LOW-TEMPERATURE DEPENDENCES
OF THE POLARIZATION OF TERAHERTZ EMISSION
FROM n-GERMANIUM IN HEATING ELECTRIC FIELDS

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As was noted in [3], in order to verify the assumption that the behavior of the polarization dependences of the terahertz emission by hot electrons from n-Ge is determined by the type of carrier scattering, it is necessary to perform temperature measurements of this dependence in the range between the temperatures, where the scattering is determined by impurities and by acoustic lattice vibrations, respectively. The given work presents the results of such investigations.

1. Introduction

As was noted in [1–3], the terahertz emission by hot carriers from n-Ge has a specific feature – it is polarized. Its polarization dependences as functions of the angle between the polarization vector and the heating field direction are periodic. The positions of maxima and minima of these dependences can change due to variations of the impurity concentration and the lattice temperature. In addition, the polarization depends on the intensity of a heating electric field and its direction relative to the crystallographic axes, as well as on the degree of intervalley repopulation. The reasons for a behavior of the polarization of this emission were studied in a number of works [3–5]. It is known that the main mechanisms of carrier scattering in n-Ge that determine its electric characteristics are the impurity scattering at low temperatures and the scattering by acoustic lattice vibrations at high ones.

It was noted in [3] that, in order to verify the assumption that different polarizations of the terahertz emission by hot carriers in n-Ge in pure and doped materials are caused by different prevailing scattering mechanisms, it is necessary to perform temperature measurements of this phenomenon.

The idea of the method was to obtain the mentioned polarization characteristics at temperatures, at which each of these mechanisms is determinative, and to follow the variation of these characteristics under transition from one temperature region to the other. In the case of low temperatures (impurity scattering), the mobility of carriers in n-Ge changes with the temperature as $\mu \sim T^{3/2}$, whereas it varies as $\mu \sim T^{-3/2}$ at high temperatures (scattering by lattice vibrations). The maximum point of the mobility, where the impurity scattering is replaced by the scattering by acoustic phonons lies in the region $\sim$20 K for pure n-Ge. One could expect that the polarization characteristic will change its pattern passing through zero somewhere in this temperature region. This will mean that the behavior of the polarization dependence of the emission is determined by the type of scattering of hot carriers. The experiments proposed and performed in this work were to demonstrate whether it is true or not.

2. Experiments

All measurements were carried out with the use of standard samples produced by the typical technology [3]. Rectangular pulses of a heating electric field had a length of 0.8 mus, whereas their amplitude could change in wide ranges. The detecting part of the experimental set-up differed from the previous versions in the arrangement of the filter, polarizer, detector, and emitting sample. The main experimental difficulty of these measurements consists in the fact that the n-Ge emitting sample, whose temperature should be increased by an additional heating to 50 $\div$70 K, is located near the Ge(Ga) semiconductor detector requiring helium temperature. Such a temperature gradient at a distance of 8$\div$12 mm induces very strong temperature instabilities and noise signals in the detecting part, which makes measurements practically inadequate [3]. The problem was solved in the following way: the Ge(Ga) detector immersed in helium and the emitting sample, whose temperature must be changed from the helium one to 70$\div$80 K, were located at the different ends of a vertical light guide. Locating the sample at
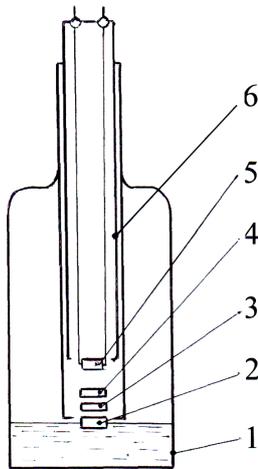
Fig. 1. Diagram of the set-up used for temperature measurements of the polarization of the terahertz emission from n-Ge: 1 — helium cryostat; 2 – Ge(Ga) detector; 3 – filter; 4 -– polarizer rotating in the horizontal plane; 5 – emitting sample; 6 – mobile light guide

Fig. 2. Polarization dependence of the terahertz emission from n-Ge (GES-2.5, $\langle 111 \rangle$) for different temperatures (the curves are shifted in amplitude): 1 –76 K; 2 – 57 K; 3 – 26 K; 4 – 14 K ; 5 – 8.8 K; 6 – 7.7 K; 7 – 7.2 K; 8 – 6.6 K

different distances from the detector (and the liquid-helium surface), we can vary the temperature of the emitting sample within the required limits. The necessity of an additional heating of the sample disappeared, and temperature gradients were reduced to a minimum. A diagram of the experimental set-up is presented in Fig. 1.

3. Experimental Results and Their Discussion

Figure 2 shows the results of measuring the temperature dependence of the terahertz emission of hot germanium carriers for a typical GES-2.5 sample with the crystallographic orientation along the large sample size $\langle 111 \rangle$. One can see that, at the lowest temperatures $(6.6 \div 6.9)$ K, the behavior of the polarization dependence is typical of doped samples. With increase in the sample temperature, this dependence becomes straight, passes through zero at 7.7 K, and then takes the form typical of a pure material. This form does not change with the further increase of the temperature up to 77 K. Thus, we observed an inflection point of the polarization dependence close to 8 K. Relating this point to the transition from the impurity scattering to the acoustic one (where the electron mobility reaches a maximum), one can see that it differs from the literature data by $\sim$10 K [6]. Additional experiments performed for a number of samples with a different concentration yielded similar results (Fig. 3). As it turned out later on, the difference in the temperature measurements was due to the
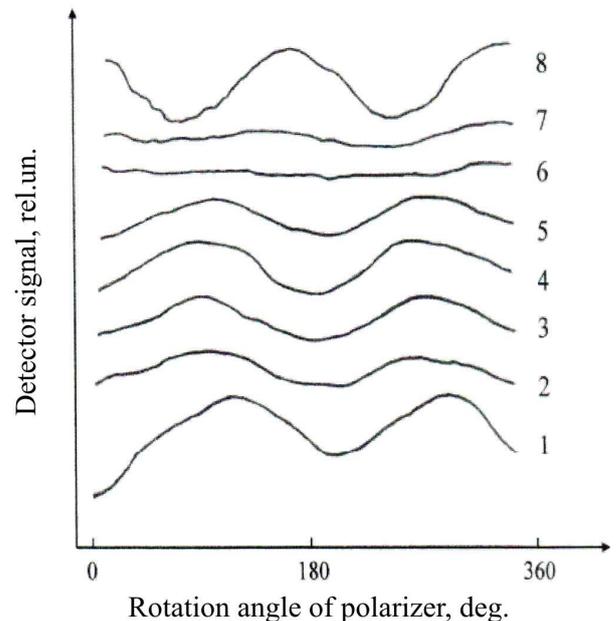
fact that the semiconductor thermometer measured the temperature of the environment surrounding the emitting sample, whereas the sample itself was heated by pulses of the strong electric field ($\tau_i = 0.8$ μs, $v =$140 V, $\Im = 2.6$ A, $E_{\rm rep} = 6$ Hz). Our calculations demonstrate that, at these temperatures (taking into account the rapid decrease of the heat capacity), the quantity of heat released in the sample (Fig. 2) increases its temperature by $10 \div 15$ K, i.e. its real temperature will be higher than that fixed by the thermometer by $\sim 10 \div 15$ K, which completely agrees with literature data.

Hence, the refined position of the point of temperature change of the dominant scattering mechanism and the form of the curves given in Figs. 2 and 3 allow us to make an unambiguous conclusion about the relation between the angular polarization dependence and the scattering mechanism. There took place a shift of the maxima (minima): the regions of maxima in the polarization dependence in the case of the impurity scattering changed to minima in the case of the acoustic one.

Thus, the presented experimental results (Figs. 2 and 3) confirm the proposed explanation of the behavior of the polarization characteristic of the terahertz emission
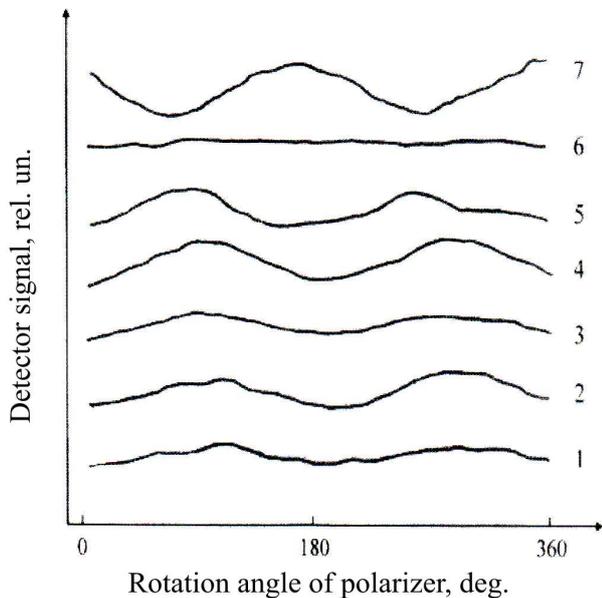
Fig. 3. Polarization dependence of the terahertz emission from n-Ge (GES-0.3, $\langle 111 \rangle$) for different temperatures (the curves are shifted in amplitude): 1 – 70 K; 2 – 57 K; 3 – 26 K; 4 – 14 K; 5 – 7.2 K; 6 – 6.4 K; 7 – 5.7 K

by hot electrons from n-Ge depending on the type of carrier scattering.

1. V.M. Bondar, O.G. Sarbey, and P.M. Tomchuk, Fiz. Tverd. Tela **44**, 1540 (2002).

2. P.M. Tomchuk, Ukr. Fiz. Zh. **49**, 681 (2004).

3. V.M. Bondar and N.F. Chornomorets, Ukr. Fiz. Zh. **48**, 51 (2003).

4. P.M. Tomchuk and V.M. Bondar, Ukr. J. Phys. **53**, 668 (2008).

5. V.M. Bondar, B.O. Danilchenko, and A.M. Kraichins'kyi, Ukr. J. Phys. **54**, 491 (2009).

6. L.P. Pavlov, *Methods of Determination of the Basic Parameters of Semiconductor Materials* (Vysshaya Shkola, Moscow, 1975) (in Russian).

ТЕМПЕРАТУРНІ ЗАЛЕЖНОСТІ ПОЛЯРИЗАЦІЇ ТЕРАГЕРЦОВОГО ВИПРОМІНЮВАННЯ ГЕРМАНІЮ n-ТИПУ У ГРІЮЧИХ ЕЛЕКТРИЧНИХ ПОЛЯХ В ОБЛАСТІ НИЗЬКИХ ТЕМПЕРАТУР

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Р е з ю м е

Як було відзначено в роботі [3] для правомірності припущення про те, що хід поляризаційних залежностей терагерцового випромінювання гарячими електронами з n-Ge визначається типом розсіювання носіїв, необхідно провести температурні виміри цієї залежності від температур, де превалює розсіювання на домішках, до температур, де превалює розсіювання на акустичних коливаннях ґратки. У даній роботі наведено результати таких досліджень.