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Terahertz reflection and emission associated with nonequilibrium surface plasmon polaritons in *n*-GaN

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Abstract. Surface plasmon polaritons are investigated in heavily doped *n*-GaN epitaxial layers. The grating etched on the surface of the epitaxial layer is used to convert photons into the surface plasmon polaritons and vice versa. The spectral study of reflection demonstrates the possibility of nonequilibrium surface plasmon polaritons excitation due to terahertz radiation scattering on the grating. Terahertz electroluminescence is investigated under lateral electric field. The luminescence spectrum demonstrates a significant contribution of nonequilibrium surface plasmon polariton scattering to terahertz radiation emission.

1. Introduction

Plasmonics provides ample opportunities for a variety of highly significant applications in modern science and technology. Signal processing components, emitters and detectors for modern photonics, subwavelength-sized elements for chemical and biological sensing with extremely high sensitivity (up to single molecular sensing), effective photovoltaic devices and solar cells are developed on the base of plasmonics [1–6]. The distinctive objects in plasmonics are surface plasmon polaritons (SPP). They represent electromagnetic excitations propagating at the interface between a conductor and a dielectric, evanescently confined in the perpendicular direction. These electromagnetic surface waves arise via the coupling of the electromagnetic fields to oscillations of the free carrier density in the conductor. Coupling of photons to charge carriers at conductor interfaces allows subdiffraction-limit localization of electromagnetic radiation and strong field enhancement. This high field localization occurs as long as the fields oscillate at frequencies close to the intrinsic plasma frequency of the conductor [1]. Many plasmonic phenomena are studied on metals such as gold, silver, or aluminium, and in such a case resonant plasma oscillations are in the visible spectral range. The modern trend in the field of plasmonics is mid infrared (mid-IR) and terahertz (THz) plasmonics which deals with heavily doped semiconductors instead of metals [5, 7]. In semiconductors the frequency of SPP can be tuned down to THz range by doping level.

One of the first experimental studies of SPP in mid-IR range was performed on *n*-InSb samples with a grating at their surface [8]. The sharp dips associated with SPP excitation were experimentally observed in the reflectivity spectra. The terahertz emission mediated by surface plasmon polaritons in doped semiconductors with regular surface grating was theoretically predicted in [9]. To the best of



our knowledge, this phenomenon was not experimentally observed so far. On the other hand, THz electroluminescence was investigated in degenerate n -InN epitaxial layers with a *random* grating formed by topographical defects [10]. It was shown that the observed THz radiation emission can be attributed to SPP scattering on the random grating. A similar mechanism of THz electroluminescence is anticipated in heavily doped semiconductors with a *regular* surface grating.

The goal of the present paper is to study the optical phenomena associated with nonequilibrium SPP in heavily doped GaN-based microstructures. Reflection investigation demonstrates excitation of SPP under THz irradiation of samples with a regular surface grating. Investigation of THz electroluminescence demonstrates excitation of SPP under lateral electric field which is accompanied by an impressive increase of radiation intensity in the grating samples.

2. Experimental details

Gallium nitride epitaxial layers were grown on sapphire substrate by MOVPE. The thickness d of epilayers was $6.2\ \mu\text{m}$. We studied samples doped by Si with the electron concentration of $3.6 \cdot 10^{19}\ \text{cm}^{-3}$ and the mobility of $122\ \text{cm}^2/\text{V}\cdot\text{s}$ (at room temperature). It is known that such heavily doped GaN layers demonstrate formation of an impurity band and its overlapping with the conduction band [11]. That is why the free electron concentration is constant in the range from helium to room temperature. A grating with a period of $\Lambda = 86\ \mu\text{m}$ was etched on the surface of epitaxial layer. The etch depth was $h = 4.5\ \mu\text{m}$. The ratio of groove width a to grating period Λ was 1 : 2. The design of the sample with a regular surface grating is shown in figure 1. The reference sample without a grating on GaN/air interface was additionally studied.

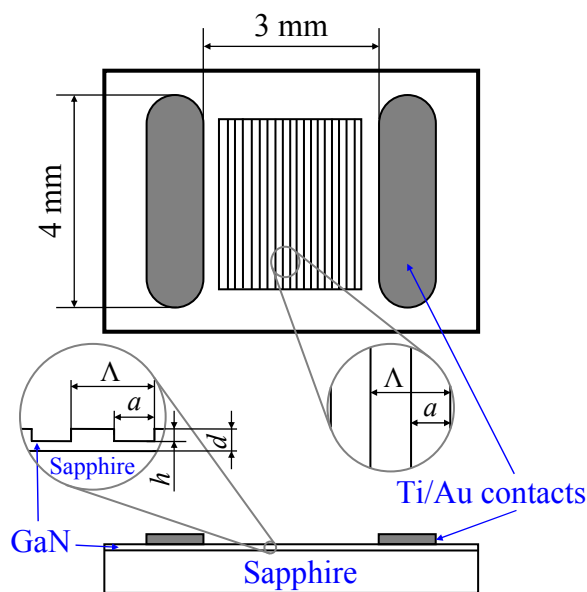


Figure 1. Design of the sample with a regular surface grating. The period of the grating Λ is $86\ \mu\text{m}$, the groove width a is $43\ \mu\text{m}$, the etch depth h is $4.5\ \mu\text{m}$, the thickness of epitaxial layer d is $6.2\ \mu\text{m}$.

The reflectivity spectra were investigated at room temperature using a Fourier spectrometer operating in a rapid-scan mode and a pyroelectric detector. The globar and the mercury lamp were used as sources of THz radiation. The incidence angle θ was about 11° , and the incidence plane was perpendicular to the grooves of the grating. The spectra were recorded for p - and s -polarized radiation. The experimental setup for reflection study is shown in figure 2.

Emission of THz radiation from the sample has been observed under applying lateral electric field. Measurements were made in a pulsed regime. The voltage pulses with duration of $2\ \mu\text{s}$ and repetition frequency of about $87\ \text{Hz}$ were applied. The spectral studies of the emitted radiation were carried out at the temperature of $9\ \text{K}$ using a Fourier spectrometer operating in a step-scan mode. A silicon

bolometer was used as a detector. The THz radiation was collected in the direction perpendicular to the sample surface, the angular aperture was $\Delta\theta \approx 16^\circ$.

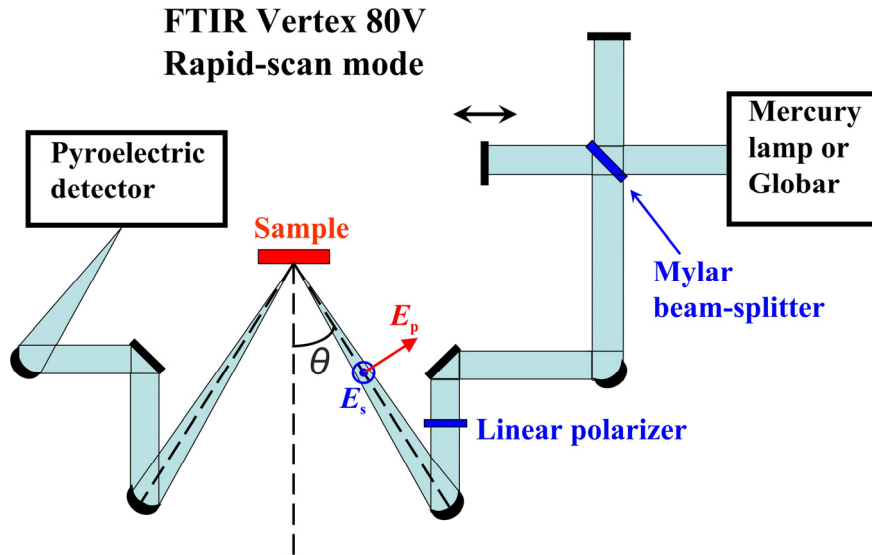


Figure 2. The experimental setup for reflection studies.

3. Results and discussion

Let us consider the surface plasmon polaritons at plane interface between two semi-infinite mediums: heavily doped *n*-GaN (conductor) and vacuum (dielectric). The dispersion law for these SPP can be described by the following expression [1]:

$$k_{\text{SPP}}(\omega) = \frac{\omega}{c} \text{Re} \left(\sqrt{\frac{\varepsilon_1(\omega)\varepsilon_2(\omega)}{\varepsilon_1(\omega) + \varepsilon_2(\omega)}} \right), \quad (1)$$

where k_{SPP} is wave vector of SPP, ω is angular frequency, $\varepsilon_1(\omega)$ is permittivity of *n*-GaN, $\varepsilon_2 = 1$ is permittivity of vacuum. The depth of SPP field decay (in GaN in the direction perpendicular to the interface) estimated in accordance with [1] does not exceed $2 \mu\text{m}$ (at the frequency more than 1 THz). This value of decay depth is less than the thickness of the studied epitaxial layer. The latter is $3.95 \mu\text{m}$ for the sample with a regular grating and $6.2 \mu\text{m}$ for the reference sample. Due to this the relationship expression (1) can be used for the description of SPP in the epitaxial layers considered.

In our experiments we deal with a “non-radiative” mode of surface plasmon polaritons for which k_{SPP} is larger than the wave vector of THz photon at the same frequency. Nevertheless, SPP can produce THz photons under scattering on the regular grating. To achieve this, two conditions must be satisfied. Firstly, the energy of a THz photon must be equal to the energy of SPP (the energy conservation law):

$$\hbar\omega_{\text{THz}} = \hbar\omega_{\text{SPP}} \equiv \hbar\omega, \quad (2)$$

where ω denotes the joint angular frequency of the both quasiparticles. Secondly, phase-matching condition for SPP and photons must be fulfilled [1]:

$$k_{\text{SPP}} = k_0 \sin \theta + m \frac{2\pi}{\Lambda}, \quad m = \pm 1, \pm 2, \pm 3, \dots, \quad (3)$$

where $k_0 = \omega/c$ is wave vector of a THz photon, θ is angle of radiation incidence, $2\pi/\Lambda$ is the reciprocal vector of the grating, Λ is grating period. Relation (3) is equivalent to the momentum conservation law.

If we consider backward transformation of the THz photon into the surface plasmon polariton, again the both conditions (2) and (3) must be satisfied. This process can take place under THz radiation reflection from the sample with a grating. The reflectivity decrease is expected at certain THz photon energies.

Let us first analyze the experimental results on reflection. We have measured the reflectivity spectra outside the GaN reststrahlen band at the photon energies $\hbar\omega < \hbar\omega_{\text{TO}}$, where $\hbar\omega_{\text{TO}} = 69.3$ meV [12] is the energy of the transverse optical phonon in wurtzite GaN (E_1 symmetry). The experimental spectra for two linear polarizations are presented in figure 3. The reflectivity spectrum for p -polarization demonstrates a set of dips, whereas the s -polarization spectrum does not demonstrate them. It should be noted that the SPP is the TM -type electromagnetic wave, so in our experimental conditions (see figure 2, the incidence plane is perpendicular to the grating grooves) the surface plasmon polaritons can be excited only by p -polarized radiation. In figure 3, the arrows denote the positions where the energy conservation law (2) and the phase-matching condition (3) at the angle of 11° for an incident photon and SPP are realized. One can see a good correlation between theoretically expected positions of the reflectivity dips and experimentally observed ones. Thus the polarization peculiarities of reflection prove the excitation of nonequilibrium surface plasmon polaritons by the incident THz radiation.

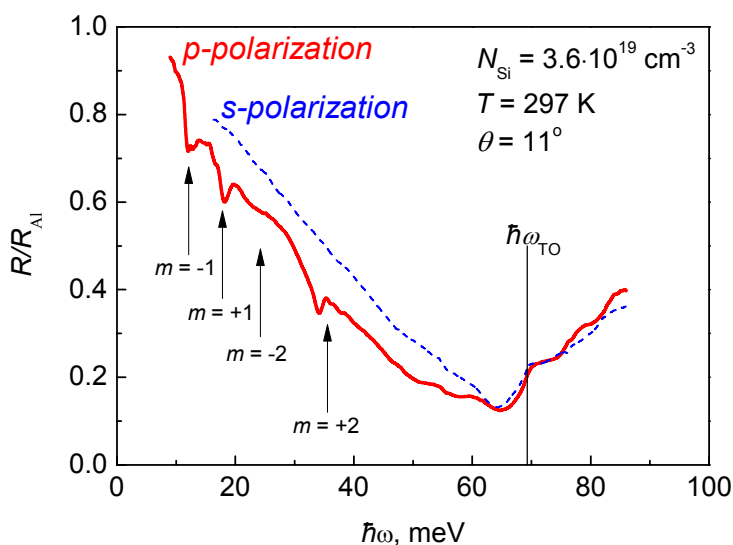


Figure 3. Reflectivity spectra of the epitaxial layer GaN with a grating normalized to an aluminum mirror. Solid (dashed) line demonstrates the experimental results for p -polarization (s -polarization). The arrows denote the positions where the energy conservation law (2) and the phase-matching condition (3) at the angle of 11° for an incident photon and SPP are satisfied.

The emission of terahertz radiation was investigated in GaN epilayers under applying lateral electric field. The microscopic origin of the THz emission is associated with field-induced deviation of the electron and SPP ensembles from the equilibrium distribution. THz emission associated with two dimensional (2D) plasmons was experimentally observed in Si MOSFETs and AlGaAs/GaAs heterointerfaces [13–15]. We investigated the spectral radiation density for n -GaN epitaxial layer with a grating $D_\omega(h)$ and the reference sample without a grating $D_\omega(0)$. Samples had the same concentrations of free electrons. In the samples without a grating the observed terahertz radiation is related to the blackbody-like radiation emission from hot electrons. We have previously studied this phenomenon in GaN-based nanostructures [16]. The spectral density of THz emission from the grating sample $D_\omega(h)$ normalized to the sample without a grating under dissipated electric power 1500 W is displayed in figure 4. This dependence demonstrates sequence of peaks. The arrows denote the positions where the energy conservation law (2) and the phase-matching condition (3) at the angle $\theta = 0^\circ$ for an emitted THz photon and SPP are fulfilled. The arrows are close to the observed THz

emission peaks. The dispersion dependence for surface plasmon polaritons calculated according to (1) is demonstrated in figure 5. Gray fill indicates energy ranges (and corresponding wave numbers) of the SPP where conditions (2) and (3) are satisfied for the angular range of $-8^\circ \leq \theta \leq +8^\circ$. In these energy ranges THz photon emission due to nonequilibrium SPP scattering on the grating can be observed. As it is seen from figure 5, an increase of the factor m in (3) is accompanied by an extension of energy range where THz photons can be emitted. The experimental data on the ratio $D_\omega(h)/D_\omega(0)$ shown in figure 4 are consistent with the theoretical calculation displayed in figure 5. In particular, the experimentally observed radiation linewidths are less or equal to the calculated values, with increase of m the radiation linewidths increases. All the above-mentioned results confirm that THz emission is associated with the scattering of nonequilibrium surface plasmon polaritons on a grating.

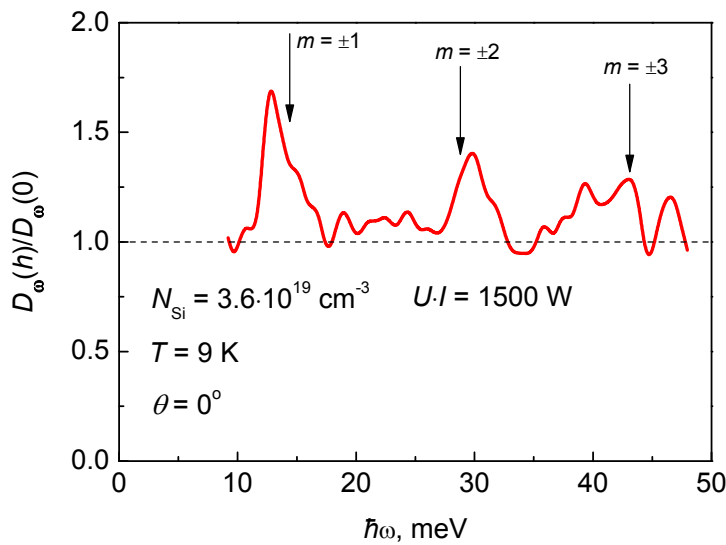


Figure 4. The spectral radiation density ratio for the sample with a grating $D_\omega(h)$ and the reference sample without a grating $D_\omega(0)$ at the same dissipated electric power 1500 W. The arrows denote the positions where the energy conservation law (2) and the phase-matching condition (3) at the angle $\theta = 0^\circ$ for an emitted photon and SPP are satisfied.

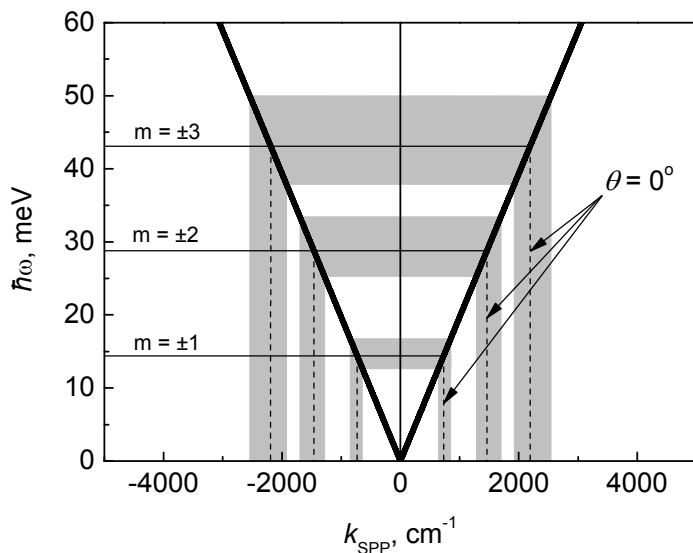


Figure 5. Dispersion dependence for surface plasmon polaritons. Gray fill indicates energy ranges (wave numbers) of the SPP where the energy conservation law (2) and the phase-matching condition (3) for an emitted photon and SPP are satisfied in the case of angular aperture $\Delta\theta = 16^\circ$ (angle $\theta = -8^\circ \dots +8^\circ$).

We obtained the good agreement between theoretical evaluations and experimental data. It proves that the expression (1) describing surface plasmon polaritons at plane interface between semi-infinite conductor and vacuum can be used adequately for the considered n -GaN/vacuum interface (thickness of a few micrometers, a regular grating on the epilayer surface).

4. Conclusions

We have investigated the reflection and electroluminescence spectra of heavily doped GaN-based microstructures. The samples with a regular grating on a surface of the microstructure, as well as with the flat surface GaN/vacuum have been studied.

The investigation of optical reflection demonstrated the possibility of nonequilibrium SPP excitation under THz radiation scattering on a surface grating. The study of electroluminescence spectra demonstrated a significant contribution of nonequilibrium SPP scattering on the grating to THz radiation emission. The good agreement between theoretical evaluations and experimental results has shown that the behavior of surface plasmon polaritons on the interface GaN/vacuum in investigated epitaxial layers can be successfully described by the expressions for the semi-infinite mediums. Our studies can be applied for the development of portable sources of THz radiation operating under electric pumping.

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