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Two-dimensional plasmons in a GaN/AlGaN heterojunction

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Abstract. We report the studies on optical properties of a GaN/AlGaN heterostructure with a surface metal grating. The fabricated structures were optimized for the observation of 2D plasmon resonances in the spectral range of 2–5 THz. The spectra of the equilibrium optical transmission were experimentally investigated and the 2D plasmon resonance was found. The current-voltage characteristics of the grating sample and a reference sample without grating were measured and the dependence of the hot 2D electron temperature on electric field was established. Terahertz electroluminescence was studied in both samples in the sensitivity band of the Ge:Ga detector in electric fields of up to 400 V/cm. It has been shown that, due to the contribution of nonequilibrium 2D plasmons, the integral photoresponse signal for the sample with a surface metal grating increases 2–4 times as compared with the sample without grating, where the terahertz emission is due only to hot 2D electrons.

1. Introduction
In recent decades, a significant amount of research has been devoted to developing efficient and compact sources of terahertz (THz) radiation. One of the promising directions in this area is based on electron heating by an electric field. In particular, the THz emission under 2D electron heating was investigated in a GaN/AlGaN heterostructure [1]. The opportunity to create selective THz emitters based on 2D plasmon excitation was also considered. The first such experiments were carried out with nonequilibrium 2D plasmons in a GaAs/AlGaAs heterojunction [2, 3]. In such a case, the emission spectrum represents a sequence of narrow resonant peaks corresponding to different 2D plasmon modes. It was found that the THz radiation intensity in the band of the 2D plasmon resonance can be an order of magnitude higher than the radiation intensity of hot 2D electrons (with the same effective temperature as that of 2D plasmons).

From the point of view of 2D plasmonics, the nitride-based heterostructures (in particular, GaN/AlGaN ones) are more promising [4–6]. A recent paper [7] was aimed at investigating the selective THz radiation from the GaN/AlGaN heterostructure under electrical excitation of incoherent 2D plasmons. However, only a weak peak related to 2D plasmon scattering at a metal grating was detected in the THz emission spectrum. The peak amplitude did not exceed 20% of the wideband...
background signal caused by significant Joule heating of the whole sample during the applied voltage pulse. The reason for this was the use of electrical pulses of very long duration (800–2000 μs).

The main goal of the present work is to obtain intensive selective THz electroluminescence due to incoherent 2D plasmon excitation in a GaN/AlGaN heterojunction under conditions of negligible Joule heating of the samples. We report the study on optical properties of the GaN/AlGaN heterojunction grown on a sapphire substrate with a metal grating at the outer heterojunction surface. Equilibrium optical transmission spectra have been investigated and a 2D plasmon resonance with a high quality factor has been found. Current-voltage characteristics have been studied for the samples with a metal grating and without it. The field dependence of the hot 2D electron temperature has been established for both samples. A fast Ge:Ga detector was used for the THz electroluminescence investigation, which enabled the use of short voltage pulses (~1 μs) to provide a negligible Joule heating of the sample during the pulse. The intensity of corresponding thermal radiation was about two orders of magnitude less than in [7]. Our experiments demonstrated that nonequilibrium 2D plasmon scattering at a metal grating can result in THz intensity that amplified by several times (in the 2D plasmon resonance band) compared with the radiation emission from hot 2D electrons (in the same spectral band).

2. Results and discussion
First, a theoretical simulation was performed of terahertz transmittance, reflectivity, absorptivity and emissivity spectra for a GaN/AlGaN heterojunction on a sapphire substrate with a metal grating at the outer heterojunction surface. To study 2D plasmons, it is necessary to consider the spectra corresponding to the linearly polarized radiation with the electric field vector \( E_\omega \) directed perpendicular to the grating strips (we denote this radiation polarization as 'active'). The main features of these spectra are the dips in the transmittance spectrum and the peaks in the absorptivity (emissivity) spectrum at the photon energies corresponding to different modes of the 2D plasmon resonance. During the simulation we varied the following model parameters: the 2D electron concentration \( n_s \), the distance between the 2D channel and the structure surface \( d \), the grating period \( a \) and the metal strip width \( w \). The dispersion law for 2D plasmons was calculated taking into account the ratio \( w/a \). The structure was designed to ensure the maximum amplitude of the fundamental 2D plasmon mode under the condition of a significant overlap of this mode with the Ge:Ga detector's sensitivity band (10.1–18.6 meV at the level of 50%).

The structure with following design was grown by MOVPE: a 2.8-μm-thick GaN layer, a 0.7-nm-thick AlN layer, a 12-nm-thick undoped Al\(_{x}\)Ga\(_{1-x}\)N layer (\( x = 0.25 \)), a 23-nm-thick Al\(_{x}\)Ga\(_{1-x}\)N:Si layer, a 4-nm-thick GaN:Si layer and a 2.5-nm-thick Si\(_3\)N\(_4\) layer. Si doping level was about of \( 5 \cdot 10^{18} \) cm\(^{-3} \). In accordance with the Hall measurements in low fields, 2D electrons in the grown structure are characterized by the following parameters: concentration \( n_s = 1.2 \cdot 10^{13} \) cm\(^{-2} \) and rather high mobility \( \mu_0 = 7200 \) cm\(^2\)/(V s) at temperature \( T_0 = 77 \) K. A set of samples with Ohmic contacts for applying a lateral electric field was fabricated from the same nanostructure. The contacts were patterned at the structure surface by photolithography followed by metallization and liftoff. The metal grating (Ti/Au) with a period \( a = 800 \) nm and a filling factor of 1/2 was manufactured in the area between contacts using electron beam lithography. For comparison, the reference samples without metal gratings were also fabricated and studied.

Equilibrium optical transmission of the samples was studied in the THz spectral range using a Fourier spectrometer and a closed-cycle cryostat. The spectra of the transmittance at a temperature of 77 K are presented in figure 1. The transmittance spectrum for the reference sample without a grating is monotonous and does not demonstrate any resonance features. On the contrary for the sample with a metal grating, one can see a narrow (~1 meV) dip, the spectral position of which (11.5 meV, i.e. 2.8 THz) corresponds to the theoretically expected location of the fundamental 2D plasmon mode with a wavevector \( q = 2\pi/a \). That is why we attribute this resonance to the 2D plasmon excitation under THz radiation illumination during transmittance measurements. It should be noted that the quality
factor for this resonance is relatively high (about 10) due to abovementioned high value of the 2D electron mobility.

![Transmittance spectra of the samples in the THz spectral range. Transmittance for the sample with a metal grating was examined for active linear polarization. Transmittance for the sample without a grating was recorded for unpolarized radiation.](image)

**Figure 1.** Transmittance spectra of the samples in the THz spectral range. Transmittance for the sample with a metal grating was examined for active linear polarization. Transmittance for the sample without a grating was recorded for unpolarized radiation.

The current-voltage characteristics were studied for both samples in a wide range of electric fields: $0 < E < 2500$ V/cm. Measurements were carried out using short single pulses of the applied voltage (with a pulse duration of 0.5–2 μs) in a temperature range of 4.2–320 K. An analysis of the experimental current-voltage characteristics demonstrated that the dependencies of the hot 2D electron temperature ($T_e$) on the electric field are the same for the sample with a metal grating and for the reference sample without a grating. The algorithm for establishing the dependence $T_e(E)$ was described in [1]. Two-dimensional electrons in the samples cooled down to liquid helium temperature were heated by an electric field $E = 2500$ V/cm up to a temperature $T_e = 370$ K.

Terahertz electroluminescence was studied in the same samples. The experiments were carried out on the samples immersed directly into liquid helium, so that in the absence of electric field $T_e = T_0 = 4.2$ K. A Ge:Ga detector (also immersed into liquid helium) was used to measure the integral intensity of THz radiation in the spectral range of 10.1–18.6 meV. It is known that THz electroluminescence in GaN/AlGaN heterostructures without metal gratings at their surface is associated with thermal radiation of hot 2D electrons [1] and consequently is unpolarized. It is this mechanism of THz radiation emission that occurs in the reference sample. As the electric field increases from 20 to 450 V/cm, the hot electron temperature $T_e$ in the reference sample increases from 60 to 225 K. This is accompanied by a magnification in the integral radiation intensity by about two orders of magnitude (blue curve in figure 2). As mentioned above, the same dependence $T_e(E)$ is inherent for the sample with a metal grating. If only this THz emission mechanism took place in the grating sample, then it would give half the integral radiation intensity for a given value of the electric field, since the metal grating transmits waves with only one linear polarization (active polarization) and totally reflects the waves with orthogonal linear polarization. However, the experiment showed that the metal grating on the sample surface does not cause a decrease in the intensity of THz radiation but, on the contrary,
causes it to increase by 2.6–4 times (see figure 2). This can be explained by an additional contribution to the THz emission due to nonequilibrium 2D plasmons generated during heating of the electrons by the electric field. This contribution to radiation has an active polarization and is resonant. It should be noted that the spectral position of the fundamental 2D plasmon mode for the grating used coincides with the sensitivity maximum of the Ge:Ga detector. This circumstance explains such a significant increase in the integral photoresponse for the sample with a metal grating (up to 4 times higher), in spite of the fact that 2D plasmons contribute to THz emission only in a narrow band of about 2 meV width.

![Figure 2](image_url)

**Figure 2.** Field dependence of the integral intensity of THz radiation from different samples in the sensitivity band of the Ge:Ga detector.

3. Conclusions
The optical properties of a GaN/AlGaN heterojunction grown on a sapphire substrate with a metal grating at the outer heterojunction surface have been studied. A 2D plasmon resonance with the quality factor of about 10 has been found in the transmittance spectrum. Terahertz radiation emission under conditions of 2D electron heating and nonequilibrium 2D plasmon generation in an electric field has been investigated. It has been demonstrated that nonequilibrium 2D plasmon scattering at the metal grating can lead to a significant magnification of the THz radiation intensity (up to 4 times). The presented data on terahertz radiation emission are preliminary. The terahertz electroluminescence spectra under various levels of electrical excitation will be studied at the next stage of the research, which may provide deeper understanding of the properties of nonequilibrium 2D plasmons.

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