Optical phenomena associated with surface plasmon polaritons in GaN-based microstructures

D S Mostovoy, G A Melentyev, V A Shalygin, M D Moldavskaya and L E Vorobjev
St. Petersburg State Polytechnical University, 29 Polytechnicheskaya Street, St. Petersburg 195251, Russia
E-mail: denmostovoy@mail.ru

Abstract. Surface plasmon polaritons in $n$-GaN are investigated. Experiments on optical reflection demonstrate the possibility of surface plasmon polariton excitation on the surface of the grating structure using terahertz radiation. Study of terahertz radiation emission under lateral electric field shows that the scattering of hot surface plasmon polaritons on the grating makes a significant contribution to the radiation intensity. In the certain spectral range this emission mechanism prevails.

1. Introduction
One of the most promising materials for terahertz (THz) emitters is gallium nitride. Emission of THz radiation has been observed in various micro- and nanostructures based on GaN. THz radiation emission due to intracenter optical transitions was studied in lightly doped $n$-GaN epitaxial layers [1]. Thermal radiation of the hot electrons in the THz range was investigated in single heterojunction AlGaN/GaN [2]. THz emission due to plasmon excitation was observed in GaN/AlGaN HEMT structures with submicron gate length [3]. It is promising to obtain THz radiation emission by means of surface plasmon polaritons (SPP). In [4] the emission of THz radiation was detected in degenerate $n$-InN epitaxial layers with the random grating formed by topographical defects. It was shown that the observed radiation is due SPP scattering on the epilayer inhomogeneities. A similar mechanism is anticipated for intentionally formed grating.

In the present paper, the optical phenomena in heavily doped $n$-GaN epitaxial layers with a regular grating formed on their surface has been studied. The main goal of the study is to reveal the effects associated with the scattering of the SPP on the regular grating.

2. Experimental details
GaN epitaxial layers with a different concentration of Si donors ($5 \times 10^{18}$ and $3.6 \times 10^{19}$ cm$^{-3}$) were investigated. As is well known, at such high doping level an impurity band is formed in GaN:Si epitaxial layers [5]. That is why free electrons are not frozen under samples cooling from room to helium temperature and their concentration is constant and equal to the donor concentration. The epilayer thickness $d$ was in the range from 6 to 10 $\mu$m. The diffraction grating on the surface of epitaxial layers was fabricated by means of photolithography and had a period of 86 $\mu$m. The grating depth $H$ varied from 2 to 4.5 $\mu$m. The reference samples with a flat semiconductor/air interface were also fabricated and investigated.
The reflection spectra were studied at room temperature using Fourier spectrometer and pyroelectric detector. Globar was used as radiation source, the incidence angle $\theta$ was about 11°, and the plane of incidence was perpendicular to the grooves of the grating. The spectra were recorded for $p$- and $s$-polarized radiation.

Under applying lateral electric field, the THz radiation emission from the sample has been observed. Pulsed voltage was applied to the samples. The pulse duration and repetition frequency were about 2.5 $\mu$s and 87 Hz, respectively. Spectral studies of the emitted radiation were performed at a temperature of 12 K using Fourier spectrometer. A silicon bolometer was used as a detector. The THz radiation was collected in the direction perpendicular to the sample surface ($\theta = 0^\circ$).

The field dependence of the integral intensity of the THz luminescence was measured at $T = 4.2$ K. Measurements were carried out also in a pulse regime (with pulse duration of 2 $\mu$s and repetition frequency less 1 Hz). By means of a Ge:Ga detector, the radiation was detected at $\theta = 0^\circ$ in the spectral range from 2.2 to 7 THz.

### 3. Results and discussion

It should be emphasized that we investigate co-called “non-radiative” mode of surface plasmon polaritons. At any frequency, the wave vector of such mode is larger than the wave vector of light in vacuum $k_0 = \omega/c$. The dispersion law for SPP at the plane interface between two semi-infinite mediums can be described by following expression [6]:

$$k_{\text{SPP}}(\omega) = \text{Re} \left( k_0 \frac{\varepsilon_1(\omega)\varepsilon_2(\omega)}{\varepsilon_1(\omega) + \varepsilon_2(\omega)} \right),$$

where $\omega$ is angular frequency, $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ are permittivities of two semi-infinite mediums. In our case we assume that $\varepsilon_1(\omega)$ is permittivity of heavily doped $n$-GaN and consider the spectral range where $\text{Re}(\varepsilon_1(\omega))$ is negative. The permittivity of vacuum $\varepsilon_2 = 1$. In the samples with grating, SPP with a certain frequency can be excited with the help of THz radiation with the same frequency if the following phase-matching condition for SPP and photons is satisfied [7]:

$$k_{\text{SPP}} = k_0 \sin \theta + m \frac{2\pi}{a}, \quad m = \pm 1, \pm 2, \pm 3, \ldots ,$$

where $\theta$ is angle of radiation incidence, $a$ is grating period.

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**Figure 1.** The reflectance spectra for $p$- and $s$-polarized radiation (solid and dashed lines, respectively). The epilayer thickness $d$ is 6 $\mu$m, grating depth $H$ is 4.5 $\mu$m, concentration of free electrons is $3.6 \cdot 10^{19}$ cm$^{-3}$, incidence angle $\theta$ is 11°. The arrows denote expected dip positions in accordance with equation 2.
Experimental reflection spectra for two linear polarizations are presented in figure 1. One can see a few dips on the reflection spectrum for \( p \)-polarization. The reflection spectrum for \( s \)-polarization demonstrates no dips. The observed polarization dependence of the reflectance indicates that the dips can be associated with the excitation of the SPP, as the latter are electromagnetic waves of \( TM \)-type. According to the simulation, the spectral positions of the dips correspond to the phase-matching condition for the SPP and photons (2). The features of the reflection spectrum for \( p \)-polarization proves SPP initiation under THz irradiation of the samples.

THz emission was detected in the samples under lateral electric field. We associate the microscopic origin of the emission with a deviation of the electron and SPP ensembles from equilibrium. We measured experimentally a spectral radiation density and compared its spectrum for the sample with grating, \( I(H) \), with one for the reference sample without grating, \( I(0) \). The both samples had the same free electron concentration (5 \( \cdot \) 10\(^{18} \) cm\(^{-3} \)). As it was found earlier, the THz radiation emission in the reference sample is related to the blackbody-like radiation emission from hot electrons, similar to [2]. It has been found that the ratio \( I(H)/I(0) \) (figure 2) exceeds unity in the spectral range from 8 to 41 meV and reaches about 3 around the photon energy of 11 meV. We conclude that the increase of the spectral radiation density in the sample with grating results from hot SPP scattering on the grating.

![Figure 2](image-url)

**Figure 2.** The spectral radiation density ratio for sample with grating \( I(H) \) and reference sample without grating \( I(0) \). The epilayer thickness \( d \) is 10 \( \mu m \), grating depth \( H \) is 2 \( \mu m \), concentration of free electrons is 5 \( \cdot \) 10\(^{18} \) cm\(^{-3} \), electric power is 1.4 kW, \( \theta = 0 \).

Dependence of integral intensity of the THz radiation on electric power (figure 3) demonstrates twofold increase of the THz emission from the samples with regular grating as compared with the samples without grating in the spectral range of Ge:Ga detector (2.2 – 7 THz). It also proves the significant contribution of the SPP scattering to the THz radiation emission.
4. Conclusion

Spectra of reflection, spectra of THz radiation emission and integral intensity of the THz electroluminescence were investigated in heavily doped GaN:Si epitaxial layers. Samples with grating on the surface of the epitaxial layers were studied. Reference samples with a flat surface were studied as well.

Experiments on optical reflection demonstrate the possibility of surface plasmon polariton excitation on the surface of the grating structure using terahertz radiation. Spectral study of terahertz radiation emission under lateral electric field shows that the scattering of hot surface plasmon polaritons on the grating makes a significant contribution to the radiation intensity. Investigation of integral intensity of the THz electroluminescence demonstrates twofold increase of THz emission in the samples with grating as compared with the samples without grating (in the spectral range from 2.2 to 7 THz). This proves feasibility of THz emitter based on hot surface plasmon polaritons.

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