Terahertz Emission and Reflection Associated with Surface Plasmon Polaritons in *n*-GaN Microstructures

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***Abstract*—Surface plasmon polaritons at the *n*-GaN/vacuum interface are investigated. Experimental studies of terahertz radiation reflection and emission are performed on heavily silicon-doped GaN epitaxial layers grown on sapphire substrates. To provide interaction of THz radiation with the surface plasmon polaritons, a regular grating was fabricated on the outer surface of the epitaxial layer. Study of terahertz radiation emission from the microstructures under lateral electric field shows that the scattering of non-equilibrium surface plasmon polaritons on the grating makes a significant contribution to the radiation intensity.**

I. Introduction

GALLIUM nitride provides wide opportunities for development of terahertz (THz) emitters. THz electroluminescence due to intracenter optical transitions in lightly silicon-doped *n*-GaN epitaxial layers was studied [1]. THz radiation emission from free 2D electrons in single heterojunction GaN/AlGaN under conditions of their heating in lateral electric field was investigated [2]. THz emission due to plasmon excitation in GaN/AlGaN HEMT structures with submicron gate length was observed [3]. It is promising to obtain THz radiation emission by means of surface plasmon polaritons (SPP). In [4] THz electroluminescence was investigated in degenerate *n*-InN epitaxial layers with the random grating formed by topographical defects. It was shown that the observed THz radiation emission can be attributed to SPP scattering on the random grating. A similar mechanism of THz emission is anticipated for intentionally formed regular grating.

The goal of the present paper is to study the optical phenomena associated with the scattering of the SPP on the regular grating formed on the surface of heavily doped *n*-GaN epitaxial layers.

II. Results

GaN-based microstructures were grown on sapphire substrates by MOVPE. We studied GaN:Si epitaxial layers with donor concentrations $N_{\mathrm{Si}} = 5\cdot10^{18}$ and $3.6\cdot10^{19}$ cm^{-3}. At such high doping levels an impurity band is formed [1], that is why free electrons are not frozen under sample 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 µm. The diffraction grating on the surface of epitaxial layers was fabricated by means of photolithography and had a period a = 86 µm. The grating depth H varied from 2 to 4.5 µm. The reference samples with a flat GaN/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 a radiation source. Spectra were recorded at oblique incidence under angle $\theta = 11°$. The plane of incidence was perpendicular to the grooves of the grating. Experimental reflection spectra for *p*- and *s*-polarized radiation are presented in Fig. 1 for one of the samples ($N_{\mathrm{Si}} = 3.6\cdot10^{19}$ cm^{-3}, $d = 6$ µm, $H = 4.5$ µm). There are a few dips on the reflection spectrum for *p*-polarization. The reflection spectrum for *s*-polarization demonstrates no dips. Such polarization dependence of the reflectivity indicates that the dips can be associated with the excitation of SPP, as the latter are electromagnetic waves of *TM*-type. To confirm this conclusion, we performed a simulation based on the phase-matching condition for the SPP and THz photons [5]:

$$k_{SPP} = k_0 \sin\theta + m\frac{2\pi}{a}, \quad m = \pm1, \pm2, \pm3, \ldots \quad , \qquad (1)$$

where k_{SPP} and k_0 are the wavevectors of SPP and THz photon, respectively. Due to the energy conservation law, THz photon can excite SPP with the same angular frequency (we denote it as ω). Taking into account the dispersion law for THz photons in vacuum ($k_0 = \omega/c$) and dispersion law for SPP at the GaN/vacuum interface [5]:

$$k_{SPP}(\omega) = \mathrm{Re}\left(k_0\sqrt{\frac{\varepsilon(\omega)}{1+\varepsilon(\omega)}}\right), \qquad (2)$$

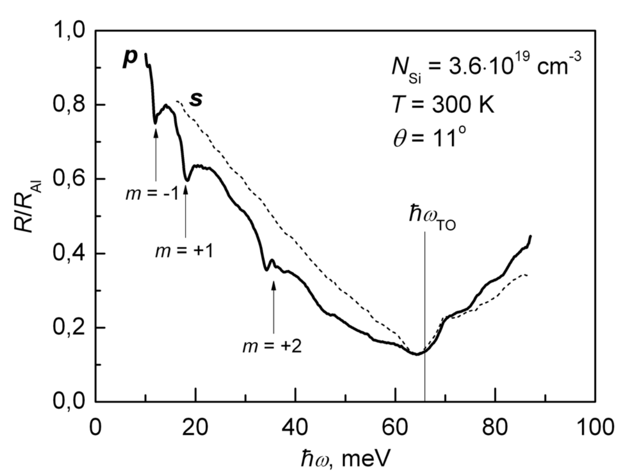

Fig. 1. Reflectivity spectra of the GaN grating structure normalized to aluminum mirror. Solid (dashed) line demonstrates experimental results for *p*-polarization (*s*-polarization). The arrows denote expected dip positions for *p*-polarized radiation in accordance with the phase-matching condition (1).

where ε(ω) is the dielectric permittivity of the GaN epitaxial layer, one can find the theoretically expected photon energies corresponding to SPP excitation. It turns out that they are very close to the positions of dips in the experimental reflectivity spectrum for *p*-polarization (see Fig.1). Hence it can be concluded that the microscopic origin of the spectrum peculiarities is related to SPP excitation.

The THz radiation emission was observed under applying pulsed lateral electric field to the samples. The THz radiation experiments were performed at cryogenic temperatures by means of Fourier spectrometer and silicon bolometer. The THz radiation was collected in the solid angle of 0.042 sr in the direction perpendicular to the sample surface. We associate the microscopic mechanism of the observed emission with a field-induced 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, $D(H)$, with one for the reference sample without grating, $D(0)$. The both samples had the same free electron concentration. 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 under electric power of 1400 W the ratio $D(H)/D(0)$ exceeds unity in the spectral range from 8 to 41 meV and reaches about 3 around the photon energy of 11 meV (Fig. 2). We conclude that the significant increase of the spectral radiation density in the sample with grating results from non-equilibrium SPP scattering on the grating.

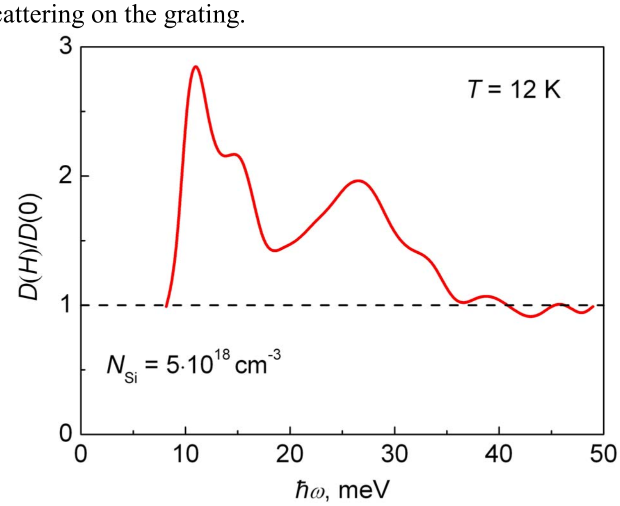

Fig. 2. Spectral radiation density for the GaN grating structure $D(H)$ normalized to spectral radiation density for the reference sample without grating $D(0)$. Measurements we performed at lateral electric field under the same dissipated power in the both samples. $d = 10$ μm, $H = 2$ μm.

A Ge:Ga photodetector was used to measure the integral intensity of THz electroluminescence in the spectral range 9–30 meV. Both the sample and photodetector were immersed in liquid helium ($T = 4.2$ K). The THz radiation was collected in the solid angle of 0.043 sr in the direction perpendicular to the sample surface. Dependence of integral intensity of the THz radiation on applied electric power (Fig. 3) demonstrates twofold increase of the THz emission from the samples with regular grating as compared with the samples without grating. It also proves the significant contribution of the SPP scattering to the THz radiation emission.

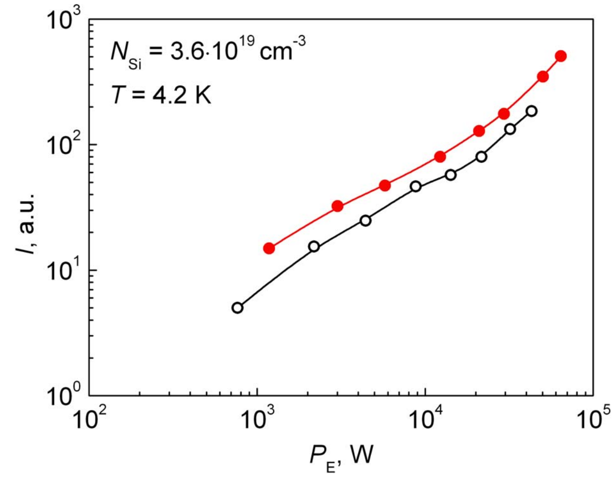

Fig. 3. Dependence of the integral intensity of THz radiation on electric power dissipated in the sample. The filled circles correspond to the GaN grating structure ($d = 6$ μm, $H = 4.5$ μm), open circles correspond to the reference sample without grating ($d = 6$ μm, $H = 0$).

III. Summary

Spectra of reflection, spectra of THz radiation emission and integral intensity of the THz electroluminescence were investigated in heavily doped GaN:Si epitaxial layers. Experiments on optical reflection demonstrate the possibility of SPP excitation on the surface of the grating structure using THz radiation. Spectral study of THz radiation emission under electric field shows that the scattering of hot SPP 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. Our findings can be applied for the creation of portable terahertz emitters.

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