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POLARIZATION DEPENDENCES OF RADIATION EMISSION BY HOT CARRIERS IN InSb

Polarization dependences of the spontaneous radiation emitted by hot carriers in p- and n-InSb have been measured experimentally and explained theoretically. A periodic dependence of the spontaneous radiation intensity on the polarizer rotation angle with respect to the direction of the heating electric field is found. This dependence is associated with a field-induced deviation of the even component in the distribution function of hot carriers from the spherical shape (a deviation from the diffusion approximation).

Keywords: InSb, polarization dependences of radiation emission, hot carriers.

1. Introduction and Theoretical Part

Free charge carriers in the conduction band of a semiconductor can participate in both light absorption and light emission processes. The absorption processes dominate when a thermodynamically equilibrium specimen is irradiated with an external electromagnetic flux, whereas the emission ones when the carriers are heated up by an external electromagnetic field. If the dispersion law of charge carries is anisotropic, radiation emitted by hot carriers becomes angle-dependent. Just this situation takes place in multivalley semiconductors of the n-Ge and n-Si types. However, despite the dispersion law of electrons in each valley is anisotropic, the valleys themselves are arranged symmetrically in the Brillouin zone of n-Ge or n-Si. Therefore, the radiation of hot electrons summed up over all equivalent valleys can be either dependent on or independent of angles. The polarization dependence of the total (summed up over all valleys) radiation emitted by hot electrons takes place if the electron-heating field is directed non-symmetrically with respect to the valleys, so that the temperature of electrons is not identical in all valleys [1–5]. The same situation with polarization arises, when the electron concentrations in different valleys become different under the action of a uniaxial pressure applied to the specimen [3, 5].

Under certain conditions (low temperatures, relatively strong fields), the polarization dependences of the intensity of radiation emitted by hot carriers in n-Ge also appear in the case where the electron-heating field is oriented symmetrically with respect to the valleys [4, 5]. This phenomenon was explained by us [4] as a consequence of the deformation of the distribution function of electrons over their velocities by the electric field. To make it clear which deformation of the electron distribution function by the field is meant here, let us consider a model with the isotropic dispersion law for the energy of charge carriers, $\varepsilon = \varepsilon(p)$, where ε is the energy and p the momentum of carriers. This model describes the situation in InSb, which this work is dealt with. However, it also explains why such a mechanism becomes possible in n-Ge, when the electric field is oriented symmetrically with respect to the valleys.

So, let the dc electric field $\mathbf{F}$ be applied to a semiconductor. Now, the distribution function for the charge carrier velocities (or momenta) differs from the equilibrium Maxwellian one and should be determined from the solution of the Boltzmann kinetic equation. If the mechanisms of free charge carrier scattering are quasielastic, the distribution function in a field $\mathbf{F}$ can be written as the series expansion (see, e.g., work [6])

$$f(\mathbf{p}) = f_0(\varepsilon) + f_1(\varepsilon) P_1(\cos\theta) + + f_2(\varepsilon) P_2(\cos\theta) + f_3(\varepsilon) P_3(\cos\theta) + ..., \quad (1)$$

where $P_n(\cos\theta)$ are the Legendre polynomials, θ is the angle between $\mathbf{p}$ and $\mathbf{F}$,

$$f_1(\varepsilon) \approx eF\tau(p)\frac{df_0}{dp};$$

$$f_2(\varepsilon) \approx \frac{2}{3}(eF)^2\,\tau(p)\,\frac{d}{dp}\left(\frac{\tau(p)}{p}\frac{df_0}{dp}\right),\ \ldots, \tag{2}$$

and $\tau(p)$ is the relaxation time. In the overwhelming majority of works, series (1) is confined to two first terms. This approximation is called the "diffusion approximation" in the literature. In the general case, by substituting expansion (1) into the kinetic equation for the function $f(\varepsilon)$, we obtain a chain of equations, which contain the functions $f_n(\varepsilon)$ with different (neighbor) n. For the functions with $n = 1$ and 2, the approximate solutions (2) are obtained. For the function with $n = 0$, we obtain an equation, which should be solved, or the Maxwellian distribution function with an effective electron temperature is approximately accepted as $f_0(\varepsilon)$ [6].

However, there are semiconductors, InSb being among them, for which the diffusion approximation turns out insufficient under certain conditions [7]. In particular, not only the function $f_1(\varepsilon)$, but also $f_3(\varepsilon)$ gives a contribution to the kinetic coefficients.

Note also that the kinetic coefficients are determined by the functions $f_n(\varepsilon)$ with odd n-values ($n = 1, 3, \ldots$), whereas the polarization is described by the functions $f_n(\varepsilon)$ with even n-values ($n = 2, 4, \ldots$).

Expansion (1) and the approximate solution (2) are valid, when the drift velocity does not exceed the average (thermal) one. However, there are situations (strong fields, low temperatures) when the drift velocity exceeds the average thermal one. In this case, the so-called Baraff prolate ("needle-like") approximation [8] is often used:

$$f(\mathbf{p}) = f_0(\varepsilon) + \varphi(\varepsilon)\,\delta(1-\cos\theta), \tag{3}$$

$$f_2(\varepsilon) = \frac{5}{2}f_1(\varepsilon). \tag{4}$$

The calculation scheme of the polarization dependences for spontaneous radiation emitted by hot electrons was considered in detail in works [2, 9]. The essence of the method is as follows, in brief. The consideration is based on the integral of collisions of charge carriers with impurities or lattice vibrations, in which the influence of the field created by an electromagnetic wave on the scattering event is taken into account. For instance, in the simplest case of isotropic electron scattering by ionized impurities, the collision integral looks like [2]

$$\left(\frac{df}{dt}\right)_{st} = \frac{4e^4}{\varepsilon_0^2}n_i\sum_{\ell=-\infty}^{\infty}\int d\mathbf{p}'\,\frac{f(\mathbf{p}')-f(\mathbf{p})}{\left\{(\mathbf{p}-\mathbf{p}')^2+(\hbar/r_D)^2\right\}^2}\times$$

$$\times\,J_l\left(\frac{e}{m\hbar\omega c}\mathbf{A}^{(0)}(\mathbf{p}-\mathbf{p}')\right)\delta\left(\varepsilon_{\mathbf{p}}-\varepsilon_{\mathbf{p}'}-l\hbar\omega\right). \tag{5}$$

Here, e is the electron charge, m the electron mass, n_i the concentration of ionized impurities, r_D the screening radius, $J_l(x)$ the Bessel function, ω the electromagnetic wave frequency, and $A^{(1)}$ the magnitude of the wave vector potential.

With the help of this collision integral, it is possible to find the energy emitted or absorbed by electrons per unit time owing to collisions:

$$Q = \int d\mathbf{p}\,\varepsilon_{\mathbf{p}}\left(\frac{\partial f}{dt}\right)_{st}. \tag{6}$$

From Eq. (6), the radiation emission (or absorption) induced by the field of an emitted electromagnetic wave can be found. Then, knowing the radiation induced by the electromagnetic wave field and using the Einstein relation for the probabilities of the induced and spontaneous radiations, it is possible to find the intensity of the spontaneous radiation emitted by hot carriers. The details can be found in works [2, 9].

Using this method and taking the function $f_2(\varepsilon)$ in form (2) in the case of classical frequency interval with regard for the dominating role of acoustic scattering, we obtain the following expression for the energy of the spontaneous radiation emitted by hot electrons per unit time in unit frequency interval, in unit volume, and into the solid angle $d\Omega$ [4]:

$$W = \frac{4}{3\pi^{5/2}}\frac{e^2 n_i (T_e)^{3/2}}{c^3 T^{1/2}}\frac{1}{m\tau^{(0)}}\times$$

$$\times\left\{1+\frac{eF\tau^{(0)}}{6mT_e^2}\mathrm{P}(\cos\theta_0)\right\}d\Omega, \tag{7}$$

where T_e and T are the electron and lattice temperatures, respectively; $\tau^{(0)}$ the relaxation time at $\varepsilon_p = T$ (the Boltzmann constant $k_\mathrm{B} = 1$); and θ_0 the angle between the polarization unit vector and the electron-heating field $\mathbf{F}$. If the impurity scattering plays the dominating role, the angular dependence of the radiation is also given by the Legendre polynomial $P_2(\cos\theta)$, but with another coefficient.

It is worth emphasizing that, in the case of semiconductors with the isotropic charge dispersion law, the angular dependence of radiation emission of the type $g(T_e, T, \omega)\,P_2(\cos\theta)$ has an almost universal character. The type of scattering mechanism, frequency interval, and type of charge carriers affect the form of

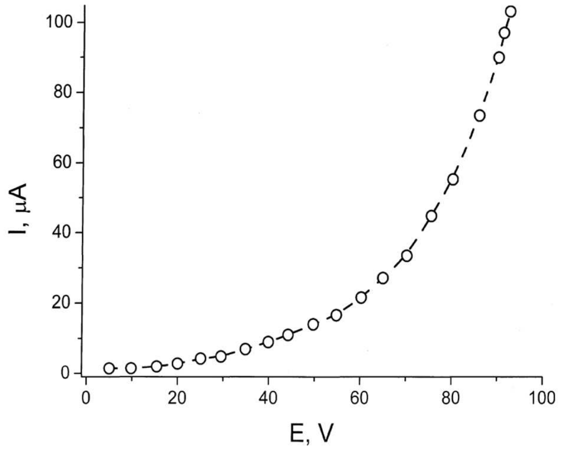

Fig. 1. Current-voltage characteristic of the p-InSb specimen at a temperature of 4.2 K. The hole concentration at room temperature $p \approx 10^{13}$ cm^{-3}

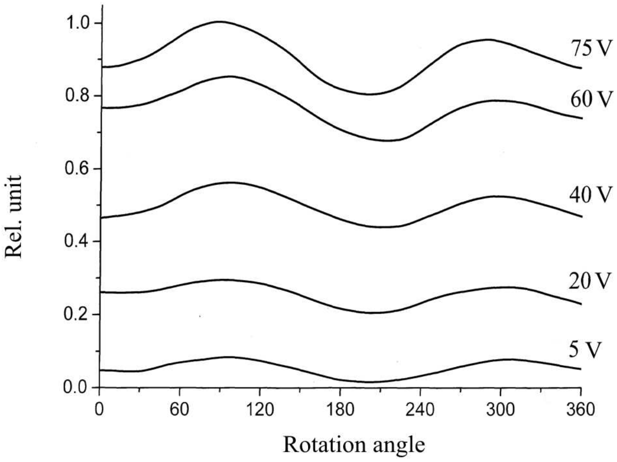

Fig. 2. Polarization dependences of the intensity of the THz radiation emitted by the p-InSb specimen before the breakdown at various carrier-heating fields (indicated near the curves). The pulse length equals 0.8 μs, the repetition frequency is 6 Hz, and the temperature $T = 4.2$ K

the coefficient $g\,(T_e, T, \omega)$, whereas the angular dependence of the type $P_2\,(\cos\theta)$ remains invariant.

However, if the drift velocity exceeds the thermal one, there appear higher even-order Legendre polynomials in the angular dependence. For an angular dependence of the type $g\,(T_e, T, \omega)\,P_2\,(\cos\theta)$ to appear in isotropic semiconductors, two conditions have to be fulfilled: the presence of hot charge carriers and a deviation of the pair part of the distribution function from the spherically symmetric form (under the action of electric field).

Earlier, we studied the polarization dependences of the radiation emitted by hot charge carriers in n-Ge [1–5]. In particular, we analyzed the polarization dependences that arise, when the electron-heating field is oriented in a direction symmetric with respect to the valleys, due to a deformation of the even part of the distribution function [4]. However, in multivalley semiconductors, there are also other reasons for the emergence of polarization dependences: e.g., the dispersion law anisotropy, the anisotropy of scattering mechanisms, and their multivalley character. Therefore, it is of interest to study the polarization dependences of the radiation emitted by hot charge carriers in semiconductors, which reveal no other reason for the appearance of polarization dependences, but due to the field-induced violation of the distribution function symmetry. The semiconductor InSb belongs to substances, in which the dispersion law of charge carriers is isotropic, and hot charge carriers can be easily generated. This work is aimed at its research.

2. Experimental Part

This work is devoted to the study of the polarization dependences of the radiation emitted by hot charge carriers in InSb of both the n- and p-types. This semiconductor is characterized by a high mobility of charge carriers. Therefore, their heating can be obtained at relatively weak electric fields. This circumstance together with the isotropic dispersion law of charge carriers in InSb makes this substance an attractive object for the study of the distribution function deformation by the electric field and the resulting polarization dependences. The method applied to the research of radiation polarization dependences was described in detail in work [3].

Specimens of two types were studied:

(i) p-InSb, $p \approx 1.2 \times 10^{13}$ cm^{-3}, $\mu_p \approx 2.6 \times 10^3$ cm^2/(V$\cdot$s), the Ge impurity, a distance of 106 meV from the valence band; and

(ii) n-InSb, $n \approx 1.2 \times 10^{14}$ cm^{-3}, $\mu_n \approx 5 \times 10^5$ cm^2/(V$\cdot$s), the Te impurity (a very shallow donor, completely ionized at 77 K). The specimen resistance was about 5 Ω at 77 K and 10 Ω at 4.2 K.

The specimen dimensions were approximately identical: the length was $l \approx 14$ mm, and the cross-section was equal to 2×0.8 mm^2. The specimens were fabricated from a wafer of p-InSb, and the crystallographic direction of its surface orientation was (III). The surface of the wafer about 1.1 mm in thickness was mechanically ground and polished until the wafer thickness reached about 0.85 mm. The destroyed layer was removed from the surface by the method of chemical-dynamic polishing using the polishing etching solution of 2% Br_2 in HBr [10].

InSb is characterized by specific parameters which should be mentioned. In Fig. 1, the current-voltage characteristic of pure *p*-InSb measured at a temperature of 4.2 K is shown. At an applied voltage of 96 V, the current was about 0.1 mA, which allowed us to avoid the appreciable thermal heating of the specimen and leave additional scattering mechanisms to be inactive. It was important to be sure that the current-voltage characteristic had no questionable features at about 4.2 K. Such features were also not observed up to a voltage of 93 V. At voltages higher than about 100 V, the avalanche breakdown occurred in the *p*-InSb specimen (recall that the working temperature was equal to 4.2 K), and the current through the specimen grew from a few tenths of a milliampere to amperes.

Note also that the parameters of polarization dependences for *p*-InSb before the breakdown were characterized by a high stability and a good repeatability. This cannot be said about them after the breakdown, when the "phase" homogeneity in the specimen becomes violated to a greater or less extent.

In Figs. 2 and 3, the periodic dependences of the radiation intensity emitted by hot charge carriers in the *p*-InSb and *n*-InSb, respectively, specimens on the polarizer rotation angle with respect to the direction of the carrier-heating electric field, i.e. on the angle between the direction of polarizer grooves and the carrier-heating field direction. A specific distinction between those polarization dependences for *n*- and *p*-InSb consists in different curve profiles, which remind, to some extent, a sinusoid (Fig. 2) or a cosinusoid (Fig. 3).

Different angular shifts of the maxima and minima for specimens of the *p*- and *n*-types can be associated with different mechanisms of scattering dominating in them (as well as slightly different dispersion laws). As one can see from Eq. (2), the expression for the function $f_2(\varepsilon)$, which plays the role of a coefficient in front of $P_2(\cos\theta_0)$ responsible for the angular dependence, includes the derivative of the momentum with respect to the relaxation time. This derivative

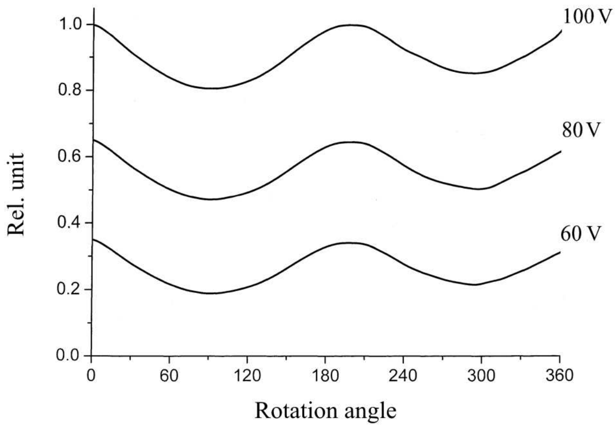

Fig. 3. The same as in Fig. 2, but for the *n*-InSb specimen after the breakdown

has different signs for the acoustic and impurity scatterings. This circumstance can determine the phase shift in the polarization dependence of the radiation intensity emitted by hot carriers. Note that although the very emergence of polarization dependences for the radiation emitted by hot carriers in *n*- and *p*-InSb is a matter of fact, this phenomenon has to be studied further.

3. Conclusions

The appearance of the periodic dependence of the radiation intensity emitted by hot charge carriers in *p*- and *n*-InSb specimens on the polarizer rotation angle with respect to the direction of the carrier-heating electric field is experimentally revealed and theoretically substantiated. This phenomenon is associated with a deviation of the even part of the charge carrier distribution over velocities from the spherical shape under the action of the electric field. The semiconductor InSb is convenient for the research of such polarization regularities because of a high mobility of charge carriers in it, so that already relatively weak electric fields give rise to the heating of carriers and the deformation of their distribution function.

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ПОЛЯРИЗАЦІЙНІ ЗАЛЕЖНОСТІ ВИПРОМІНЮВАННЯ ГАРЯЧИМИ НОСІЇЯМИ В InSb

Р е з ю м е

Експериментально встановлено і теоретично пояснено поляризаційні залежності спонтанного випромінювання гарячих носіїв в *p*- і *n*-InSb. Встановлена періодична залежність інтенсивності спонтанного випромінювання від кута повороту поляризатора відносно напрямку електричного поля, розігріваючого носіїв. Ця залежність зумовлена відхиленням під дією поля парної частини функції розподілу гарячих носіїв від сферичної форми (відхилення від дифузійного наближення).