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## Excitation and decay of surface plasmon polaritons in *n*-GaN

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**Abstract.** We report on the studies of the surface plasmon polaritons in *n*-GaN epitaxial layers. The grating etched on the surface of the epitaxial layer is used to excite surface plasmon polaritons by means of terahertz photons. The experimental reflectivity spectrum for *p*-polarized radiation demonstrates a set of resonances associated with excitation of different surface plasmon polariton modes. Spectral peculiarities due to the diffraction effect have been also revealed. Emission of terahertz radiation is investigated under epilayer temperature modulation by electric current. The emissivity spectrum of the epitaxial layer with surface-relief grating shows peaks in the frequency ranges corresponding to the decay of the surface plasmon polariton modes. The characteristic features of the reflectivity and emissivity spectra are well described theoretically by a differential method with explicit integration scheme.

### 1. Introduction

During recent years, there has been a growing interest in the study of surface plasmon polaritons (SPPs) which represent electromagnetic (EM) waves propagating at the interface between a dielectric and a conductor, evanescently confined in the perpendicular direction. The remarkable properties of the SPPs are widely utilized in science and technology [1]. The modern trend in the field of plasmonics is terahertz (THz) plasmonics which deals with heavily doped semiconductors [2]. The frequency selective properties of semiconductor plasmonic structures in the THz frequency range may find a number of applications, particularly, in the fields of THz biosensing and THz bioimaging. Among different kinds of the semiconductor compounds that are considered as a platform for sensor devices, gallium nitride is assumed to be one of the most favourable.

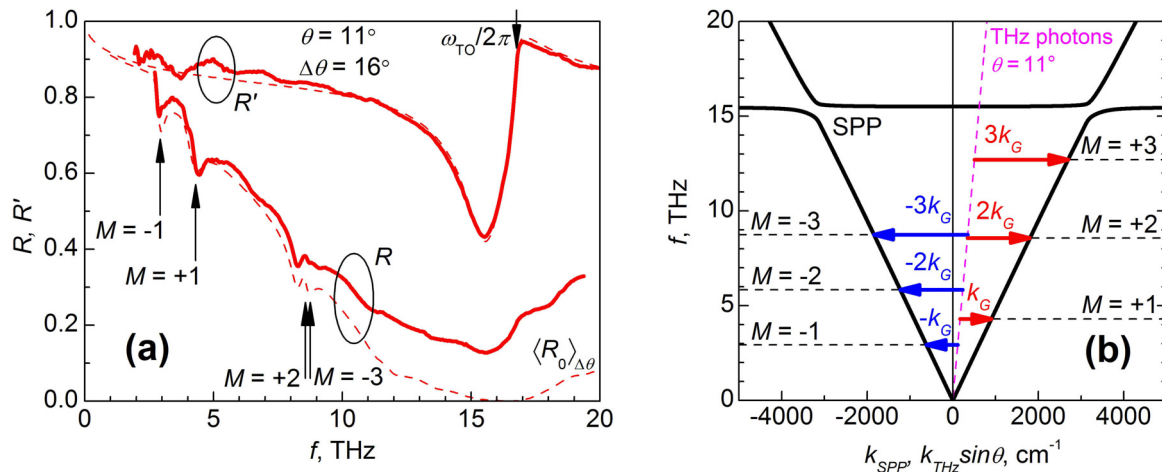
In the present paper we report on the experimental and theoretical studies of the SPPs in heavily doped GaN epitaxial layers. Reflection and emission of radiation in the frequency range of 2–20 THz including the Reststrahlen band are investigated for samples with grating etched on the sample surface, as well as for samples with planar surface. A differential method with explicit integration scheme [3] is used for theoretical interpretation of the reflectivity and emissivity spectra of the samples with profiled surface. We treat these spectra in the terms of excitation and decay of SPPs.

### 2. Results and discussion

Wurtzite GaN epitaxial layers of 6.2  $\mu\text{m}$  thickness were grown on sapphire substrate by MOVPE. The epilayers had 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. A grating with a period of  $a = 86 \mu\text{m}$  and ridge width  $w = a/2$  was etched on the surface of epilayer. The etch depth was  $4.5 \mu\text{m}$ . The reference samples without grating were studied as well. In some experiments, the epilayer temperature was modulated by pulsed electric current.



**Figure 1.** (a) Reflectivity spectra for  $p$ -polarized radiation for the samples with a surface-relief grating ( $R$ ) and with a planar surface ( $R'$ ). Experimental data are shown by solid lines, the results of theoretical simulation are depicted by dashed lines. (b) Dispersion dependences for surface plasmon polaritons (solid line) and THz photons at  $\theta = 11^\circ$  (dashed line). Horizontal dashed lines show spectral positions of the SPP resonances of different orders  $M$ .

The THz reflectivity spectra were investigated at room temperature using a Fourier spectrometer. The incident radiation beam had an angular aperture of  $\Delta\theta = 16^\circ$ . The axis of the beam formed the angle  $\theta = 11^\circ$  with the normal to the sample surface. The plane of incidence was perpendicular to the ridges of grating. Experimental reflectivity spectra for  $p$ -polarized radiation are plotted in figure 1(a). It should be emphasized that spectra for the grating and planar samples differ drastically.

For the planar sample, the recorded reflectivity spectrum (solid curve  $R'$ ) has two distinctive behaviors depending on the ratio between the contribution of electron and phonon subsystems to the complex permittivity. Theoretical simulation of the reflectivity taking into account the both contributions (dashed curve  $R'$ ) adequately describes the experimental data. In the lower frequency range ( $f < 10$  THz), the electron contribution dominates resulting in weak frequency dependence of the reflectivity. The strong frequency dependence of the reflectivity is observed in the spectral range of 14–20 THz where the contribution of the phonon subsystem dominates over electrons (Reststrahlen band). The significant decrease of the reflectivity corresponds to the low-frequency plasmon-phonon mode located closely to  $\omega_{\text{TO}}/2\pi$ . Note that the real part of the permittivity is negative at  $f < 15$  THz, thus in this spectral range the necessary condition for SPP propagation is satisfied.

For the grating sample, experiment demonstrates a significant decrease of the reflectivity (solid curve  $R$  in figure 1(a)) in the whole examined spectral range (2–20 THz). Firstly, one can see a sequence of sharp dips. They arise for  $p$ -polarized radiation only and we attribute them to an excitation of SPPs. Actually, it is known that only radiation having a component of electric field perpendicular to the grating ridges can excite surface waves. This causes dissipation of the radiation energy and is seen as a decrease of reflectivity. The excitation of SPPs has a resonant behavior, and the resonant frequencies can be found using the phase-matching condition [1]

$$k_{\text{SPP}} = k_{\text{THz}} \sin \theta + Mk_G, \quad M = \pm 1, \pm 2, \pm 3, \dots \quad (1)$$

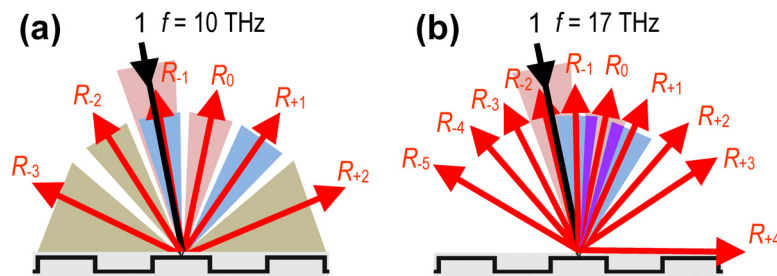
and the SPP dispersion law for the epilayer/vacuum interface [1]

$$k_{\text{SPP}}^2 = \left( \frac{\omega}{c} \right)^2 \frac{\varepsilon_c(\omega)}{\varepsilon_c(\omega) + 1}, \quad (2)$$

where  $k_{\text{SPP}}$  and  $k_{\text{THz}}$  are the wave vectors of SPP and THz photon,  $\omega$  is angular frequency,  $k_G = 2\pi/a$ ,  $\varepsilon_c(\omega)$  is the permittivity of the conducting epilayer. The integer numbers  $M$  correspond to different modes of the SPP resonances (figure 1(b)). The second feature of the grating sample reflection ( $R$ ) is the collapse of the Reststrahlen band that is well pronounced for the planar sample ( $R'$ ).

We performed theoretical calculations of the grating sample reflectivity using the model and differential method with explicit integration scheme described in [3]. Simulated reflectivity of the zero diffraction order ( $m = 0$ ) is shown in figure 1(a) by dashed curve  $\langle R_0 \rangle_{\Delta\theta}$  (angle brackets denote averaging over  $\Delta\theta$ ). Simulated spectrum matches well with the experimental spectrum in the spectral range of 0–10 THz. The frequencies, amplitudes, and widths of the resonance dips in the simulated and experimental spectra are close to each other. The SPP resonances are clearly seen at frequencies of 2.9, 4.4, 8.3 and 8.7 THz. According figure 1(b), we identified that these frequencies correspond to the SPP resonances of orders  $M = -1, +1, +2, -3$ , respectively.

A deviation between the simulated and observed reflectivity spectra arises at higher frequencies ( $f > 10$  THz). This discrepancy is due to the diffraction phenomenon. Indeed, together with the excitation of SPP modes, the surface grating splits the incident beam into several reflected beams propagating within different solid angles. The angles between the zero order ( $R_0$ ) and higher order ( $R_m$ ,  $m \neq 0$ ) diffraction beams decrease with increasing frequency (see figure 2). Consequently, in the high frequency range, the angular aperture of detection system (in our case  $\Delta\theta = 16^\circ$ ) can partially catch the beams of higher diffraction orders. The estimates show that the beams of the  $\pm 1$ st diffraction orders are partially overlap with the zero-order reflected beam at  $f > 10$  THz (see figure 2(b)). That is why the observed reflectivity exceeds the simulated reflectivity of the zero diffraction order  $\langle R_0 \rangle_{\Delta\theta}$  in this spectral range.

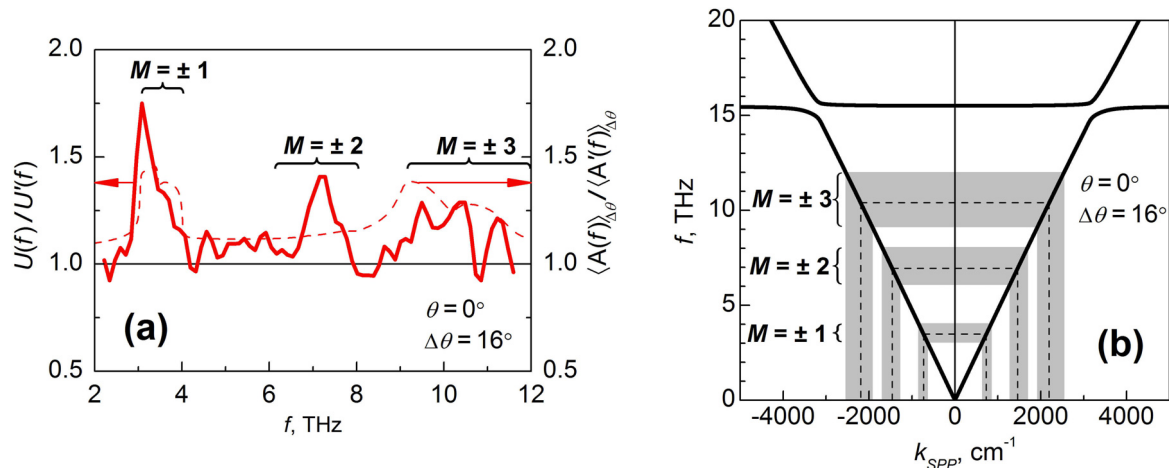


**Figure 2.** Reflected beams  $R_m$  of the different diffraction orders  $m$  for two frequencies of the incident radiation:  $f = 10$  THz (a) and 17 THz (b). Arrow “1” denotes the direction of the incident beam ( $\theta = 11^\circ$ ). Colored sectors show the angular apertures of the reflected beams corresponding to the angular aperture of incident beam  $\Delta\theta = 16^\circ$ .

Emission of THz radiation from the samples was measured under epilayer temperature modulation by the pulsed electric current. The spectral studies of the emitted radiation were carried out under sample cooled down to 9 K using a Fourier spectrometer operating in a step-scan mode. The THz radiation was collected in the direction perpendicular to the sample surface, the angular aperture was  $\Delta\theta \approx 16^\circ$ . A silicon bolometer was used as a detector.

To clarify the distinctive emission properties related to SPPs, we measured spectral dependencies of the detector photoresponse for the grating and planar sample, denoted as  $U$  and  $U'$ , respectively. The same electric power of 1500 W was applied to the sample in both cases providing Joule heating of the epitaxial layer up to  $\sim 100$  K. The experimental results on THz emission from the grating and

planar samples are presented in figure 3(a) by thick line which shows the ratio  $U(f)/U'(f)$ . Three peaks of THz emission in spectral intervals corresponding to the phase matching condition for SPPs and THz photons for  $M = \pm 1, \pm 2$  and  $\pm 3$  (see figure 3(b)) were detected in the grating sample. Therefore, one



**Figure 3.** (a) Emissivity spectra of the grating sample normalized to the planar epitaxial layer. Solid line represents experimental data on the photoresponse ratio at applied electric power of 1500 W, dashed line shows the results of theoretical simulation. (b) Spectral intervals corresponding to the plasmonic resonances of different orders  $M$  (simulation at  $\theta = 0^\circ$ ,  $\Delta\theta = 16^\circ$ ).

can conclude that the characteristic emission peaks originate from the radiative decay of SPP excitations. In the framework of the model of blackbody-like radiation [3], this ratio is expected to be equal to the ratio  $\langle A(f) \rangle_{\Delta\theta} / \langle A'(f) \rangle_{\Delta\theta}$ , where  $A$  and  $A'$  are the simulated absorptivities of the grating and planar samples, respectively. Indeed, the calculated curve (dashed line in figure 3(a)) describes qualitatively the major features of the experimental spectrum. In particular, the calculated positions and widths of the SPP peaks for  $M = \pm 1$  and  $\pm 3$  are very close to the experimentally measured. We associate a mismatch between theory and experiment for the second-order SPPs ( $M = \pm 2$ ) with the certain restrictions of the considered theoretical model.

### 3. Conclusions

The experimental and theoretical results of this work provide insights for the development of GaN-based devices aimed to absorb/emit terahertz radiation selectively. In particular, our studies can be applied for the development of portable sources of THz radiation operating under electric pumping. The effects of essential light absorption in a narrow spectral and angular intervals analyzed above can find applications in chemical and bio-chemical surface plasmon grating detectors working in THz frequency range.

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