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2D electrons and 2D plasmons in AlGa_N/Ga_N nanostructure under highly non-equilibrium conditions

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Abstract. We report on studies of electrically excited non-equilibrium 2D electrons and 2D plasmons in an AlGa_N/Ga_N nanostructure. Optical access to 2D plasmons is provided by means of a metal grating fabricated at the nanostructure surface, while the properties of 2D electrons are examined in the samples without metal grating. The paper focuses on the creation of highly non-equilibrium conditions when the effective temperature of 2D electrons is much higher than the crystal lattice temperature. Such conditions are realized by applying short electrical pulses with a low repetition frequency. A method has been developed for independently determining the temperature of hot electrons and the temperature of the crystal lattice under an applied electric field. It has been shown that under highly non-equilibrium conditions the spectral density of terahertz electroluminescence of 2D plasmons can significantly exceed that of 2D electrons at a certain frequency.

1. Introduction

Compact terahertz (THz) radiation sources based on the electroluminescence of 2D electrons and 2D plasmons are very promising (see [1–4] and references therein). Recently, we studied electrically excited 2D plasmons in an AlGa_N/Ga_N nanostructure [5, 6]. The electroluminescence studies performed on samples with a surface metal grating have revealed a significant selective enhancement of THz radiation emission in the vicinity of the 2D plasmon resonance in comparison with the level of blackbody-like thermal emission of hot 2D electrons. This enhancement has been associated with a radiative decay of nonequilibrium 2D plasmons. It has been experimentally demonstrated that the frequency of THz emission can be varied by changing the geometry of the metal grating on the surface of the nanostructure. As it was shown in [6], the pronounced peaks of 2D plasmon resonances in the THz electroluminescence spectra can be observed only under certain conditions. The main goal of the present work is to examine the necessary conditions in detail.

The present paper focuses on the creation of highly non-equilibrium conditions when the effective temperature of 2D electrons is much higher than the crystal lattice temperature. Such conditions are realized by applying short single electrical pulses or periodical pulses with a relatively low repetition



frequency. A method was developed for independently determining the temperature of hot 2D electrons T_e (which coincides with the temperature of non-equilibrium 2D plasmons T_p in the considered nanostructure) and the temperature of crystal lattice T_L under an applied electric field. An appropriate ratio was found between the pulse duration and the repetition period, which provides the condition $T_e \gg T_L$ in the operating field range (up to 500 V/cm) and the field dependencies of both temperatures were determined. A sharp peak of the 2D plasmon resonance was observed experimentally in the THz emission spectrum under the condition $T_e / T_L = 4$.

2. Experimental results and discussion

Experimental studies were performed on an AlGaIn/GaN nanostructure grown on a sapphire substrate. The nanostructure growth process and postgrowth device fabrication (including contact and grating fabrication) are described in detail in [6]. The 2D electron concentration deduced from the Hall effect and conductivity measurements by the Van der Pauw method was $n_s = (1.1-1.2) \times 10^{13} \text{ cm}^{-2}$ with the low-field mobility $\mu_0 = 7000-7700 \text{ cm}^2/\text{V s}$ at a temperature of 77 K. A few samples with lateral sizes of $5 \times 7 \text{ mm}^2$ were made from the wafer. Two electrical contacts spaced 3.5 mm apart were processed at the surface of each sample (see figure 1, left panel). Some of the samples additionally had a metal grating ($3 \times 4.5 \text{ mm}^2$) in the area between contacts (see figure 1, right panel). Below we will refer to the latter samples as “grating samples”. The geometry of the grating (period $a = 801 \pm 5 \text{ nm}$ and a filling factor of 0.498 ± 0.009) provided the position of the fundamental 2D plasmon mode at a frequency of 2.8 THz, which was confirmed by the optical transmission measurements [5].

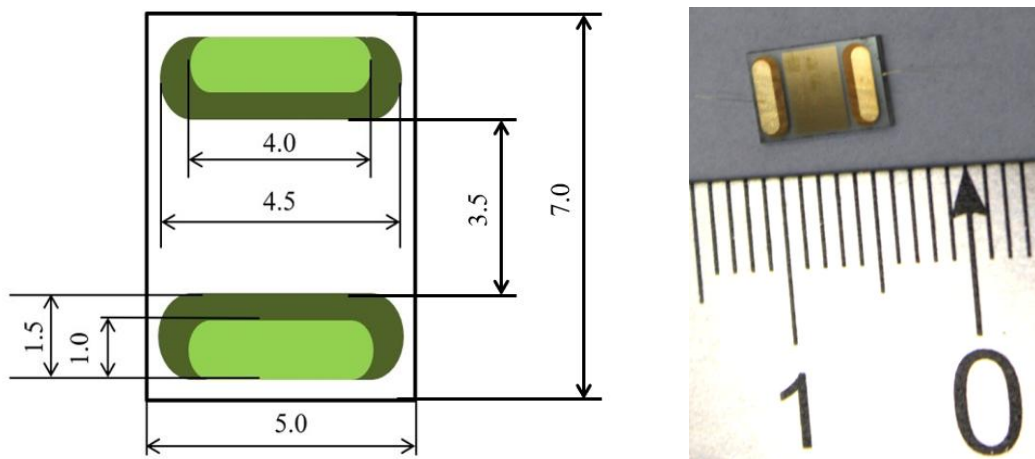


Figure 1. Contact geometry (left panel) and grating sample image (right panel).

Hot 2D electrons and non-equilibrium 2D plasmons were excited in the nanostructure by applying voltage pulses to the contacts. The experiments were performed on the samples immersed into liquid helium (at a temperature of 4.2 K). Firstly, we studied current-voltage characteristics for the samples without a metal grating. In the case of single $2 \mu\text{s}$ electrical pulses, the shape of the current oscillogram repeated the rectangular shape of the applied voltage pulse in the field range up to 2300 V/cm. With an increase in the duration of the pulse to $4 \mu\text{s}$ (or more), the current oscillogram showed a gradual decrease in the current at the end of the pulse due to substantial Joule heating of the crystal lattice of the sample during a long pulse. This current decrease is caused by the acceleration of electron scattering processes with increasing lattice temperature. Usually, in our experiments, we applied field pulses with a duration of $2 \mu\text{s}$ or a few times less, which provided a negligible lattice heating.

Let us consider 2D electron gas heating during a pulse with a constant electric field E , assuming that the crystal lattice has a constant temperature T_0 . The average power that an electron gains from the

applied electric field is equal to $e\mu_E E^2$ and can be easily found from the experimental current-voltage characteristic (here μ_E denotes 2D electron mobility at a given electric field E). The field dependence of this physical quantity for the sample without a metal grating at a temperature $T_0 = 4.2$ K is shown in the left panel in figure 2. Obviously, in the stationary conditions, this physical quantity should be equal to the average rate of energy loss through all inelastic scattering processes $\left\langle \frac{d\varepsilon}{dt} \right\rangle$. The latter physical quantity can be calculated theoretically at a certain lattice temperature T_0 using the distribution function of hot 2D electrons with an effective temperature T_e (for details see [1]). The simulated dependence of $\left\langle \frac{d\varepsilon}{dt} \right\rangle$ on the hot electron temperature T_e is shown in the right panel in figure 2 (for $T_0 = 4.2$ K). Then, a simple algorithm for determining the dependence $T_e(E)$ can be realized using figure 2 as it is illustrated by the red arrows. Firstly, the left panel enables one to find the $e\mu_E E^2$ value corresponding to an arbitrary strength of the electric field E . As it was mentioned above, the equation

$$e\mu_E E^2 = \left\langle \frac{d\varepsilon}{dt} \right\rangle \quad (1)$$

should be satisfied. This gives a value of $\left\langle \frac{d\varepsilon}{dt} \right\rangle$ corresponding to the considered value of E . Finally, one can find the corresponding value of the hot electron temperature T_e using the right panel of figure 3.

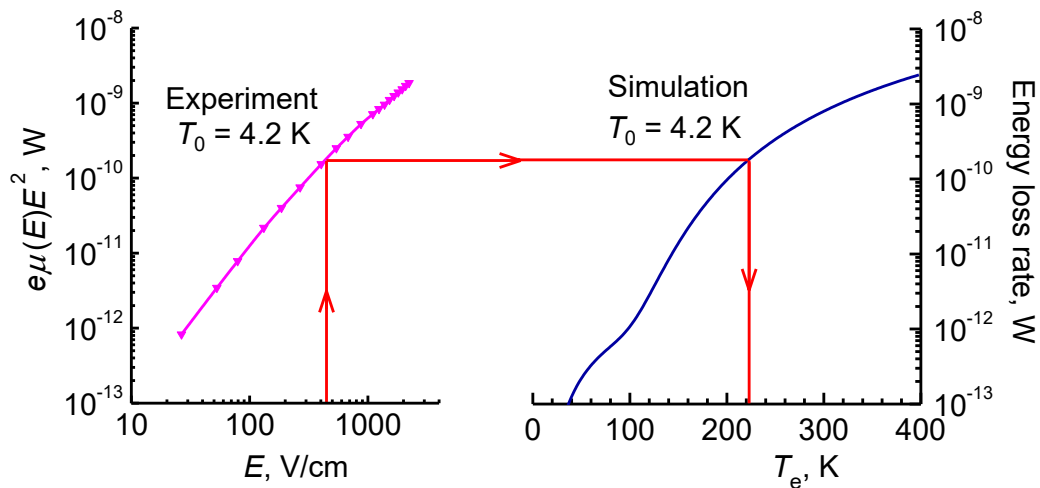


Figure 2. Algorithm for determining the dependence $T_e(E)$. Left panel: experimental data on the power that one electron gains from the applied electric field E . The experiment was carried out for the sample without a metal grating with single voltage pulses of $2 \mu\text{s}$ duration. Right panel: theoretically simulated energy loss rate. The red arrows indicate the effective temperature of hot electrons T_e corresponding to a given value of electric field E .

The field dependence of the hot 2D electron temperature, found using this algorithm for the sample without a metal grating, is shown in figure 3. In a similar way, the dependence $T_e(E)$ was determined for the grating sample. The both dependences coincided within the experimental error.

The next problem was the determination of the magnitude of crystal lattice heating during single rectangular electrical pulses of various amplitudes and durations. This problem was solved by studying

the THz electroluminescence in the samples and analyzing the recorded oscillograms. The integral intensity of THz radiation emitted from the sample was measured by a Ge:Ga detector, which was also immersed into liquid helium. After amplification, the photoresponse signal was recorded by a digital oscilloscope. Typical photoresponse oscillograms are shown in figure 4. Let us consider, for instance, the oscillogram for an electrical pulse of 8 μs duration (black curve). It should be noted that the photoresponse decay can be decomposed into two components. The fast component of the photoresponse decay (we denote its amplitude as U_F) decreases exponentially with time and vanishes

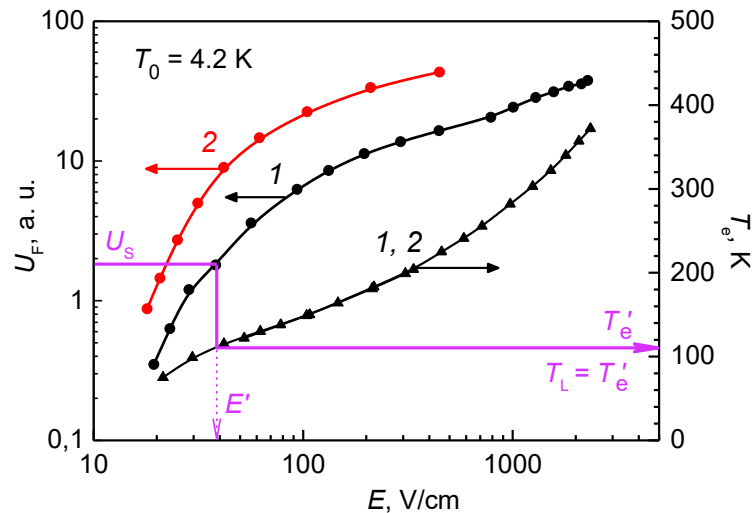


Figure 3. Field dependences of the hot 2D electron temperature (right axis) and the amplitude U_F of the integral photoresponse of the Ge:Ga detector (left axis). 1 – sample without a metal grating, 2 – grating sample. The violet arrows demonstrate the algorithm for determining T_e' and T_L (see the text).

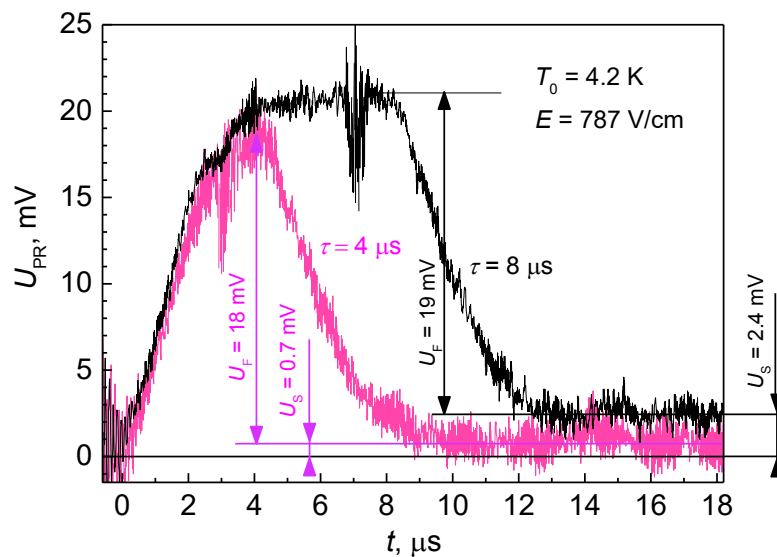


Figure 4. Photoresponse oscillograms for the sample without a metal grating under excitation by single rectangular electrical pulses of different durations τ .

in a few microseconds; its duration is determined by the time constant of the Ge:Ga photodetector ($\sim 2 \mu\text{s}$). The slow component has a much longer duration, and its amplitude (denoted by U_S) increases with increasing field pulse duration. We assumed that the amplitude of the slow decay component U_S is determined by the Joule heating of the sample lattice during the field pulse. In the considered spectral range, electroluminescence from the sample without a metal grating is associated with only one emission mechanism, namely, blackbody-like thermal emission of hot 2D electrons [1]. Obviously, the temperature of 2D electrons T_e' just after their very rapid thermalization should be equal to the lattice temperature T_L , corresponding to the very beginning of the slow decay component (thermalization time is about 10^{-12} – 10^{-10} s [7]). Consequently, the amplitude of the slow decay component U_S enables one to determine the corresponding value of $T_e' = T_L$, using the dependence $U_F(E)$. The latter for the sample without a metal grating is shown in figure 3 by black circles. For comparison, a similar dependence is plotted for the grating sample (red circles), which demonstrates enhancement of THz emission. As it will be shown below, this amplification is caused by an additional contribution to THz emission due to 2D plasmon scattering at the metal grating.

The algorithm for determining T_e' and T_L at a given electric field E is the following. Firstly, we measure the amplitude U_S at this field and, using figure 3, find the electric field E' , which ensures the satisfaction of the equation $U_F(E') = U_S$. Secondly, using the field dependence of hot electron temperature $T_e(E)$, we find $T_e' = T_e(E')$. Finally, we assume $T_L = T_e'$. This algorithm is illustrated in figure 3 by the violet arrows.

In fact, T_L characterizes the temperature of the crystal lattice in the quantum well (QW) layer at the very end of the electrical pulse. The experiment demonstrated that this temperature rises with increasing applied power, as well as with increasing pulse duration (solid curves in figure 5). At a given pulse duration, the temperature T_L can be experimentally determined only in the limited range of applied power densities. The low limit is restricted by the sensitivity of the THz detector. In accordance with figure 3, our experimental method did not allow measuring values of T_L less than 75 K. The upper limit of the applied power density is restricted by the rate of heat removal through the sample surface. One should avoid boiling of helium around the sample, which results in an abrupt

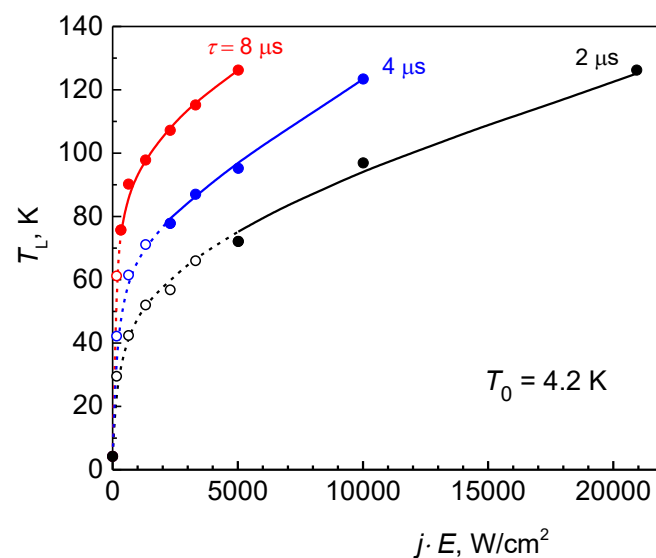


Figure 5. Crystal lattice temperature at the end of an electric pulse as a function of the applied power density. The filled circles represent experimental data at different pulse durations for the sample without a metal grating immersed into liquid helium. The open circles show the results of extrapolation to low values of the applied power density. The solid and dashed lines in the figure are a guide for the eye.

decrease in the heat removal rate and QW layer melting. In our experiments, we did not exceed $T_L = 130$ K, which kept the samples safe. We extrapolated experimentally determined dependencies $T_L(j \cdot E)$ to low values of the applied power density $j \cdot E$ (where j is the current density), given that $T_L(0) = 4.2$ K regardless of the pulse duration. The results of the extrapolation are plotted in figure 5 by dashed curves.

It is interesting to compare the values of the hot 2D electron temperature T_e (for the considered nanostructure, it coincides with the temperature of non-equilibrium 2D plasmons T_p [6]) and the lattice temperature T_L at the same amplitude of the electric pulse. The corresponding experimental plots for the case of $2 \mu\text{s}$ single pulses are presented in figure 6. One can see that highly non-equilibrium conditions for 2D electrons and 2D plasmons can be realized under such short pulses. Actually, in the field range from 100 to 2000 V/cm, the ratio T_e / T_L exceeds 3.

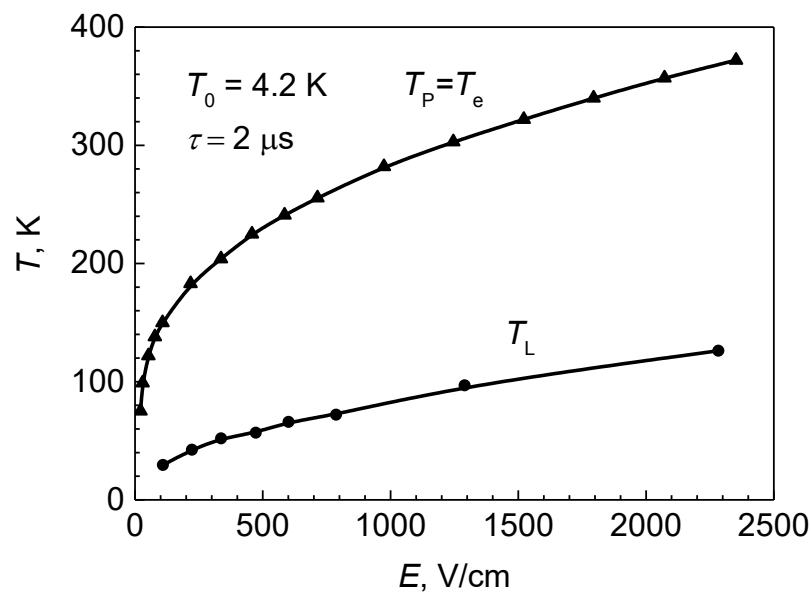


Figure 6. Field dependencies of the temperatures of hot 2D electrons T_e , non-equilibrium 2D plasmons T_p and crystal lattice T_L for the sample immersed into liquid helium. The duration of the electrical pulse $\tau = 2 \mu\text{s}$.

Finally, we studied the THz electroluminescence spectra under highly non-equilibrium conditions using $2 \mu\text{s}$ electrical pulses. A magnetic-field-tuned InSb filter was mounted between the sample and the Ge:Ga detector. The detailed description of the experimental set-up was given in [6]. To increase the signal-to-noise ratio, we applied periodic electrical pulses to the sample and measured the photoresponse signal using a low-noise current preamplifier and a gated integrator with a boxcar averager. Compared to single pulses, when using periodic pulses, the maximum electric field strength in the sample should be reduced. During the time between pulses, the crystal lattice of the QW layer is required to cool down to the temperature $T_0 = 4.2$ K, otherwise an increase in this temperature is inevitable, which may be accompanied by heating the whole sample, boiling of helium and melting of the sample. It was established experimentally that at a pulse repetition frequency of 10 Hz and electric fields up to 500 V/cm, the current density for periodic pulses is the same as for single ones. In other words, at these conditions, the thermal behavior for the QW layer is the same for both measurement regimes. For higher electric fields, periodic pulses give a lower current density in comparison with single ones, which is caused by an increase in the temperature T_0 . In order to avoid this undesirable shift of the operating temperature, we used only the fields $E < 500$ V/cm in the spectral measurements of THz electroluminescence.

The experimental results on the electroluminescence in AlGaIn/GaN nanostructures at electric field $E = 447$ V/cm are presented in figure 7. In accordance with figure 6, the hot 2D electron temperature at this field reaches the value $T_e = 224$ K, while the lattice temperature in the end of the pulse is much lower: $T_L = 56$ K. The ratio $T_e / T_L = 4$ indicates highly non-equilibrium conditions for 2D electrons and 2D plasmons.

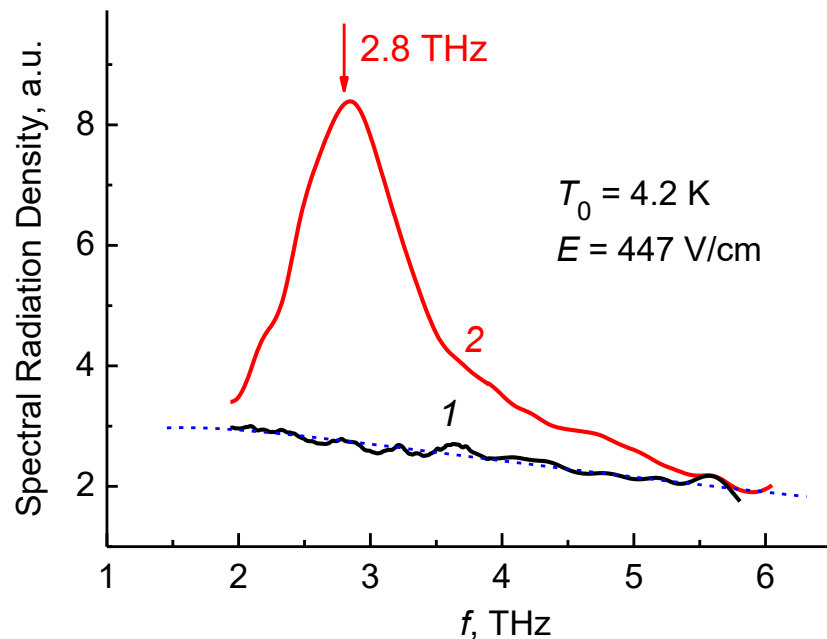


Figure 7. Terahertz emission spectra of AlGaIn/GaN nanostructures under pulsed electrical excitation. The experimental data for the sample without a metal grating (curve 1) and the grating sample (curve 2). The dashed line shows a simulated spectrum for the sample without a grating. The arrow marks the spectral position of the fundamental 2D plasmon mode for the grating sample.

The experimental spectrum of THz emission from the electrically excited sample without a metal grating demonstrates a monotonic decrease in the spectral density of radiation with a frequency in the range of 2 – 6 THz (see curve 1 in figure 7). The microscopic origin of this emission is blackbody-like emission of hot 2D electrons [1]. The experimental curve corresponds to the model of thermal radiation of hot 2D electrons with the temperature $T_e = 224$ K (in the limits of experimental error).

On the contrary, the spectrum of THz electroluminescence in the grating sample shows a resonant behavior with a sharp peak at a frequency of 2.84 THz (curve 2 in figure 7). This frequency practically coincides with the frequency of the fundamental 2D plasmon mode in the considered nanostructure (as mentioned above, it is 2.8 THz). Thus, we associate the observed sharp peak with a radiative decay of nonequilibrium 2D plasmons. At the resonance frequency, the grating sample provides an increase in the spectral radiation density by 3 times compared with the sample without a metal grating. It should be noted that in the grating sample, the additional contribution of 2D plasmons to the spectral radiation density is 5 times greater than the contribution of hot 2D electrons. The evaluation of the latter parameter took into account the transmittance of the grating for unpolarized spontaneous radiation from hot 2D electrons (of 50%).

It should be emphasized that such a vivid manifestation of THz emission due to 2D plasmons is the result of applying the experimental technique based on the creation of highly non-equilibrium conditions for a 2D electron gas.

3. Conclusions

Terahertz radiation emission due to hot 2D electrons and nonequilibrium 2D plasmons has been experimentally studied in electrically excited AlGaIn/GaN nanostructures. A method has been developed for independently determining the temperature of hot 2D electron gas and that of crystal lattice under applied electric field. Experimental studies of the integral intensity of THz electroluminescence and its spectral dependence have been performed at highly non-equilibrium conditions when the effective temperature of 2D electrons and 2D plasmons is much higher than QW layer crystal lattice temperature. For AlGaIn/GaN nanostructure with a surface metal grating, it has been experimentally demonstrated that contribution of 2D plasmons to the spectral radiation density can exceed the hot 2D electron contribution by 5 times.

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