Linear photogalvanic effect in *p*-type GaSb at infrared and submillimeter wavelengths

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(Submitted September 29, 1992)
Fiz. Tverd. Tela (St. Petersburg) **35**, 461–464 (February 1993)

Results are reported of an experimental investigation of the linear photogalvanic effect in *p*-type GaSb crystals.

The linear photogalvanic effect appears in homogeneous crystals as a result of uniform illumination and is due to an anisotropy of the processes of photoexcitation, scattering and recombination of carriers in noncentrosymmetric crystals. In semiconductors this effect has been investigated extensively in the infrared[1] and submillimeter[2-4] ranges. The present paper reports the discovery and investigation of this effect in *p*-type GaSb crystals excited with light from a wide range of wavelengths (9-400 μm). The results are used to draw conclusions on the general relationships governing the linear photogalvanic effect in III-V crystals at submillimeter wavelengths.

EXPERIMENTAL METHODS AND RESULTS

The experiments were carried out on *p*-type GaSb crystals with a carrier density $p = 1.2 \times 10^{17}$ cm^{-3} at temperatures in the range 78-300 K. The light sources were a pulsed CO$_2$ laser and an optically pumped NH$_3$ laser. The wavelength of linearly polarized light was 9.2, 90.5, 152, or 385 μm. We studied the dependences of the photoemf- and of the absorption coefficient on the temperature of a sample and on the wavelength. Light was incident on a sample, which was a plane-parallel plate cut along the [111] crystallographic axis. Two ohmic electrical contacts were formed at the ends of a sample. The photocurrent was measured along the [11$\bar{2}$] direction.

The emf signal observed on excitation of light with any of the wavelengths repeated the shape of a laser pulse of 40 ns duration. Rotation of the plane of polarization of the incident light about the [111] direction showed that the observed emf depended on the angle θ between the polarization vector and the [11$\bar{2}$] direction in accordance with the cos 2θ law (Fig. 1). Rotation of a sample about the [11$\bar{2}$] axis by 180° without a change in the direction of propagation of light did not alter the signal polarity.

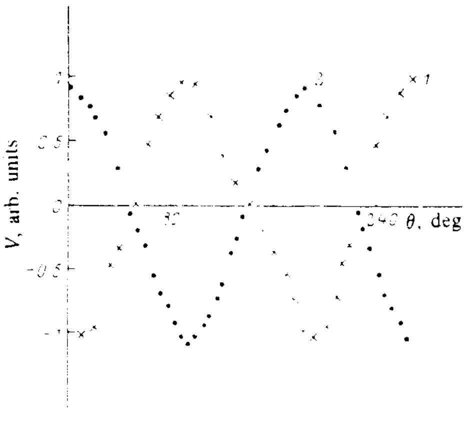

FIG. 1. Dependence of the photoresponse on the angle θ between the polarization vector of light and the $\{11\bar{2}\}$ direction in *p*-type GaAs with $p = 1.2 \times 10^{17}$ cm^{-3} at $T = 300$ K (1) and 78 K (2).

This behavior of the emf was in full agreement with the phenomenological expression for the photogalvanic current in crystals of the T_d symmetry,[1] which include GaSb:

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

where j is the current density; I is the intensity of the light wave; e is the polarization vector; $\delta_{\alpha\beta\gamma}$ is a unit antisymmetric tensor; χ is the only linearly-independent component of the linear photogalvanic effect tensor.

The expression for the photocurrent along the [11$\bar{2}$] direction excited by light incident along the [111] crystallographic axis is

$$j_{[11\bar{2}]} = I\frac{\chi}{\sqrt{6}}\cos 2\theta. \tag{2}$$

It follows from the experimental results that the value of the constant χ determined at $T = 300$ K was practically independent of the wavelength in the range 90-400 μm and decreased at shorter wavelengths (Fig. 2). The observed emf depended on temperature and its sign changed on increase in temperature (Fig. 3). A similar behavior of the effect was observed by us for *p*-type GaAs.[2,3]

The experimentally determined absorption coefficient of *p*-type GaSb was ~170 cm^{-1} for $p = 1.2 \times 10^{17}$ cm^{-3} and $T = 300$ K at the wavelength of 9.2 μm and in the range of wavelengths exceeding 90 μm it amounted to ~240 cm^{-1} and was independent of the wavelength.

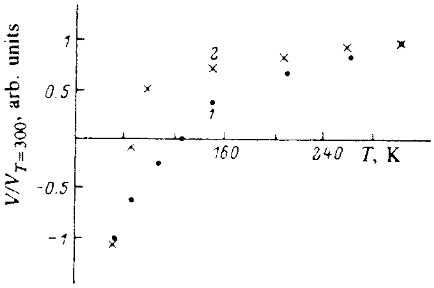

FIG. 2. Dependence of the photoresponse of *p*-type GaAs with $p = 1.2 \times 10^{17}$ cm^{-3} on the temperature of the sample at wavelengths $\lambda = 9$ μm (1) and 90.5 μm (2).

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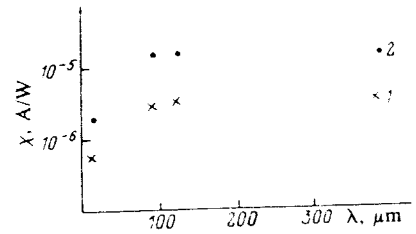

FIG. 3. Dependence of the constant χ ($T = 300$ K, $p = 1.2 \times 10^{17}$ cm^{-3}) on the wavelength in the case of p-type GaAs (1) and p-type GaSb (2).

DISCUSSION OF RESULTS

The linear photogalvanic effect and of the absorption of infrared and submillimeter radiation in p-type III-V semiconductors at temperatures such that the impurities are ionized may be due to both direct optical transitions between the heavy- and light-hole branches of a degenerate valence band and indirect optical transitions.

In the infrared range ($\lambda \sim 9$ μm) where the absorption resulting from direct transitions is considerably stronger (by two orders of magnitude) than the absorption caused by indirect transitions, the photocurrent is due to direct optical transitions between the heavy- and light-hole subbands.

An increase in the wavelength reduces considerably the absorption coefficient of light corresponding to direct transitions and increases that corresponding to indirect transitions. The temperature and frequency dependences show that in the case of p-type GaSb at $T = 300$ K, as in the case of p-type GaAs (Refs. 2 and 3), when the wavelength is 90 μm or more the absorption is primarily due to indirect transitions assisted by polar optical phonons and is independent of the wavelength. The absence of a dependence of the absorption coefficient on the wavelength is in agreement with the classical Drude expression when the conditions $\hbar\omega \ll kT$, $\omega\tau \ll 1$, where τ is the momentum relaxation time, are satisfied (which is true of our experiments). The relationship between the absolute values of the absorption coefficients of GaSb and GaAs in the range $\lambda > 90$ μm is then described satisfactorily by an expression for indirect transitions assisted by optical phonons ($\hbar\omega_L = 29$ meV for GaSb and $\hbar\omega_L = 36$ meV for GaAs) occurring within the heavy-hole subband.[2]

The experimentally observed absence of a spectral dependence of the absorption coefficient and of the constant χ at wavelengths $\lambda > 90$ μm allows us to draw the conclusion that indirect transitions play the dominant role in the linear photogalvanic effect.

It thus follows that in the case of p-type GaSb and p-type GaAs the potogalvanic effect is due to the same optical transitions that determine the optical absorption coefficient.[2-4] A detailed analysis of the mechanisms of the formation of the photocurrent in such cases had been made earlier in the infrared range[1] and in the submillimeter part of the spectrum.[2-4]

The experimentally observed rise of χ between $\lambda \sim 9$ μm and $\lambda > 90$ μm, in spite of similar values of the absorption coefficient is due to an increase in the role of asymmetric scattering by ionized impurities because of a reduction in the energy ε_i of the states participating in the formation of the photocurrent and disappearance of the processes responsible for optical phonon emission ($\varepsilon_i < \hbar\omega_0$).

The temperature dependences obtained for GaSb (Fig. 2), like those reported for GaAs (Refs. 2 and 3), indicate a change in the mechanism of the linear photogalvanic effect between $T = 300$ K and $T = 77$ K. The change in the magnitude of the effect at $T \leq 300$ K is due to the temperature dependence of the number of phonons, which determines largely the mechanisms of the photoexcitation and photocarrier relaxation. Cooling results in the freezeout of carriers at impurities and transitions from an impurity level to an energy band become important. This gives rise to a photocurrent associated with these transitions and, consequently, it results in a change in the direction of the total current.

We shall conclude by noting that the much higher values of the constant χ obtained for p-type GaSb (Fig. 2), compared with p-type GaAs, make it possible to utilize this material in fast-response detectors of the polarization of infrared and submillimeter radiation[5] with the aim of increasing the sensitivity.

One of the authors (SDG) is grateful to the A. Von Humboldt Foundation for support.

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Translated by A. Tybulewicz