Experimental study of surface plasmon-phonon polaritons in GaAs-based microstructures

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Abstract. Optical properties of a heavily-doped GaAs epitaxial layer with a regular grating at its surface have been experimentally investigated in the terahertz spectral range. Reflectivity spectra for the layer with a profiled surface drastically differ from those for the as-grown epilayer with a planar surface. For s-polarized radiation, this difference is totally caused by the electromagnetic wave diffraction at the grating. For p-polarized radiation, additional resonant dips arise due to excitation of surface plasmon-phonon polaritons. Terahertz radiation emission under significant electron heating in an applied pulsed electric field has also been studied. Polarization measurements revealed pronounced peaks related to surface plasmon-phonon polariton resonances of the first and second order in the emission spectra.

1. Introduction

One of the most promising phenomena in plasmonics is the surface electromagnetic waves at a semiconductor/dielectric interface. There are three types of such waves: surface plasmon polaritons (SPP), surface phonon polaritons (SPhP) and surface plasmon-phonon polaritons (SPPhP) [1]. In the particular case of the semiconductor/vacuum interface, the surface waves can occur only in the spectral ranges where the dielectric permittivity of semiconductor $\varepsilon$ satisfies the condition Re($\varepsilon$) $<$ −1 [2]. A possible type of the surface wave in a polar semiconductor is determined by the relation between the plasma frequency $\omega_p = \frac{4\pi e^2 N_e}{\varepsilon m_e}$ (here $N_e$ and $m_e$ are the concentration and the effective mass of free electrons, respectively, $e$ is the elementary charge, $\varepsilon_m$ is the high-frequency permittivity) and the frequency of transverse optical phonons $\omega_{TO}$. In semiconductors with a low doping level (when $\omega_p < \omega_{TO}$), one can observe “pure” SPP and SPhP, the former being in the spectral range $0 < \omega < \omega_p$ and the latter in the range $\omega_{TO} < \omega < \omega_{LO}$, where $\omega_{LO}$ denotes the frequency of longitudinal optical phonons. In heavily-doped semiconductors (when $\omega_p > \omega_{TO}$), surface waves represent mixed plasmon-phonon modes on the semiconductor surface, which are referred to here as SPPhP. These types of surface waves can be observed in a wide spectral range from...
0 to $\omega_+$, excluding a narrow interval around the point $\omega_-$, where $\omega_+$ and $\omega_-$ denote the frequencies of the mixed plasmon-phonon modes in a bulk semiconductor [3].

The direct excitation of the SPPhP by external electromagnetic radiation at the planar semiconductor/vacuum interface is impossible. The excitation becomes possible when spatial inhomogeneity is introduced at the interface. For instance, the surface-relief grating can allow coupling between the incident radiation and the SPPhP excitations. In our previous papers [4, 5], we investigated optical properties of heavily-doped $n$-GaN epitaxial layers with a surface-relief grating. In the terahertz reflectivity spectra, pronounced dips due to the SPPhP excitation have been observed. Under a pulsed lateral electric field, the selective terahertz radiation emissions at the frequencies of SPPhP resonances have been observed from the profiled $n$-GaN epitaxial layer.

In the present paper, we investigate SPPhP at the $n$-GaAs/vacuum interface. The electron mobility in GaAs is by one order of magnitude higher than in GaN, which provides an opportunity to observe higher-quality SPPhP resonances. We study optical properties of a heavily-doped $n$-GaAs epitaxial layer with a surface-relief grating and reveal specific features related to SPPhP excitations in the reflectivity and radiation emission spectra in the terahertz spectral range. For comparison, we perform similar optical experiments on the reference samples with a planar $n$-GaAs surface.

2. Experimental technique

In accordance with our preliminary simulations [6], we fabricated an $n$-GaAs-based microstructure suitable for the observation of SPPhP in the terahertz spectral range. The microstructure was made of a 7.6-$\mu$m-thick $n$-GaAs:Si epitaxial layer with an electron concentration $n \sim 2 \cdot 10^{18} \text{cm}^{-3}$, grown by molecular beam epitaxy on a semi-insulating GaAs substrate. A set of samples containing a pair of Au/Ge/Ni/Au electrical contacts was fabricated. A regular grating was patterned by conventional photolithography and wet chemical etching in the area between contacts. The grating period $a$ was 54 $\mu$m, while the depth of the grating grooves was about 3 $\mu$m. A few reference samples with a planar surface between contacts were also prepared.

Properties of the epilayer were characterized by means of the Hall effect and conductivity measurements (at temperatures $T = 77$ and 300 K) and analysis of current-voltage characteristics (at $T = 4.2, 77$ and 300 K) and reflectivity spectra (at $T = 300$ K). It was found that free electrons are not frozen even at liquid helium temperature, which indicates impurity band formation. The electron concentration is practically constant and equal to $1.9 \cdot 10^{18} \text{cm}^{-3}$ across the entire temperature range examined. The electron mobility $\mu$ at room temperature is equal to 2300 cm$^2$/V⋅s and slightly increases (by about 9%) under microstructure cooling to 77 K.

We investigated the terahertz reflectivity spectra of the samples under equilibrium conditions at room temperature. Measurements were carried out by means of a Fourier spectrometer operating in a rapid-scan mode. Terahertz radiation emission under significant electron heating by a pulsed electric voltage applied to the contacts was also studied at cryogenic temperatures. For these studies, we used a Fourier spectrometer operating in a step-scan mode. The experimental methods are described in more detail in [4].

3. Results and discussion

The experimental reflectivity spectra under slightly oblique incidence of radiation in the frequency range of 2–19 THz (with photon energies of 8–80 meV) are presented in figure 1. The spectra for the sample with a surface-relief grating (the incidence plane was oriented perpendicular to the grating ridges) demonstrate a lower reflectivity for both $p$- and $s$-polarized radiation in comparison with the reflectivity of the reference sample (measured for unpolarized radiation under any orientation of the incidence plane). This decrease is due to radiation diffraction at the grating. The diffracted beams of non-zero orders are deflected by rather large angles and propagate beyond the angular aperture of the photodetector ($\Delta\theta = 4^\circ$) which collects the zero-order diffracted beam only (for more details, see [5]). Nevertheless, all three spectra show two common features, namely a sharp dip at the photon energy $\hbar\omega_-$ and the reflection edge near the phonon energy $\hbar\omega_+$. Both of these features are characteristic of
the bulk plasmon-phonon polaritons (see [3]) in the $n$-GaAs epilayer. The fingerprints of the surface plasmon-phonon polariton excitation that we are interested in are clearly seen in the reflectivity spectrum of the grating sample for $p$-polarized radiation (solid line in figure 1). The spectrum demonstrates a few additional dips in comparison with the spectrum for $s$-polarized radiation (dashed line in figure 1). It is known (see, e.g., [4]) that only the radiation having a component of the electric field perpendicular to the grating ridges (i.e. $p$-polarized radiation in the above-mentioned geometry of the experiment) can excite the surface waves. This causes dissipation of the radiation energy and is seen as a decrease in reflectivity.

We used the SPPhP model considered in [6] to interpret the experimental spectra. Following this model, the dielectric permittivity can be simulated as

$$
\varepsilon(\omega) = \varepsilon_\infty \left[ 1 + \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_0^2 - \omega^2 - i\omega\gamma} - \frac{\omega_p^2}{\omega^2 + i\omega\tau^{-1}} \right]
$$

(1)

where $\gamma$ is the damping constant for TO phonons, and $\tau$ is the electron relaxation time determined by the mobility $\mu$: $\tau = \mu m_e/e$. For numerical calculations, we used the above-mentioned results of the epilayer characterization and $\tau = 0.006\omega_{TO}$. The dispersion law for SPPhP at the semiconductor/vacuum interface is described as [1, 6]

$$
K_{SPPhP}^2 = \left( \frac{\omega}{e} \right)^2 \frac{\varepsilon(\omega)\omega}{\varepsilon(\omega)+1},
$$

(2)
where we assume that the angular frequency $\omega$ is the complex quantity, while the wave vector $k_{\text{SPPhP}}$ is the real quantity. In this case, the real and imaginary parts of the frequency correspond to the eigenfrequency and decrement of SPPhP oscillations, respectively. SPPhP with a certain frequency $\omega$ can be converted into terahertz photons with the same frequency (and vice versa) by means of a regular surface grating, which provides an opportunity to meet the phase-matching condition for the SPPhP and photon [1, 6]:

$$k_{\text{SPPhP}} = k_{\text{THz}} \sin \theta + M \cdot k_G,$$

(3)

where $k_{\text{THz}} = \omega / c$ is the wave vector of a terahertz photon in vacuum, $\theta$ is the incidence angle, $k_G = \frac{2\pi}{a}$ is the reciprocal vector of the grating, $a$ is the grating period, and $M = \pm 1, \pm 2, \pm 3 \ldots$ is the order of the SPPhP resonance under their decay (or excitation).

Spectral positions of possible SPPhP resonances simulated in accordance with equations (1) – (3) for the particular conditions of our reflectivity measurements on the $n$-GaAs/vacuum interface are shown in figure 1 by up arrows. One can see that in the experimental reflectivity spectrum for $p$-polarized radiation, one dip is located close to the theoretically expected position of the SPPhP resonance of the +1 order, while another dip corresponds to the −1 order, and the third dip can be considered as a common resonance for the SPPhP of the −2 order. It should be emphasized that very similar features were observed earlier for the reflectivity of the $n$-GaN/vacuum interface with a surface-relief grating [4, 5]. Namely, the dips corresponding to photoexcitation of SPPhP modes of the orders +1, −1, +2 and −3 were also observed, while the mode with $M = −2$ was not excited. Such behavior was theoretically justified in [4] using a differential method with an explicit integration scheme for the analysis of electromagnetic fields in the near-field zone of the grating.

Our findings in the study of terahertz radiation emission from the regularly profiled $n$-GaAs/vacuum interface when applying a lateral electric field seem to be more significant than the previous results obtained in a similar study on the $n$-GaN/vacuum interface [4]. Firstly, in $n$-GaAs we are able to provide substantial heating of free electrons under a rather small increase of the lattice temperature, while in $n$-GaN we heated electrons and the lattice simultaneously to the same temperature. As a result, using short electric field pulses (∼3 μs), we provided much stronger electron heating in the $n$-GaAs epilayer compared to the $n$-GaN one. Secondly, in the present work we additionally study the polarization dependence of terahertz radiation emission that provides a deeper insight into the physics of SPPhP (see figure 2).

Terahertz radiation was detected by a silicon bolometer in the direction perpendicular to the $n$-GaAs/vacuum interface. The photoresponse at a repetition frequency of the electric field pulses of 1.6 Hz was measured by a lock-in amplifier. The photoresponse spectra for the samples with a surface-relief grating and reference samples are qualitatively different. The emission spectrum of the reference sample with a planar surface is totally determined by "hot" bulk plasmon-phonon-polariton modes. Analysis of the polarization dependence of the photoresponse spectra for the grating sample reveals resonant contributions to terahertz emission due to radiative decay of non-equilibrium SPPhP excitations. As a result of SPPhP decay, additional terahertz photons with the electric field $E$ parallel to the reciprocal vector of the grating $k_G$ (we call this radiation polarization "active") are emitted. However, no additional photons with $E \perp k_G$ (we call this polarization "passive") are emitted. The ratio of the photoresponse signals for active and passive polarizations demonstrates the selective amplification of the terahertz emission in the vicinity of the SPPhP resonance of the first order ($M = \pm 1$) by about 3 times. For the SPPhP resonance of the second order ($M = \pm 2$), the amplification is about 2 times. Both polarizations have the same radiation intensity in the vicinity of the bulk plasmon-phonon mode $\hbar \omega_n$. The presented data on terahertz emission are preliminary. To determine the actual spectral density of the terahertz radiation emission from the investigated samples,
Figure 2. Polarization dependence of terahertz radiation emission from the \( n \)-GaAs epilayer with a surface-relief grating under electron heating by electric field (experiment). Conditions: temperature \( T = 5 \) K, electric field \( E = 618 \) V/cm, \( \theta = 0^\circ \), \( \Delta \theta = 16^\circ \). The arrows denote the simulated spectral positions of the SPPhP resonances \((M = \pm 1 \) and \( \pm 2\)) and low-frequency plasmon-phonon mode \((\hbar \omega_-)\).

the spectral measurements of the transmission of the optical path of the installation (including a beamsplitter) should be carried out. The detectivity spectrum of the photodetector should be measured as well. This will be done at the next stage of the research.

4. Conclusions
We have investigated the interaction of surface plasmon-phonon polaritons at a regularly profiled \( n \)-GaAs/vacuum interface with terahertz photons. The spectra of the terahertz reflectivity and emissivity in a wide frequency range have been measured and their polarization dependencies have been examined. Resonant dips related to photoexcitation of SPPhP modes of the orders +1, −1, +2 and −3 have been revealed in the reflectivity spectra for \( p \)-polarized radiation. Under electron heating and non-equilibrium SPPhP excitation by a pulsed lateral electric field in the profiled \( n \)-GaAs epitaxial layer, terahertz emission has been detected in the spectral range of 3.5–13 THz (15–55 meV). In addition to unpolarized radiation emission related to "hot" bulk plasmon-phonon polariton modes, pronounced peaks related to surface plasmon-phonon polariton resonances of the first and second orders have been found in the emitted radiation with the electric field polarized perpendicularly to the ridges of the surface-relief grating. It has been shown that the selective amplification of terahertz emission in the vicinity of the SPPhP resonance of the first order is rather high (about 3 times).

The results of our studies can be applied for the development of portable sources of terahertz radiation operating under electrical pumping.

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