-3} in the temperature interval T=200-500 K. The time resolution of our method was 5 ns. The samples have been fabricated as a narrow plate with two ohmical contacts along [1$\bar{1}$0] direction, and the direction of the incident light unit vector is [110].

The fast photo-e.m.f. has been observed reproducing the shape of the laser pulse. The signal depends on the angle Θ between the polarisation vector and the crystalographic axis [110] as sin2Θ (Figure 1a) and its sign changes if the sample is rotated round [110] axis on 180° . Therefore, the observed signal is described by the phenomenological formula for LPVE:

$$j_\alpha = I \chi |\delta_{\alpha\beta\gamma}| e_\beta e_\gamma \tag{1}$$

here I is the intensity, $\vec{e}$ is the polarization vector of the incident light, $\delta_{\alpha\beta\gamma}$ is the unit antisymmetrical tensor, χ is the constant determining LPVE.

SUBMILLIMETER LIGHT ABSORPTION

The value of LPVE is determined by the mechanisms of light absorption and asymmetric scattering of photocarriers. Investigations of the absorption coefficient have been shown that the main mechanisms of the radiation absorption is the nondirect intraband transitions with participation of polar optical phonons. The cross section at $\lambda > 90$ μm is $2*10^{-15}$cm^2 and smoothly depends on the radiation frequency. The value of the parameter $\omega\tau$ in the spectral range investigated lie between 0.48 at $\lambda = 90$ μm and 0.11 at 385 μm and the value of the parameter $\hbar\omega/kT$ lie between 0.55 and 0.13 (ω is the light frequency,τ is the momentum relaxation time). Thus, the absence of the absorption coefficient frequence dependence can be easily explained from the classical point of view, and in this way the absorption coefficient is determined by the Drude mechanism.

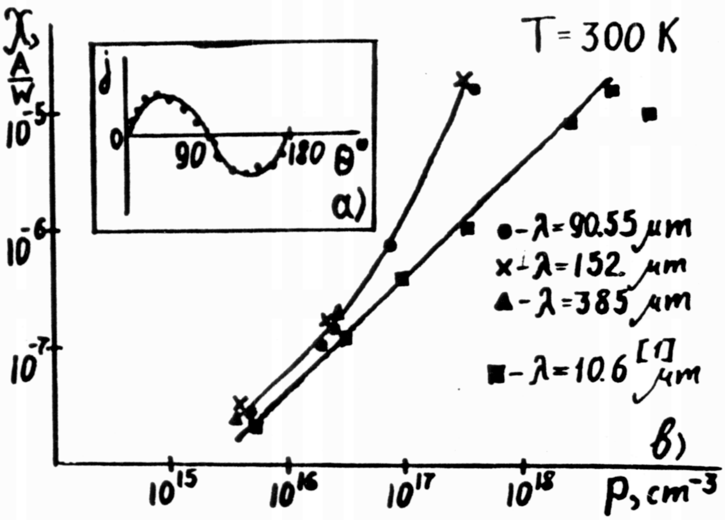

Fig.1 a) LPVE signal in p-GaAs at $\lambda = 90.55$ μm
b) LPVE constant χ vs p-GaAs holes density

LPVE MECHANISMS IN SUBMILLIMETER REGION

The wavelength increasing changes LPVE mechanisms in the semiconductors with the degenerated valence band. It has been established (see [1]) that the LPVE includes two contributions: (i) the shift photocurrent arising due to the shift in R-space of holes undergoing quantum transitions, and (ii) the ballistic photocurrent related to a nonzero average velocity of the photoexcited carriers. The carrier shift can occur for direct and nondirect optical transitions or during the scattering of the photoexcited carriers by phonons or impurities. The average velocity arises as a result of the optical transitions undergoing the scattering of the carriers or on the step of the scattering of the photoexcited carriers. In the IR spectral range [1] the LPVE is caused by light absorption due to direct optical transitions between heavy hole and light hole subband. The main scattering mechanisms is the emission and absorption of polar optical phonons.

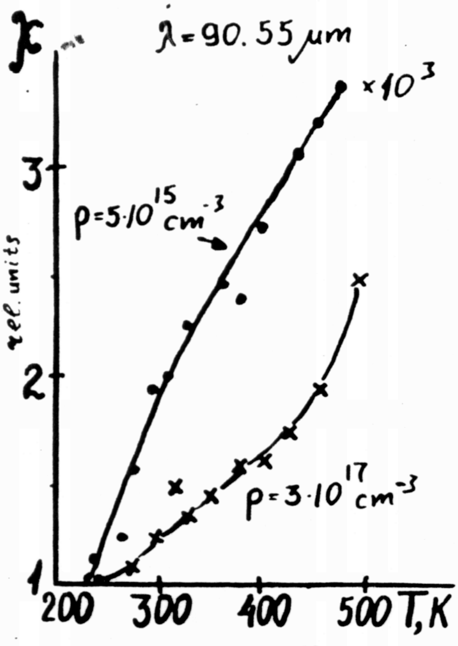

Fig.2. LPVE constant χ vs temperature

In the investigated spectral range the energies of the initial and final states of direct optical transitions lie below the optical phonon energy. As a result, the contributions to the photocurrent due to the phonon emission disappears. In this case the LPVE temperature dependence reduces to the temperature dependence of the absorption coefficient. Therefore, the temperature rise might have caused a decriese of the photogalvanic current magnitude.

On the contrary, the experimental data shows a rise of the photocurrent with the temperature (Figure 2). Therefore LPVE is determined by the mechanisms related to the nondirect intraband transitions.

Firstly, it is a shift current caused by the holes shift in R-space during the nondirect transition with the partisipation of LO-phonon. Secondly, it is a shift current in a single-process of the relaxation of the nondirect-transition-induced photocarrier distribution anisotropy. Such an anisotropy takes place in the case of the nondirect optical transitions as well as for the direct optical transitions. The anisotropic component of the hole momentum distribution, corresponding to the optical transitions undergoing the absorption of the polar LO-phonon with the initial, intermediate and final states in the heave-hole subband, for instance, can be written as

$$\delta f^{+}_{1\underline{K}} = -\frac{K_0 I}{\hbar\omega}\tau_{1K}\,\eta\, o_x o_y e_x e_y \qquad (2)$$

where the orientation degree is determined by

$$\eta = 6\Big[\frac{D_0(\varphi)}{2}t - \frac{3}{5}D_3(\varphi) - \frac{7}{5}D_1(\varphi) + \frac{D_2(\varphi)}{2}(t+t^{-1}) + \\ + \frac{t^{-1}}{2}\Big(\frac{18}{35}D_4(\varphi) + \frac{2}{7}D_2(\varphi) + \frac{D_0(\varphi)}{5}\Big)\Big], \qquad (3)$$

$$\varphi = \frac{2K^2 + 2m_1(\Omega+\omega)/\hbar}{2K\sqrt{2m_1(\Omega+\omega)/\hbar}}, \quad t = \frac{K}{\sqrt{K^2 + 2m_1(\Omega+\omega)/\hbar}},$$

where $\underline{K}$ is the hole wavevector, D_i Legandre second type function.

The value of η for λ =90.55 μm, for example, in two-three times lower than the orientation degree corresponding to the anisotropic hole distribution appearing at the direct optical transitions [1]. η =-3 and besides η_d [1] doesn't depend on the wavevector. But the light absorption resulting from the nondirect optical transition dominates, and that's why the photocurrent connected with the corresponding distribution anisotropy can exceed the photocurrent resulting from the anisotropy of the photoexcitation due to direct optical transitions.

The one-fold scattering of photoexcited holes resulting the shift don't leads to the average velocity. That's why the ballistic contribution on the step of the momentum distribution relaxation arises as a result of two scattering-process interference with participation of phonons, impurities, or phonons and impurities simultaneously. The ballistic photocurrent can arise also on the step of the generation due to the interference of different quantum transitions with the participation of a photon and two phonons.

The carriers density dependences on the constant χ at the wavelength region 10.6-385 μm are shown on Figure 1b (the data for λ =10.6 μm is taken from [1]). It has been shown, that χ linearly depends on p up to the densities of the order of $3*10^{16}$ cm^{-3} and the values of χ were similar at the spectral range λ =10.6-385 μm. At the densities $p>3*10^{16}$ cm^{-3} in the case of λ =10.6 μm linearly depends on p, too, and in the case $\lambda > 90\ \mu m$ the dependence $\chi(p)$ becomes quadratic in p. In the latter case χ doesn't depend on λ.

We shall analyze now the experimental data at the low densities p, when the photocurrent dependence is linear on p. Linear photocurrent dependence corresponds to the mechanisms in which the carrier relaxation and the appearance of the average velocity (or the shift) both are caused by the optical phonon scattering. The effectivence of asymmetry processes χ/K increases with the rise of the temperature (Figure 3).

In the case of higher densities $p > 3*10^{16}$ cm^{-3} the photocurrent dependence changes from linear in p to quadratic. Quadratic dependence $\chi(p)$ shows that in this case the photoholes relaxation time is governed by the carriers scattering by the optical phonons, and the shift or carrier average velocity results from the scattering by ionized impurities.

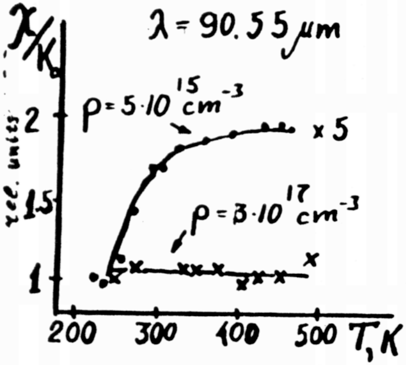

Fig.3. LPVE constant χ normalized to absorption coefficient vs temperature.

The absence of LPVE frequency dependence at $\lambda > 90\ \mu m$ can be explained by the statement that its value is governed by the energy and the momentum of photoexcited carriers in the initial and the final state. In the spectral range investigated this values are practically independent from the wavelength because the photon energy is essentially less than the optical phonon and the initial state energy. The absence of the frequence dependence can be understand also from the classical point of view. Namely, the absorption of the electromagnetic wave energy and the scattering probabilities don't depend on the electric field frequence. In this way the photovoltaic effect in submillimeter spectral range is the equivalent of the even electroconductivity in the crystals lacking a centre of symmetry.

[1] Andrianov, A.V. et al. Sov. JETP, 1981, 6(10), 2080-2094