Optical properties of GaN/AlGaN nanostructures in the terahertz frequency range

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Abstract. Optical transmission and reflection for a single GaN/AlGaN heterojunction grown on sapphire have been investigated with high and low spectral resolution in the spectral range of 8–47 meV. For comparison, the same spectra have been measured for the sapphire substrate. Refractive index dispersion has been determined for sapphire from the spectra measured with high resolution. Then the data on 2D electron absorption in the GaN/AlGaN heterojunction were obtained from the low resolution spectra. The spectra of terahertz emission from the GaN/AlGaN heterojunction under 2D electron heating in strong electric field have been measured for the first time.

1. Motivation
In the last decade, intensive studies of GaN based structures are conducted with the aim of application in terahertz (THz) photonics [1–6]. Development of THz emitters and detectors based on GaN/AlGaN nanostructures calls for reliable experimental data on their optical properties in the terahertz frequency range. In the present work, we first carried out a series of far infrared optical investigations of a single GaN/AlGaN heterojunction grown on a sapphire substrate including measurements of THz reflection, transmission and emission spectra. The THz reflection and transmission were studied in equilibrium conditions at room and cryogenic temperatures. The THz emission spectra were studied under conditions of 2D electron heating by lateral electric field.

2. Samples
The heterostructure was grown by metal-organic vapor phase epitaxy (MOVPE) on a (0001) sapphire substrate with a thickness of 430 μm. The heterostructure consists of a 2.8 μm GaN buffer layer, a 1 nm AlN interface layer, a 31.7 nm $Al_{0.214}Ga_{0.786}N$ barrier layer and a 4.4 nm GaN cap layer. No intentional doping was performed during MOVPE growth. Two dimensional electron gas (2DEG) is formed at the GaN/AlN interface due to piezoelectric and spontaneous polarization induced effects in the heterostructure [7]. In accordance with the Hall effect and conductivity measurements, 2DEG with a concentration N_e of 1.0×10^{13} cm^{-2} and a low-field mobility of 1500 and 8000 cm^2/V·s at temperatures of 300 and 77 K, respectively, was formed in the structure under investigation. For the optical reflection and transmission measurements, the samples with an area of about 1cm^2 were cut from a

wafer. For investigation of the THz emission, two Ti/Ni/Al/Au electrical contacts of 7 mm length with a distance of 3 mm were fabricated on the sample surface. By applying a voltage to the contacts, we produced 2D electron heating in the GaN/AlGaN heterojunction.

3. Results and discussion

The optical transmission spectra of the GaN/AlGaN nanostructures were experimentally studied in the THz spectral range using a Fourier spectrometer Bruker Vertex 80v operating in a rapid-scan mode. The measurement pressure was about 4 mbar. A globar was used as a source of THz radiation and a Mylar beam-splitter was applied. The intensity of THz radiation was measured by a pyroelectric detector. Measurements were carried out at room and cryogenic (77 K) temperatures. The experimental transmission spectra for the case of normal incidence of radiation (incidence angle $\theta = 0°$, angular aperture of the beam $\Delta\theta = 16°$) are presented in figure 1.

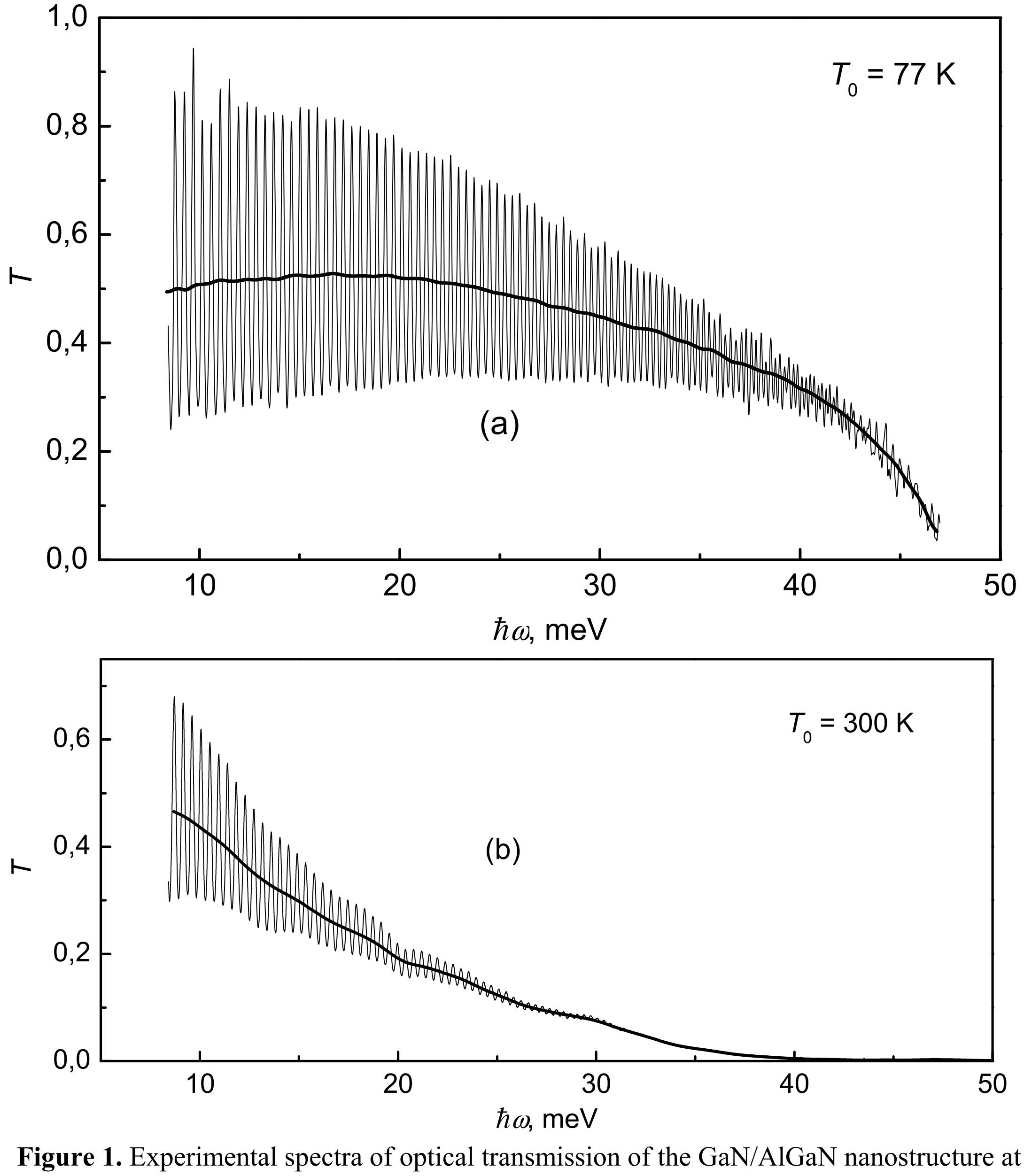

Figure 1. Experimental spectra of optical transmission of the GaN/AlGaN nanostructure at temperatures of 77 K (a) and 300 K (b). Thin and thick lines correspond to the spectral resolutions of 0.06 and 1 meV, respectively.

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The transmission spectra of the GaN/AlGaN nanostructure measured at high spectral resolution (0.06 meV) demonstrate oscillations caused by the radiation interference under multiple reflections on the outer facets of the structure. In the case of low enough resolution, when the radiation coherence length becomes less than the structure thickness, these oscillations disappear (see thick lines in figure 1).

Similar transmission spectra were measured also for the sapphire substrate before nanostructure growth. Analyzing interference oscillations in the spectra, we determined the refractive index for the sapphire with the help of the following formula:

$$n_S = \frac{\pi\hbar c}{\hbar(\Delta\omega)_{2\pi} d_S}, \quad (1)$$

where $\hbar(\Delta\omega)_{2\pi}$ is a spectral period of the transmission curve (the period monotonically decreases with the photon energy $\hbar\omega$), d_S is the thickness of the sapphire substrate, and c is the light velocity in vacuum. The spectral dependencies of the refractive index n_S obtained for temperatures of 77 K and 300 K are presented in figure 2. The both dependencies coincide within the limits of experimental accuracy. A monotonic increase of the refractive index n_S in the spectral range of 8–42 meV is associated with the low-frequency phonon mode [8]. These data give us an opportunity to find the reflection coefficient r_S for the vacuum/sapphire and sapphire/vacuum interfaces in accordance with the relationship:

$$r_S = \frac{(n_S - 1)^2}{(n_S + 1)^2}, \quad (2)$$

which is true for the case of normal incidence of radiation in approximation $n_S >> k_S$ (here k_S is the extinction coefficient for sapphire).

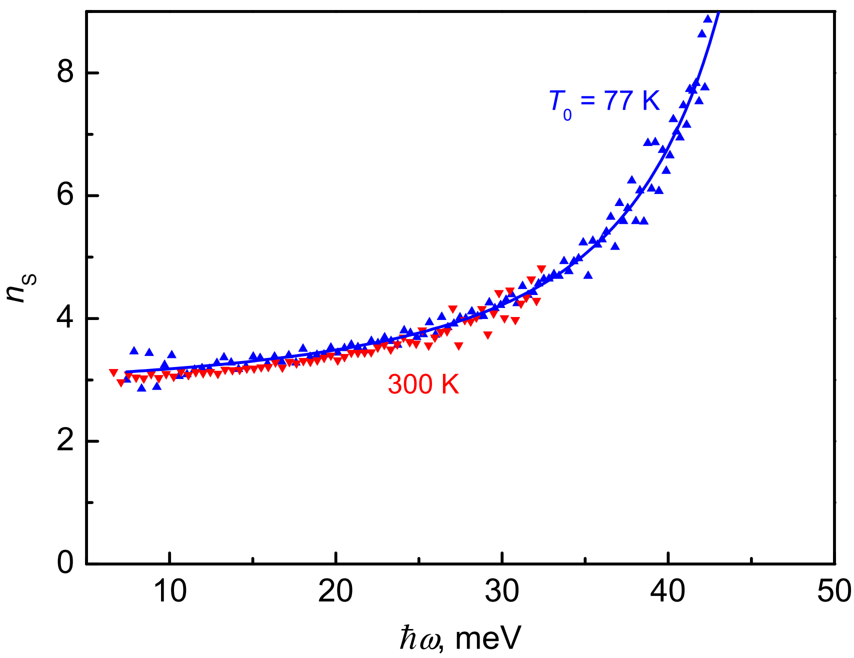

Figure 2. Spectral dependencies of the refractive index n_S of the sapphire substrate at two temperatures T_0. Triangles show experimental points, the solid line represents the Lorentzian fit to the experimental data at T_0 = 77 K.

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The value of the optical transmission of the sapphire substrate measured at low spectral resolution (when interference oscillations are completely smoothed) can be described by the formula for incoherent radiation taking into account multiple reflections:

$$T_S = \frac{(1-r_S)^2 V_S}{1-r_S^2 V_S^2}, \tag{3}$$

where $V_S = \exp(-\alpha_S d_S)$ and α_S is the absorption coefficient which is related to the extinction coefficient by the equation:

$$\alpha_S = 2\frac{\omega}{c}k_S. \tag{4}$$

Analyzing the low-resolution transmission curve for the sapphire substrate we determined the spectral dependence of the optical absorption in sapphire with the help of equations (3) and (2). Results of this analysis for room temperature are shown in figure 3 by the dotted red curve representing the values of $\alpha_S d_S = -\ln V_S$. The same analysis for the temperature T_0 = 77 K has shown that, in this case, the sapphire substrate has negligible optical absorption ($\alpha_S d_S < 0.03$) in the spectral range of 8–42 meV (it is not plotted in figure 3).

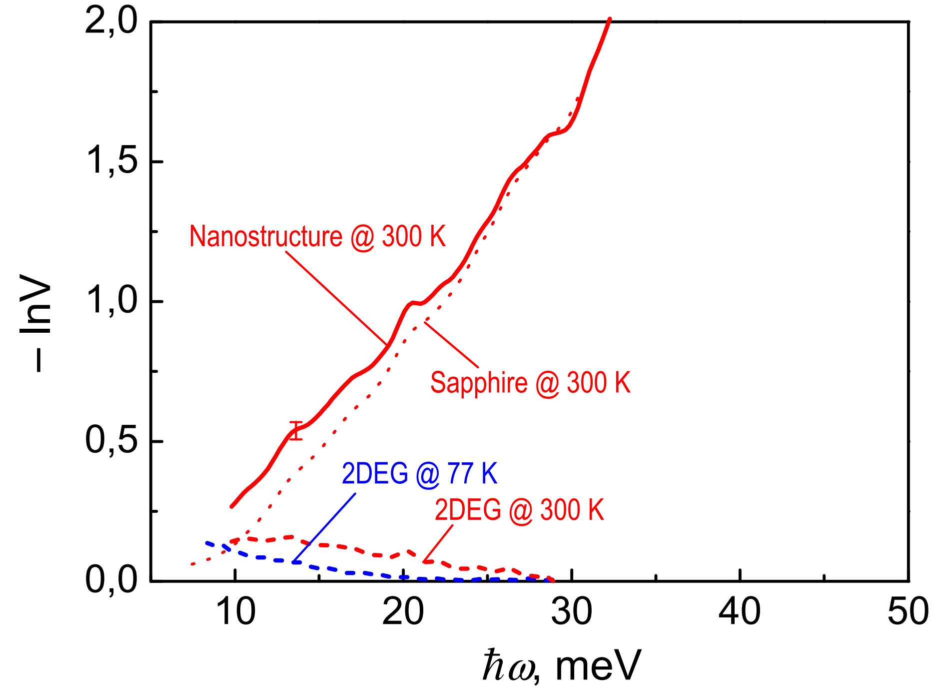

Figure 3. Optical absorption spectra for the GaN/AlGaN nanostructure (solid red line) and sapphire substrate (dotted red line) at room temperature. Contribution of 2D electrons to the absorption is shown by the dashed red line (at T_0 = 300 K) and the dashed blue line (at T_0 = 77 K).

The main goal of the optical transmission study of the GaN/AlGaN nanostructure was to determine 2D electron contribution to the optical absorption. For this purpose, the transmission spectra with totally smoothed interference effects are more appropriate (thick curves in figure 1). In the first approximation, these spectra can be described by the formula for incoherent radiation taking into account multiple reflections:

$$T_N = \frac{(1-r_S)(1-r_{GaN})V_S V_{2DEG}}{1-r_S r_{GaN} V_S^2 V_{2DEG}^2}, \quad (5)$$

where r_{GaN} is the reflection coefficient for the interface vacuum/GaN and V_{2DEG} is the optical transmittance of 2D electron gas at the GaN/AlGaN interface (we assume the absence of THz absorption in intentionally undoped GaN, AlN and AlGaN layers of the nanostructure and negligible reflection at the GaN/sapphire interface).

Let us first analyse the experimental results on the nanostructure transmission for room temperature (thick curve in figure 1 (b)). Using equation (5) and previously determined data on the optical properties of sapphire, namely $n_S(\hbar\omega)$, $r_S(\hbar\omega)$ and $V_S(\hbar\omega)$, we extracted the experimental dependence $V_{2DEG}(\hbar\omega)$. The esulting data for room-temperature 2DEG absorption are presented in figure 3 by the dashed red line. One can see that 2D electrons give a significant contribution to the total nanostructure absorption at photon energies less than 30 meV. The magnitude of this contribution monotonically rises with photon energy decrease.

Then we analyzed nanostructure transmission data for T_0 = 77 K (thick curve in figure 1 (a)) using previously obtained data on $n_S(\hbar\omega)$ and $r_S(\hbar\omega)$ for this temperature. We took into account that V_S(77 K) ≈ 1 in the spectral range $\hbar\omega < 30$ meV. The resulting data on 2D electron absorption at T_0 = 77 K are presented in figure 3 by the dashed blue line. One can see that 2D electron absorption decreases with temperature decrease from 300 to 77 K. In accordance with the Drude model, it can be explained by the increase of 2D electron mobility under sample cooling. Nevertheless, 2D absorption is rather significant for photon energies $\hbar\omega < 20$ meV.

By means of the same experimental technique, the optical reflection of the nanostructure was studied as well. Reflectivity measurements were carried out under oblique incidence of a radiation beam at an angle $\theta = 11°$. An aluminum mirror was used as a reflectivity reference. The reflectivity spectrum of the nanostructure at room temperature is shown in figure 4. For comparison, the spectrum of the sapphire substrate is also presented.

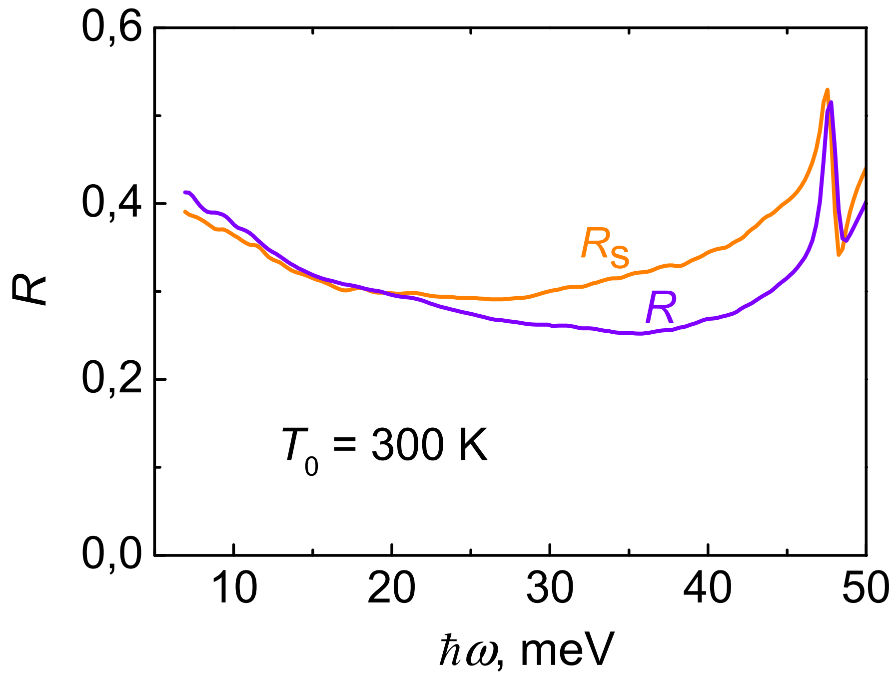

Figure 4. Optical reflectivity spectra of the GaN/AlGaN nanostructure (R) and sapphire substrate (R_S) at room temperature.

Both spectral curves demonstrate a sharp reflection maximum at the photon energy of 47.5 meV which is a fingerprint of the low-frequency phonon resonance in sapphire [8]. At lower photon energies, the both spectra represent non-monotonic dependencies with a minimum. Increase of the reflectivity at the lowest photon energies is caused by multiple reflections inside the sample which arise when the sample becomes partially transparent. It is clearly seen from comparison of figure 4 and figure 1. It should be emphasized that an arbitrary increase of the reflectivity at the long-wavelength edge of the spectrum for the nanostructure is significantly larger than for the sapphire substrate. This feature indicates a substantial contribution of 2D electrons to the reflectivity of the nanostructure.

Applying lateral electric field to the GaN/AlGaN nanostructure, we heated 2DEG and studied emission of THz radiation. The sample under investigation was placed into an optical closed cycle cryostat and cooled to the temperature of about 9 K. The voltage pulses with a duration of about 1 μs and a repetition frequency of 77 Hz were applied via the sample contacts. The THz radiation was collected in the direction perpendicular to the sample surface within the angular aperture of 16°. The emission spectra were investigated using a Fourier spectrometer operating in a step-scan mode. A liquid-helium-cooled silicon bolometer was used as a detector. The signal from the detector was measured at the frequency of 77 Hz by means of a lock-in amplifier.

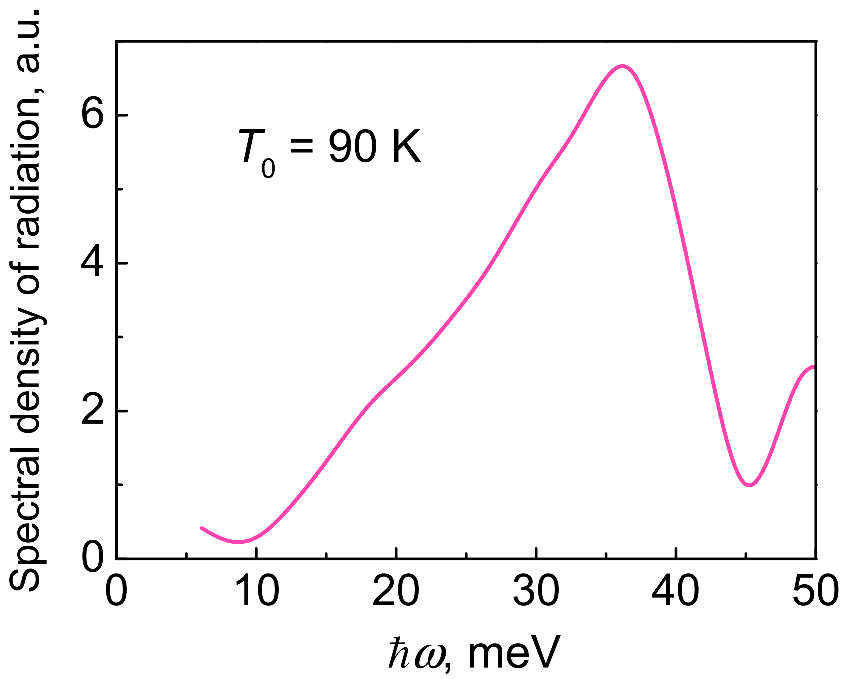

Figure 5. Spectrum of THz radiation emission from the GaN/AlGaN nanostructure under 2D electron heating in electric field. Electric field E = 1000 V/cm. The effective temperature of hot electrons $T_e \sim 280$ K.

Before the emission study, a study of the current-voltage characteristics was performed. Electrical measurements were carried out at different sample temperatures (T_0 = 4.2–300 K) in a wide range of electric fields (E = 30–3000 V/cm). Single voltage pulses of different duration (1–4 μs) were applied. The field dependencies of the 2D electron mobility at different values of T_0 have been determined. On the basis of these dependencies, the effective temperature of hot 2D electrons T_e has been found as a function of two parameters: T_0 and E (by the method described in [5]). The THz emission was investigated under rather high heating electric field (E = 1000 V/cm). It should be noted that due to periodic sample excitation, the stationary value of the time-averaged sample temperature T_0 was about 90 K (much higher than the initial value of 9 K). During the voltage pulse we observed 2D electron heating up to $T_e \sim 280$ K. The amplitude of the electron temperature modulation $\Delta T_e \sim 190$ K was determined with the help of the above mentioned dependence $T_e(T_0, E)$. It was found that the temperature of the sapphire substrate is also slightly modulated with a frequency of 77 Hz.

From the measured spectrum of the photoresponse signal, we restored the spectral density of THz radiation from the nanostructure as a function of photon energy (figure 5). The presented curve is obtained taking into account the spectra of the bolometer detectivity and optical path transmission. As far as we know, this is the first experimental result on the spectral dependence of THz emission from a GaN/AlGaN nanostructure under 2D electron heating. The preliminary analysis of the THz emission spectrum shows that in addition to THz emission by hot 2D electrons which we are interested in, there is some contribution caused by a weak temperature modulation of the sapphire substrate.

4. Conclusions

We have investigated optical properties of the GaN/AlGaN nanostructure with 2D electron gas. The measurements of the transmittivity, reflectivity and spectral density of THz radiation emission have been performed in the spectral range of 8–47 meV. For comparison, the transmittivity and reflectivity spectra have been measured for the sapphire substrate as well. The contribution of 2D electrons to the optical absorption has been determined. At a temperature of 77 K, it is significant in the spectral range $\hbar\omega < 20$ meV. At room temperature, optical absorption of 2D electrons becomes observable also at higher photon energies ($\hbar\omega \sim 30$ meV). THz radiation emission has been investigated under conditions of 2DEG heating by lateral electric field. The spectrum of THz radiation emission from the GaN/AlGaN nanostructure under 2D electron heating has been experimentally determined for the first time.

The results of our studies can be applied for the development of portable sources of THz radiation operating under electric pumping, in particular in the field of THz plasmonics.

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