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POLARIZATION DEPENDENCES OF TERAHERTZ RADIATION EMITTED BY HOT CHARGE CARRIERS IN p-Te

Polarization dependences of the terahertz radiation emitted by hot charge carriers in p-Te have been studied both theoretically and experimentally. The angular dependences of the spontaneous radiation emission by hot carriers is shown to originate from the anisotropy of their dispersion law and the anisotropy of the dielectric permittivity of a tellurium crystal. We have shown that the polarization dependences of radiation are determined by the angle between the crystallographic axis C_3 in p-Te and the polarization vector; they are found to have a periodic character.

K e y w o r d s: terahertz radiation, hot carriers, polarization dependences

1. Introduction

Free charge carriers can neither absorb nor emit light, because the laws of energy and momentum conservation cannot be satisfied simultaneously in such processes. These processes become possible if "a third body" participates in them. Various impurities, lattice vibrations, or a boundary can play this role. Which phenomenon (absorption or radiation emission) dominates at that depends on external conditions.

If charge carriers are in the thermodynamic equilibrium state, and if the semiconductor is irradiated with an external electromagnetic flux, the processes of light absorption by free carriers dominate. On the other hand, if no external radiation is present, and if carriers are heated up by an electric field applied to the semiconductor, then the processes of light emission by free carriers prevail. This radiation emission belongs mainly to the terahertz frequency range.

In semiconductors, the dispersion law for charge carriers and the mechanisms of their scattering are anisotropic, so that the spontaneous emission by hot carriers depends on the polarization. Earlier, we have studied similar polarization dependences with the use of n-Ge as an example [1–3]. However, despite the fact that the dispersion law of electrons in the minima (valleys) of the Brillouin zone in multivalley semiconductors of the n-Ge type has a pronounced anisotropic character, the valleys themselves

are arranged symmetrically in this zone. As a result, the angular dependences of the spontaneous radiation emission by hot electrons arise only at certain orientations of a heating electric field. Namely, in crystals with the cubic symmetry of the n-Ge and n-Si type, the polarization dependences of the spontaneous radiation emission by hot electrons appear only at such orientations of a heating electric field, at which the temperatures of electrons in different valleys is also different. One can also break the cubic symmetry and, hence, induce the polarization dependences by applying a unidirectional pressure to a semiconductor [1].

An absolutely different situation takes place in p-Te, to which this work is devoted. Tellurium is a considerably anisotropic semiconductor, although, provided that certain restrictions are imposed upon the hole concentration [4], the isoenergetic hole surfaces in tellurium can be accepted with a sufficient accuracy in the form of ellipsoids of revolution, similarly to what takes place for electrons in n-Ge and n-Si. However, there is a basic difference. Namely, the rotation axes of ellipsoids for the electron mass tensor in p-Te (there are six ellipsoids) are parallel to one another and to the axis C_3. At the same time, in n-Ge and n-Si, the ellipsoids of the electron mass tensor are oriented differently, but so that the symmetry of a crystal as a whole remains cubic. Therefore, the polarization dependences caused by the presence of the mass tensor of charge carriers can be observed in tellurium in their bare form, i.e. without any modification related to different contributions of different

valleys to the radiation process, as it takes place in n-Ge and n-Si.

The processes of radiation absorption and emission by free carriers can be studied in the framework of various mathematical methods. In works [1, 6], we suggested a method to study such processes, which has definite advantages in comparison with the available methods. Those advantages consist in that a common approach can be used to analyze absorption and emission of light by free carriers, in both the classical (when the light quantum energy, $\hbar\omega$, is much lower than the thermal energy of carriers, kT_e) and quantum-mechanical (when $\hbar\omega > kT_e$) frequency ranges. In this approach, the results can be obtained in the analytical form even if the anisotropy of both the dispersion law and the scattering mechanisms is taken into account. Just this method was used in this work.

2. Theory and Adopted Model

In accordance with works [5, 7], the dispersion law for holes in p-Te is taken in the form

$$\varepsilon(\mathbf{p}) = \frac{p_\perp^2}{2m_\perp} + \frac{p_\parallel^2}{2m_\parallel}, \tag{1}$$

where $p_\parallel$ and $p_\perp = (p_x^2 + p_y^2)$ are the longitudinal and transverse, respectively, components of the momentum vector $\mathbf{p}$ with respect to the direction of the axis C_3 in the crystal. For p-Te, according to work [8], we have $m_\parallel = 0.26\,m_0$ and $m_\perp = 0.11\,m_0$, where m_0 is the free electron mass.

Let an external constant electric field be applied to a p-Te specimen, and let this field heat up holes. On the basis of our experimental conditions (the lattice temperature $T = 4$ K and the concentration of ionized impurities $n_i \approx 5 \times 10^{14}$ cm^{-3}), we may suppose [9, 10] that the relaxation of hole momenta is driven by the hole scattering at ionized impurities, and the relaxation of the hole energy is determined by the inelastic hole scattering at acoustic and optical lattice vibrations. In the framework of this model, if the temperature is low, the contribution to the energy exchange between holes and the lattice can be given by the interaction between holes and only those optical vibrations of the lattice, whose Debye temperature is the lowest. In particular, for p-Te, it is the A_2 optical mode, for which the Debye temperature equals 138 K [11].

Below, we describe a scheme of the construction of the theory of spontaneous radiation emission by hot carriers in brief, readdressing the reader to work [6] for details.

Hence, in order to obtain the collision integral that involves the influence of the electromagnetic wave field on the scattering processes of free carriers, let us do it as follows. While deriving the collision integral, we use the wave functions of free carriers in the electromagnetic wave field

$$\Psi_{\mathbf{p}} = \frac{1}{V} \exp\left(\frac{i}{\hbar}\,\mathbf{p}\,\mathbf{r}\right) \times$$

$$\exp\left\{-\frac{i}{\hbar}\int_0^t dt' \sum_j^3 \frac{1}{2m_j}\left(p_j - \frac{e}{c}\,A_j(t')\right)^2\right\}, \tag{2}$$

instead of their basic wave functions. Here, V is the volume, t' the time, e the carrier charge, c the velocity of light, and $\mathbf{A}(t)$ the vector-potential in the dipole approximation, $\mathbf{A}(t) = \mathbf{A}^{(0)}\cos\omega t$. Note that the inclusion of the electromagnetic wave field into the collision integral, rather than into the left-hand side of the kinetic equation as an external force, is valid if the inequality $\omega\tau > 1$, where τ is the relaxation time, is satisfied.

As was shown in work [6], the collision integral for the scattering of carriers by ionized impurities can be obtained with the use of basis (2) in the form

$$\hat{I}f = 4\,e^4\,N_i \times$$

$$\times \sum_{l=-\infty}^{\infty}\int d\mathbf{p}'\,\frac{f(\mathbf{p}') - f(\mathbf{p})}{\left\{\chi_\perp(\mathbf{p}_\perp - \mathbf{p}'_\perp)^2 + \chi_\parallel(p_\parallel - p'_\parallel)^2 + (\hbar/r_D^{(0)})^2\right\}^2} \times$$

$$\times \Im_l^2\left(\frac{e}{c\,\hbar\,\omega}\sum_{j=1}^3 A_j^{(0)}\frac{p_j - p'_j}{m_j}\right)\delta(\varepsilon(\mathbf{p}) - \varepsilon(\mathbf{p}') - l\,\hbar\,\omega), \tag{3}$$

Here, $f(\mathbf{p})$ is the distribution function of charge carriers over their momenta $\mathbf{p}$'s, N_i the concentration of ionized impurities, and $\Im_l(x)$ the Bessel function of the l-th order. Moreover, we have additionally considered the tensor character of the dielectric permittivity of tellurium in formula (3) in contrast to work [6]. In particular, in the coordinate system with the axis $0z$ directed along the axis C_3 in tellurium, we

have $\chi_{xx} = \chi_{yy} \equiv \chi_\perp$ and $\chi_{zz} \equiv \chi_\parallel$. Expression (3) includes low-frequency values of χ_{ii}. The parameter $r_D^{(0)}$ is the radius of charge screening by free carriers. In particular, in the case of non-degenerate statistics,

$$\left(\frac{1}{r_D}\right)^2 = \frac{4\pi e^2 n}{kT_p}, \tag{4}$$

where n is the concentration of free carriers, and T_p is their temperature.

If we are not interested in a special action of powerful laser pulses, the argument of the Bessel function in Eq. (3) is, as a rule, less than 1. Therefore, the multiplier $\Im_l^2(\ldots)$ in formula (3) can be expanded in a series, and only the first term of the series can be retained. In addition, in what follows, we will confine the consideration to one-quantum processes, i.e. only the terms in expression (3) corresponding to $l = \pm 1$ will be taken into account. Then, by multiplying expression (3) by $\varepsilon(\mathbf{p})$ and integrating the product over $d\mathbf{p}$, we obtain the variation of the electron system energy per unit time, which is related to the processes of absorption and emission of light quanta, $\hbar\omega$:

$$p = \int d\mathbf{p} \, \hat{I}f = P(+) + P(-),$$

$$P(\pm) = \pm \frac{e^6}{c^2 \, \hbar \, \omega} \times$$

$$\times \int \frac{d\mathbf{p} \, d\bar{p}' \, f(\mathbf{p}') \, \delta\{\varepsilon(\mathbf{p}) - \varepsilon(\mathbf{p}') \pm \hbar\omega\}}{\{\chi_\perp(\mathbf{p}_\perp - \mathbf{p}'_\perp)^2 + \chi_\parallel(p_\parallel - p'_\parallel)^2 + (\hbar/r_D)^2\}^2} \times$$

$$\times \left(\sum A_j^{(0)} \frac{p_j - p'_j}{m_j}\right)^2. \tag{5}$$

While calculating integral (5), let the Maxwell function with the effective hole temperature $\theta_p \equiv kT_p$ be used as a distribution function for hot holes,

$$f(\mathbf{p}) = \frac{n}{(2\pi\theta_p)^{3/2} \, m_\perp \sqrt{m_\parallel}} \exp(-\varepsilon(\mathbf{p})/\theta_p). \tag{6}$$

The sign "+" in Eq. (5) describes the process of $\hbar\omega$-quantum absorption (i.e. the energy of charge carriers increases), and the sign "−" corresponds to the emission of a quantum $\hbar\omega$ (i.e. the energy of charge carriers decreases).

The quantity $P(-)$ describes the variation of the hot hole energy per unit time, which is related to the

emission of a quantum $\hbar\omega$. To obtain the total energy change induced by the emission of all quanta in a unit frequency interval into the space angle $d\Omega$, we have to multiply $P(-)$ by the density of final field states in a solid angle $d\Omega$, i.e. by

$$d\rho(\omega) = \frac{V}{(2\pi c)^3} \omega^2 d\Omega. \tag{7}$$

Then, the product $P(-)d\rho(\omega)$ describes the radiation emission of charge carriers induced by the electromagnetic wave field. However, we are interested in the spontaneous radiation emission by hot carriers. To find this quantity, we use the Einstein ratio between the probabilities of induced and spontaneous emissions (see, e.g., work [12]). For this purpose, we must first normalize the vector-potential $\mathbf{A}^{(0)}$ (see Eq. (5)) in such a way that the volume V would contain N_{ph} photons, i.e. we have to use the condition

$$\frac{1}{V} N_{\mathrm{ph}} \, \hbar \, \omega = \frac{E^2}{4\pi} = \frac{1}{8\pi} \left(\frac{\omega}{c}\right)^2 A^{(0)2}. \tag{8}$$

Whence,

$$A^{(0)} = 2c \left(\frac{2\pi \, \hbar}{V\omega} N_{\mathrm{ph}}\right)^{1/2}. \tag{9}$$

After substituting Eq. (9) in Eq. (5), the quantity $W^{(-)} \equiv [P(-)d\rho(\omega)]_{N_{\mathrm{ph}}=1}$ is the power of spontaneous radiation emission by hot carriers in a unit spectral interval into the solid angle $d\Omega$.

As was shown in work [6], after the transition in Eq. (5) to a deformed coordinate system, in which the elliptic isoenergetic surfaces (1) transform into spherical ones, the integrals in expression (5) can be calculated, and we obtain

$$W^{(-)} = \frac{e^6 n \, N_i \sqrt{m_\parallel}}{(2\pi)^{3/2} c^3} \frac{\Psi(\infty) \, d\Omega}{(m_\parallel \chi_\parallel - m_\perp \chi_\perp)^2} \times$$

$$\times \begin{Bmatrix} \frac{2\sqrt{\pi}}{\sqrt{\theta_p}} \ln\left(\frac{C_1^2 \hbar^2}{8m_\perp \chi_\perp \theta_p}\right)^{-1} & \text{for } \hbar\omega \ll \theta_p, \\ \frac{1}{\sqrt{\hbar\omega}} \exp\left(-\frac{\hbar\omega}{\theta_p}\right) & \text{for } \hbar\omega \gg \theta_p, \end{Bmatrix} \tag{10}$$

where $\ln C_1 = 0.577\ldots$ is the Euler constant.

According to the results of work [6], the quantity $\Psi(\infty)$ equals

$$\Psi(\infty) = \frac{1}{b_0^3} \left[b_0 + (1 - b_0^2) \operatorname{arctg} \frac{1}{b_0}\right] \sin^2 \varphi +$$

$$+2\frac{m_\perp}{m_\parallel}\left[-\frac{1}{1+b_0^2}+\frac{1}{b_0}\mathrm{arctg}\,\frac{1}{b_0}\right]\cos^2\varphi,\qquad(11)$$

where φ is the angle between the polarization vector and the axis C_3 (the latter is parallel to the axis of revolution of ellipsoids of the effective-mass tensor), and

$$b_0=\frac{m_\perp\chi_\perp}{m_\parallel\,\chi_\parallel-m_\perp\,\chi_\perp}.\qquad(12)$$

At $\chi_\parallel=\chi_\perp$, the quantity b_0 coincides with the corresponding quantity obtained in work [6].

Substituting expression (11) in Eq. (10), we obtain

$$W^{(-)}=\left\{a_\perp\,\sin^2\varphi+a_\parallel\cos^2\varphi\right\}d\Omega.\qquad(13)$$

The coefficients $a_\perp$ and $a_\parallel$ can be easily obtained by comparing expressions (10) and (13). It is not difficult to get convinced that if $m_\perp=m_\parallel$ and $\chi_\perp=\chi_\parallel$, we have $a_\perp=a_\parallel$, and the angular dependence disappears from expression (13).

Hence, we have obtained the explicit expression for the angular dependence of the spontaneous radiation emission by hot holes in the form (13). The coefficients that characterize this angular dependence – these are $a_\perp$ and $a_\parallel$ – are known functions of the mass tensor components ($m_\perp$ and $m_\parallel$), the dielectric permittivity tensor components ($\chi_\perp$ and $\chi_\parallel$), the light frequency ω, and the hot electron temperature θ_p. All those parameters, but θ_p, are known.

To obtain the simplest expression for the hot-hole temperature, we confine the consideration to low temperatures ($4\,\mathrm{K}\le T\le 20\,\mathrm{K}$) and weak enough electric fields, at which $T_p\ll 138$ K, i.e. when the value of kT_p is much lower than the energy of optical phonons. In those ranges of temperatures and fields, it is possible to consider that the relaxation of the momentum of holes takes place predominately at their scattering by ionized impurities, and the energy relaxation occurs at their quasielastic scattering by acoustic phonons. The energy given by hot carriers to the lattice per unit time at the quasielastic scattering by acoustic vibrations, according to the results of work [13], equals

$$\int d\bar{p}\,\varepsilon(\mathbf{p})\,\hat{I}_{ak}f=g\,n\,\theta_p^{3/2}\left(1-\frac{\theta}{\theta_p}\right),\qquad(14)$$

where

$$g=\frac{8\sqrt{2}\,m_\perp\sqrt{m_\parallel}}{\pi^{3/2}\rho\,\hbar^4}\left(\frac{2\,m_\perp^++m_\parallel}{3}\right)\sum_d^2,\qquad(15)$$

and Σ_d is the constant of the deformation potential (we confine the consideration to the one-constant approximation).

In the stationary case, the scattering power (14) must be equal to that obtained by carriers from the heating field $\mathbf{F}$, i.e.

$$\mathbf{jF}=e\,n\left\{\mu_\perp(\theta_p)F_\perp^2+\mu_\parallel(\theta_p)\,F_\parallel^2\right\},\qquad(16)$$

where $\mathbf{j}$ is the current-density vector, $\mu_\perp(\theta_p)$ and $\mu_\parallel(\theta_p)$ are the transverse and longitudinal, respectively, components of the mobility tensor arising owing to the scattering of charge carriers by ionized impurities [6],

$$\mu_\perp(\theta_p)=\frac{8}{\sqrt{\pi}}\frac{e\,\tau_\perp(\theta_p)}{m_\perp};\quad \mu_\parallel(\theta_p)=\frac{8}{\sqrt{\pi}}\frac{e\,\tau_\parallel(\theta_p)}{m_\parallel},\quad(17)$$

and $\tau_\perp(\theta_p)$ and $\tau_\parallel(\theta_p)$ are the transverse and longitudinal, respectively, components of the relaxation tensor at the impurity-driven scattering, given by the expressions

$$\frac{1}{\tau_\perp(\theta_p)}=\frac{8}{3}\frac{e^4\,\sqrt{2m_\parallel}}{\chi_\perp^2\,m_\perp\,\theta_p^{3/2}}\times$$

$$\times N_i\frac{b_0}{2}\left[b_0+(1-b_0^2)\,\mathrm{arctg}\,\frac{1}{b_0}\right]\ln\left(\frac{C_1\,\hbar^2}{8m_\perp\,\chi_\perp\,\theta_p}\right)^{-1},\qquad(18)$$

and

$$\frac{1}{\tau_\parallel(\theta_p)}=\frac{8}{3}\frac{e^4\,\sqrt{2m_\parallel}}{\chi_\perp^2\,m_\parallel\,\theta_p^{3/2}}\times$$

$$\times N_i b_0\left[-b_0+(1+b_0^2)\,\mathrm{arctg}\,\frac{1}{b_0}\right]\ln\left(\frac{C_1\hbar^2}{8m_\perp\,\chi_\perp\,\theta_p}\right)^{-1}.\qquad(19)$$

At $\chi_\perp=\chi_\parallel$, expressions (18) and (19) transform into the corresponding formulas obtained in work [6] (Unfortunately, the notations $\frac{1}{\tau_\perp}$ and $\frac{1}{\tau_\parallel}$ in formula (54) in work [6] were transposed!)

If the weak dependence on θ_p in the logarithm in formulas (18) and (19) is neglected, then Eqs. (17)–(19) yield

$$\mu_{\perp,\parallel}(\theta_p)\approx\left(\frac{\theta_p}{\theta}\right)^{3/2}\mu_{\perp,\parallel}(\theta).\qquad(20)$$

Now, let us make expressions (14) and (16) equal to each other and use relation (20). Then, from this balance equation, we easily obtain the temperature of hot holes,

$$\theta_p = \theta \left\{ 1 - \frac{e}{g\,\theta^{3/2}} \left[\mu_\perp(\theta)\, F_\perp^2 + \mu_\parallel(\theta)\, F_\parallel^2 \right] \right\}^{-1}. \quad (21)$$

The validity of this formula is restricted to fields, at which $\theta_p < \hbar\omega_0$, where ω_0 is the frequency of the lowest optical mode (it corresponds to a temperature of 138 K). If θ_p approaches the energy of optical phonons, the scattering of holes by the latter has to be taken into consideration.

Hence, we obtained an expression for the angular dependence of the spontaneous radiation emission by hot holes in tellurium in the form of formula (13) in the case where the dominating mechanism of momentum scattering is the scattering by ionized impurities. In so doing, we made allowance for the tensor character of the effective mass and the dielectric permittivity in p-Te. In work [1], we obtained an expression for the spontaneous radiation emission by hot carriers with the dispersion law (1) in the case where the acoustic scattering plays the dominating role. The angular dependence of the spontaneous radiation emission by hot carriers looks like Eq. (13) at both acoustic- and impurity-driven scattering. The only difference consists in the different dependences of the coefficients $a_\perp$ and $a_\parallel$ on the hot-carrier temperature.

3. Experiment and Its Discussion

The experimental setup is shown in Fig. 1. We used specimens of single-crystalline tellurium grown by the Czochralski method. The specimens were either cut out of single-crystalline ingots along the axis C_3 or carefully sawn out of those ingots across it. Then, the specimens were annealed in the hydrogen atmosphere at a temperature of 380 °C for 200 h and treated with a chromic etching solution $HF + CrO_3 + H_2O$ (1:1:3). After annealing and etching, the mobility and the concentration of charge carriers fell within the intervals 5200–6000 cm^2/V/s and $(1.1 \div 1.4) \times 10^{15}$ cm^{-3}, respectively. The cross-section dimensions of specimens were 1×1.2 mm^2, and their length varied from 3.2 to 7 mm. Ohmic contacts were soldered with the use of the solder 50% St + 47% Bi + 3% Sb.

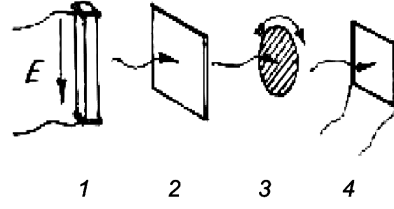**Fig. 1.** Experimental setup: p-Te specimen with either parallel ($\parallel$) or normal ($\perp$) C_3-axis orientation (*1*), black polyethylene filter (*2*), polarizer (analyzer) (*3*), and Ge(Ga) detector (*4*)

To heat up holes in Te specimens, a generator of electric pulses with a low input resistance of about 20 Ω was used, which enabled us to carry out measurements for low-resistance specimens. The pulse duration was 0.8 μs and the repetition frequency was 6 Hz. As a 3-THz radiation detector ($\lambda \approx 100$ μm), we used a Ge(Ga) detector $4 \times 5 \times 1.5$ mm^3 in size.

A signal registered by the detector was amplified with the use of a broadband amplifier, integrated, converted into a constant voltage, and supplied to a two-coordinate recorder. The short-wave section of the radiation spectrum emitted by hot holes ($\lambda < 50$ μm) was cut off by applying a filter fabricated of black polyethylene. The polarizer (analyzer, Fig. 1) was rotated at a low speed of one rotation per 2 min, and its axis was rigidly connected with the long-axis direction of the emitting specimen (and, hence, with the direction of the electric field applied to the specimen). As the "zero" rotation angle of a polarizer, its such orientation was selected, when the direction of polarizer grooves coincided with the direction of specimen's long axis and the electric field applied to the specimen. We recall that the polarizer transmits the electromagnetic wave only in the case where the electric component of the wave is perpendicular to its grooves.

The polarization dependences of the terahertz radiation emission by hot carriers in p-Te were studied using the specimens cut out along the crystallographic axis C_3 and perpendicularly to it (below, we refer to them as the specimens of the first and second types). Figures 4, *a* and *b* exhibit one of six (parallel) ellipsoids, which describe the dispersion law for holes in p-Te (1), and demonstrate the orientation of the long axis of this ellipsoid with respect to the crystallographic axis C_3 and the direction of electric field applied to the specimen. In both cases, the electric field is applied along the long axis of the specimen.
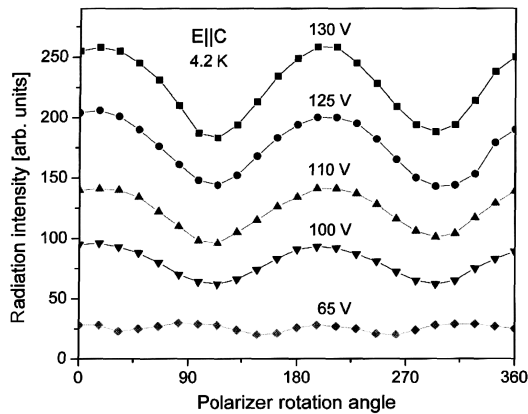
Fig. 2. Dependences of the specimen radiation emission intensity on the polarizer rotation angle for various heating fields (indicated in the figure) in the (p-Te$\parallel C_3$)-geometry of experiment
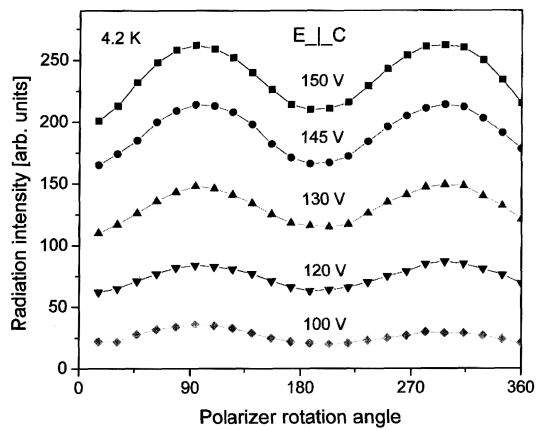

Fig. 3. The same as in Fig. 2, but for the (p-Te$\perp C_3$)-geometry of experiment

While studying the polarization dependence of the radiation emission by specimens of both the first and second types, the polarizer was rotated in the plane zy around the axis x. In Figs. 2 and 3, the dependences of the radiation intensity emitted by hot holes on the angle between the direction of polarizer grooves and the direction of electric field that heats up charge carriers are depicted. It will be recalled that the zero value of this angle corresponds to the situation where the polarizer grooves are parallel to the applied electric field.

In the theory developed above, the angular dependence of the radiation intensity was described by the angle between the axis C_3, which is parallel to the long axis of the ellipsoid, and the polarization direc-
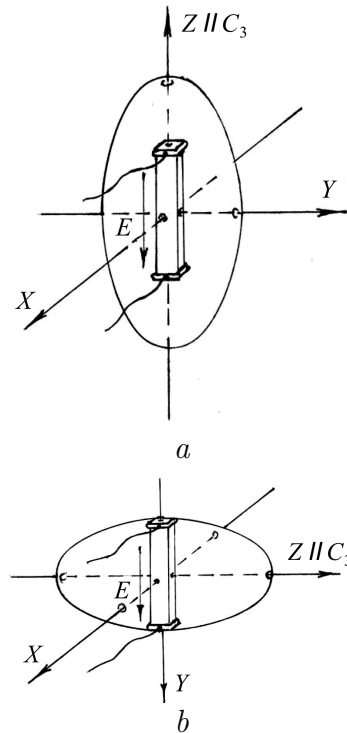

Fig. 4. Specimens and their orientation with respect to the crystallographic axis: specimen cut out (a) along the axis and (b) perpendicularly to it

tion, i.e. the direction of the electric component of an emitted electromagnetic wave. Since the polarizer transmits only the electric wave component which is perpendicular to its grooves, then, as is seen from Fig. 4,a corresponding to the case of first-type specimens, when the heating electric field, the axis C_3, and the grooves are parallel to one another, the angles in Fig. 2 and in the theoretical formula (13) are shifted with respect to one another by $\pi/2$. At the same time, for specimens of the second type, for which the heating field and the axis C_3 are mutually perpendicular, the angles in Fig. 3 and in the theory (formula (13)) coincide (see Fig. 4,b). In this case, there is a minimum at the angle $\varphi = 0$. This fact agrees with formula (13). Passing in this formula to the doubled angle, we obtain

$$W^{(-)} = \frac{1}{2}\{a_\perp + a_\parallel + (a_\parallel^- a_\perp) \cos 2\varphi\}d\Omega. \qquad (22)$$

Whence, one can see that the presence of the minimum at $\varphi = 0$ corresponds to the condition $a_\perp/a_\parallel > 1$.

From Eqs. (10) and (11), we obtain

$$\frac{a_\perp}{a_\parallel} = \frac{\frac{1}{b_0^3}\left[b_0 + (1 - b_0^2)\,\text{arctg}\,\frac{1}{b_0}\right]}{2\frac{m_\perp}{m_\parallel}\left[-\frac{1}{1+b_0^2} + \frac{1}{b_0}\,\text{arctg}\,\frac{1}{b_0}\right]} \cdot \tag{23}$$

For p-Te, $m_\parallel = 0.26\,m_0$, $m_\perp = 0.11\,m_0$, $\chi_\parallel = 56$, and $\chi_\perp = 33$. Hence, $b_0^2 \equiv \frac{m_\perp\chi_\perp}{m_\parallel\chi_\parallel - m_\perp\chi_\perp} \approx 0.35$ and $\frac{a_\perp}{a_\parallel} \approx 7$. Thus, in both the theory and the experiment, we obtain a minimum at $\varphi = 0$. Therefore, the positions of minima and maxima in the theory and the experiment coincide. Hence, our theory adequately predicts a periodic character of polarization dependences of the spontaneous radiation emission by hot holes in p-Te and correctly evaluates the positions of maxima and minima for this radiation.

It would be of interest to have not only a qualitative, but also a quantitative comparison between the theory and the experiment. However, unfortunately, it cannot be done now. First, expression (13) gives the spectral distribution of the radiation intensity, whereas experimentally the integrated radiation power in the given frequency range is measured. Therefore, for the quantitative comparison to be made, expression (10) should be integrated over a frequency interval given in the experiment. This procedure renormalizes the coefficients $a_\perp$ and $a_\parallel$ in expression (13). While integrating over the frequency, we would have to determine the temperature of hot carriers, θ_p, for every heating field, which is a separate large problem.

Second, the very expression for θ_p can change with the growth of the electric field owing to the engaging of new relaxation mechanisms. However, the angular dependence of the spontaneous radiation emission by hot carriers in form (13) has a more universal character, which is governed, first of all, by the dispersion law (1). Provide that the dispersion law is fixed, only the specific values of parameters $a_\perp$ and $a_\parallel$ in formula (13) depend on the scattering mechanism.

4. Conclusions

The dependences of the terahertz radiation emission intensity by hot charge carriers in p-Te on the angle between the crystallographic axis C_3 and the polarization vector, as well as their periodic character, have been studied both theoretically and experimentally. The periodic character of the dependence concerned and the positions of radiation intensity minima and maxima were demonstrated to coincide in the theory and the experiment. The polarization dependences of the radiation emission by hot charge carriers were found to be associated with the anisotropy of the charge carrier dispersion law and the anisotropy of the dielectric permittivity.

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ПОЛЯРИЗАЦІЙНІ ЗАЛЕЖНОСТІ ТЕРАГЕРЦОВОГО ВИПРОМІНЮВАННЯ ГАРЯЧИМИ НОСІЯМИ ЗАРЯДУ в p-Te

Р е з ю м е

В роботі теоретично і експериментально вивчено поляризаційні залежності терагерцового випромінювання гарячими носіями заряду в p-Te. Показано, що кутові залежності спонтанного випромінювання гарячих носіїв зумовлені анізотропією їх закону дисперсії і анізотропією діелектричної проникності. Встановлено, що поляризаційні залежності випромінювання визначаються кутом між кристалографічною віссю C_3 в p-Te та ортом поляризації і ці залежності мають періодичний характер.