POLARIZATION OF SUBMILLIMETER RADIATION EMITTED BY HOT CARRIERS IN GaAs/In_xGa_{1-x}As HETEROSTRUCTURES AT HELIUM TEMPERATURES

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The results of our studies of polarization dependences of spontaneous submillimeter radiation emitted by hot carriers in GaAs/In_xGa_{1-x}As heterostructures at liquid helium temperatures are reported. The polarization vector was selected to be perpendicular to the electric field direction, the current through the heterostructure, and the longitudinal axis of a specimen. The radiation polarization is explained by the influence of a strong electric field on the electron distribution function. The conventional diffusion approximation cannot describe the observed phenomenon theoretically. This can be done only going beyond the framework of the diffusion approximation, in particular, by taking the third term in the distribution function expansion into account.

As was shown experimentally and theoretically [1, 2], the submillimeter emission by hot carriers in bulk n-Ge has definite polarization, which is an additional characteristic of the processes that occur in this semiconductor. Associating the behavior of such dependences with carrier scattering processes, one can not only draw some conclusions concerning fine characteristics of both the interaction between carriers and the lattice and the process of photon generation, but even, as turned out, verify the efficiency of the widely used diffusion approximation [3]. Undoubtedly, it was also of interest to fix such a characteristic, if so, in the radiation emitted by two-dimensional objects, e.g., GaAs/In_xGa_{1-x}As heterostructures, in the interval $\lambda = 100$ μm, because we have studied this range relatively better experimentally. In addition, this range corresponds to the expected wavelength of the emission in the structures concerned.

In this connection, we studied GaAs/In_xGa_{1-x}As heterostructures ($x = 8 \div 10\%$) with double tunnel-coupled quantum wells (QWs). Every specimen contained 20 QW pairs. The QWs in a pair were 10 and 20 nm in width, and they were separated by a narrow barrier 5 nm in thickness. In turn, the QW pairs were separated by barriers, each 80 nm in thickness. The heterostructures were doped with silicon to the concentration $(1 \div 3) \times 10^{11}$ cm^{-2} in the QW region, either uniformly or selectively (a δ-layer in a narrow QW). In Fig. 1,*a*, the schematic representations of the conduction band in a heterostructure with double QWs, δ-doped in a narrow QW, and the size quantization levels that are formed in the wells are exhibited. Figure 1,*b* schematically details the experimental setup. The pulling electric field applied to the structure was pulse-like with $\tau = 0.8$ μs and $T_{\rm rep} \approx 6$ Hz. Measurements were carried out at a temperature of 5 K.

In Fig. 2, the dependence of the radiation polarization on the orientation of a specimen under study with respect to the polarizer rotation angle is depicted. The specimen was oriented horizontally, and the "zero" position of the polarizer corresponded to the vertical orientation of its strokes. As is seen from Fig. 2, the electric field of the wave is directed normally to the direction of the applied pulling field and the longitudinal specimen size (at the "zero" polarizer rotation angle, the radiation amplitude is minimal).

To characterize the emitting structure more completely, we also registered its circular radiation pattern which is presented in Fig. 3. The pattern demonstrates that the working part, the surface and the back wall of heterostructure, and the substrate radiate intensively. The narrow lateral sides radiate weakly. An insufficiently pronounced characteristic of the radiation pattern can be explained by a radiation re-reflection both in the structure bulk and from the installation details that surround this structure.

The following mechanism can be responsible for the polarization dependence of the submillimeter emission by hot electrons in a heterostructure of the GaAs/In_xGa_{1-x}As type. According to the band structure of those specimens presented in Fig. 1,*a* [7], the energy of a light quantum in this range ($\lambda = 100$ μm) corresponds to the energy distance between the first and second levels of size quantization. However, the wave functions of electrons on them are spatially separated: the carriers on the first and second levels are localized in

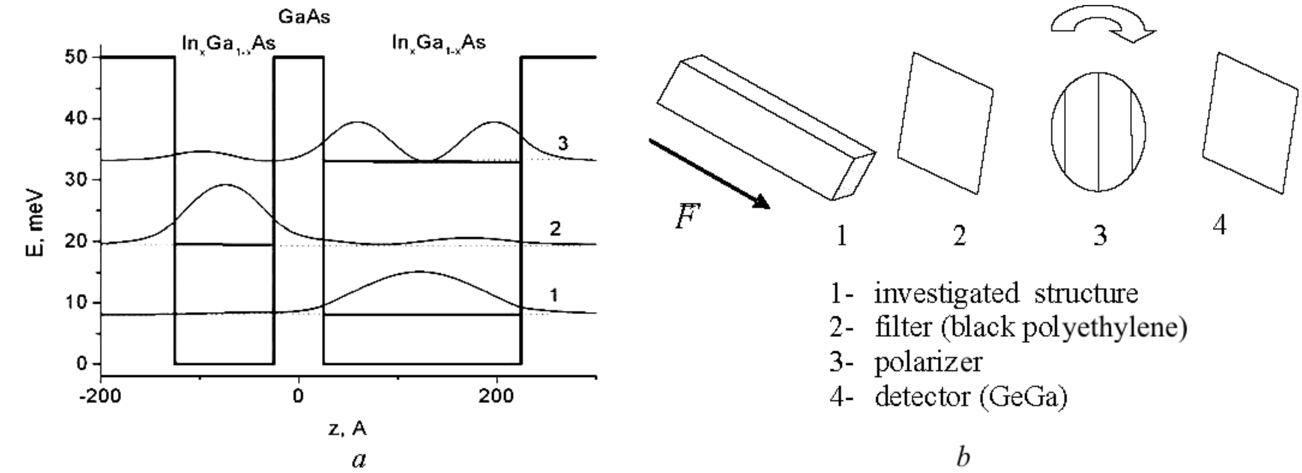

Fig. 1. (a) Schematic representation of the conduction band in the GaAs/In_xGa_{1-x}As heterostructure with QWs and the corresponding levels of size quantization [7]; (b) scheme of the experimental setup for studying the polarization dependence of the emission in a GaAs/In_xGa_{1-x}As heterostructure with QWs

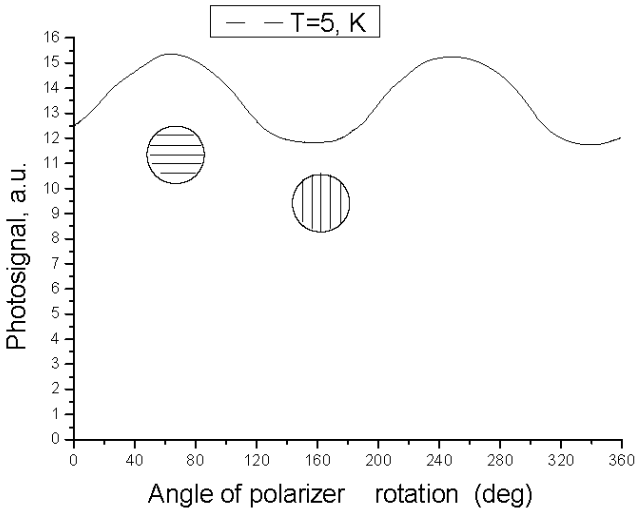

Fig. 2. Polarization dependence of the submillimeter emission by GaAs/In_xGa_{1-x}As heterostructures at $T = 5$ K

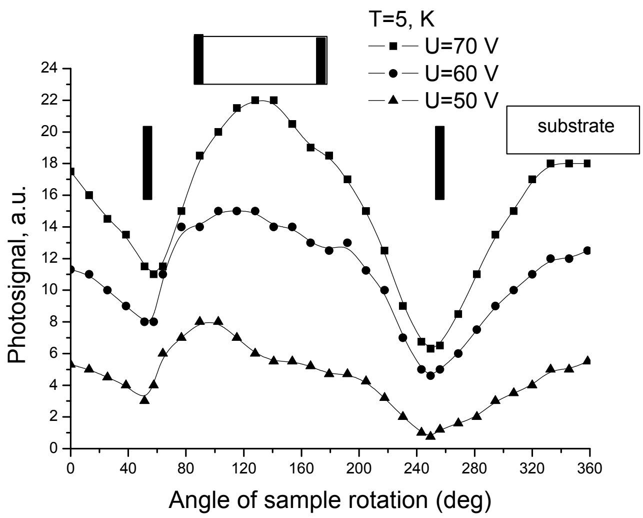

Fig. 3. Radiation pattern of GaAs/In_xGa_{1-x}As heterostructure with QWs at $T = 5$ K ($\lambda \approx 100$ μm)

the wide and narrow QWs, respectively. To obtain a sufficient population on the highest level in the narrow QW (for radiation electron transitions), the heating electric fields higher than 1 kV/cm are to be applied, which has not been done in this work. Therefore, it is justified to assume that the main contribution to the emission by hot electrons is given by those which occupy the lowest energy subband in the In_xGa_{1-x}As interlayer. The electric field **F** that heats electrons is applied in parallel to the semiconductor interlayer plane. The dispersion law and the scattering mechanisms are isotropic in this plane. Therefore, the unique reason that can cause the symmetry violation and can be responsible for the polarization dependences of the radiation is associated just with the electric field **F** that heats the charge carriers. Really, the distribution function in the field **F** looks like [4]

$$f(p, Q) = f_0(p) + \left\{ -eF\tau(p)\frac{df_0}{dp} \right\} P_1(\cos\theta) +$$

$$+\frac{2}{3}(eF)^2\tau(p)p\frac{d}{dp}\left\{ \frac{\tau(p)}{p}\frac{df_0}{dp} \right\} P_2(\cos\theta) + \ldots . \quad (1)$$

Here, $\mathbf{p}$ is the electron momentum, $\tau(\mathbf{p})$ the relaxation time, $P_i(\cos\theta)$ the Legendre polynomial, and θ the angle between the vectors $\mathbf{F}$ and $\mathbf{p}$.

It is worth noting that formula (1) was obtained in work [4] in the three-dimensional case. It remains valid in the two-dimensional case as well, but the expression for the relaxation time $\tau(\mathbf{p})$ is different (see, e.g., work [6]).

As one can see from the results of works [1, 6], the probability of electron scattering (taking the influence of an electromagnetic wave on the scattering event into account) depends on the squared angle between the wave polarization vector and the momentum vector transferred by the electron at scattering. When averaging this probability with the distribution function (1), not only the first term on the right-hand side of Eq. (1) contributes to the emission, but also the third one (the second term is odd in $\cos\theta$ and, therefore, gives no contribution). In this case, the emission intensity as a function of the angles looks like

$$I = I_0 + I_1 P_2(\cos\nu), \tag{2}$$

where ν is the angle between the wave polarization vector and the heating field $\mathbf{F}$, and the quantities I_0 and I_1 are angle-independent.

Note that the restriction of expansion (1) to two terms corresponds to the conventional diffusion approximation. Hence, we see that, in this case, the polarization dependence emerges due to going beyond its framework.

The expansion of the distribution function in series (1) means, in fact, the expansion in the ratio between the drift and thermal velocities (see work [1]). For our experiments, the contribution given by non-diffusion terms is related to the fact that, at very low temperatures and electric field strengths, the ratio between the drift and thermal velocities is not small.

One more remark concerning the way how formula (2) was derived. Works [3,4] developed a theoretical method which allows the processes of light absorption and emission by free carriers in the classical and quantum approaches to be studied on the common footing. The idea of the method consists in using a collision integral, in which the influence of an electromagnetic wave on the processes of charge carrier scattering (by lattice vibrations or impurities) is taken into consideration. While deriving such a collision integral, one has to take, as the basis set, the wave functions of electrons in the field of an electromagnetic wave rather than the wave functions of free electrons. In particular, in the case of a two-dimensional semiconducting layer of thickness a, such functions look like

$$\Psi_{n,\bar{p}_\parallel} = \frac{1}{\sqrt{S}}\sqrt{\frac{2}{a}}\exp\left(\frac{i}{\hbar}\mathbf{p}_\parallel\mathbf{r}_\parallel\right)\sin\left(\frac{n\pi}{a}z\right)\times$$

$$\times\exp\left\{-\frac{i}{\hbar 2m}\int\limits_0^t dt'\left(\mathbf{p}_\parallel-\frac{e}{c}\mathbf{A}(t')\right)^2-\frac{i\varepsilon_n}{\hbar}t\right\},$$

where $\mathbf{p}_\parallel = (p_x, p_y)$ and $\mathbf{r}_\parallel = (x, y)$ are the momentum and coordinate vectors, respectively, in the two-dimensional semiconductor layer, and S is the layer surface area. In addition, $\mathbf{A}$ in Eq. (3) is the vector potential of an electromagnetic wave. This vector potential is also assumed to be parallel to the planar two-dimensional semiconductor layer.

By putting $\mathbf{A} = 0$ in Eq. (3), we obtain the wave functions of free electrons which are used for the description of properties of two-dimensional layers (e.g., in work [8]).

Taking functions (3) as the basis set, we can do – in complete analogy to the three-dimensional case [5] – all calculations to obtain formula (2) for the polarization dependences of the radiation emitted by free carriers, in which the quantities I_0 and I_1 are included as specific functions of the field $\mathbf{F}$. However, we confined ourselves in this work to the qualitative explanation of how the polarization dependence emerges in $GaAs/In_xGa_{1-x}As$ heterostructures.

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ПОЛЯРИЗАЦІЯ СУБМІЛІМЕТРОВОГО ВИПРОМІНЮВАННЯ ГАРЯЧИХ НОСІЇВ В ГЕТЕРОСТРУКТУРАХ GaAs/In_xGa_{1-x}As ПРИ ГЕЛІЄВИХ ТЕМПЕРАТУРАХ

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Р е з ю м е

Наведено результати дослідження поляризаційних залежностей субміліметрового спонтанного випромінювання гарячими носіями в гетероструктурах GaAs/In_xGa_{1-x}As при гелієвих температурах. Вектор поляризації перпендикулярний до напрямку електричного поля, струму через гетероструктуру і поздовжньої осі зразка. Поява поляризації випромінювання зумовлюється впливом сильного електричного поля на функцію розподілу електронів. Застосування загальноприйнятого дифузійного наближення не дозволяє описати теоретично спостережуване явище. Це вдається зробити при виході за межі дифузійного наближення – врахуванні третього члена розкладу в функції розподілу.