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Terahertz absorption in GaN epitaxial layers under lateral electric field

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Abstract. Variation of absorption of terahertz radiation in lateral electric field was investigated in GaN epitaxial layers. Different behaviour of the absorption modulation in electric field was observed for radiation polarized along electric field and perpendicular to it. Joint analysis of optical and transport measurements let us obtain field dependencies of mobility, electron concentration and absorption cross-section. For terahertz radiation polarized perpendicular to the electric field, results are in accordance with Drude model of free electron absorption. Another polarization demonstrates significant deviation that is yet to be studied more thoroughly.

1. Introduction

Gallium nitride is a promising material for high-speed electronics and photonics. One of possible implementations for this material is terahertz (THz) emitters with electrical pumping [1]. In this respect investigation of GaN optical properties in THz spectral range are of a great importance. Nevertheless, until now there were no works devoted to the investigation of terahertz absorption by free electrons in GaN. The reason for this lack of knowledge is the small value of equilibrium absorption coefficient in GaN which makes direct measurements of this value in epitaxial GaN layers quite problematic. However, modulation technique can provide the possibility to measure nonequilibrium absorbance. In particular, application of electric field provides the means to detect rather small changes of the absorption coefficient.

A lot of electronics devices, in particular, high frequency transistors, operate in highly nonequilibrium conditions of carrier heating. The investigation of the hot electron distribution function as a very important characteristic of electron gas seems to be of interest. Particularly, anisotropy of distribution function is a necessary condition for the stimulated generation of millimeter radiation in semiconductors with negative effective mass [2] and under the condition of electric-field-induced electron-transit-time resonance [3]. The anisotropy of carrier distribution function in momentum space can manifest itself in the polarization dependence of terahertz radiation absorption by free electrons in high electric field.

In the present paper we publish the results of the investigation of terahertz radiation absorption modulation in GaN epitaxial layers under lateral electric field.

2. Experimental technique

Wurtzite gallium nitride epitaxial layers were grown by metal-organic vapor phase epitaxy (MOVPE) on a *c*-plane sapphire covered by 2 µm undoped GaN buffer layer. The epitaxial layer had thickness $L = 4.3$ µm. In accordance with electro-physical measurements in low electric fields at room temperature electron concentration is $1.7 \cdot 10^{17}$ cm^{-3}, and electron mobility is 212 cm^2/V·s. At the liquid nitrogen temperature these parameters have values of $5.1 \cdot 10^{16}$ cm^{-3} and 329 cm^2/V·s, respectively. Two Ti/Au electrical contacts with 4 mm length were deposited on the surface of the structure for the application of lateral electric field. Distance between the contacts was 1 mm. Gallium nitride layers were covered with protective SiO_2 layer in order to prevent surface electrical breakdown under high electric field.

The optical experimental setup is shown in figure 1. Samples were mounted into liquid nitrogen cryostat ($T_0 = 77$ K) with TPX (polymethylpentene) windows. Terahertz radiation was generated by Edinburgh Instruments CW molecular gas laser with optical pumping. Absorption studies were carried out at a fixed laser wavelength $\lambda = 118$ µm ($\nu = 2.54$ THz). A Ge:Ga photodetector at liquid helium temperature was used to detect the intensity of terahertz radiation passed through the sample. The photoresponse *I* without applied electric field was measured using mechanical chopper. Photoresponse change ΔI was measured without the chopper during electric field pulse. In order to prevent the sample heating and destruction, high lateral electric field **E** was applied in pulsed mode with 1 µs pulse duration and repetition rate less than 1 Hz using a generator based on IGBT (isolated gate bipolar transistor). Attenuator was used to reduce THz laser radiation intensity. Half-wave plate was used to rotate the polarization plane of radiation. The resulting modulation *M* was obtained as a ratio of photoresponse change signal to the equilibrium signal:

$$M = \frac{\Delta I}{I} = \frac{I(E) - I}{I} = \frac{I_0 \cdot \exp(-(\alpha + \Delta\alpha)L) - I_0 \cdot \exp(-\alpha L)}{I_0 \cdot \exp(-\alpha L)} = \exp(-\Delta\alpha L) - 1,$$

where I_0 is the input beam intensity, α is the absorption coefficient, $\Delta\alpha$ is the change of absorption coefficient in electric field, *L* is the thickness of the GaN epitaxial layer. In case of a small absorption change, the modulation is proportional to $\Delta\alpha$: $M = -\Delta\alpha L$.
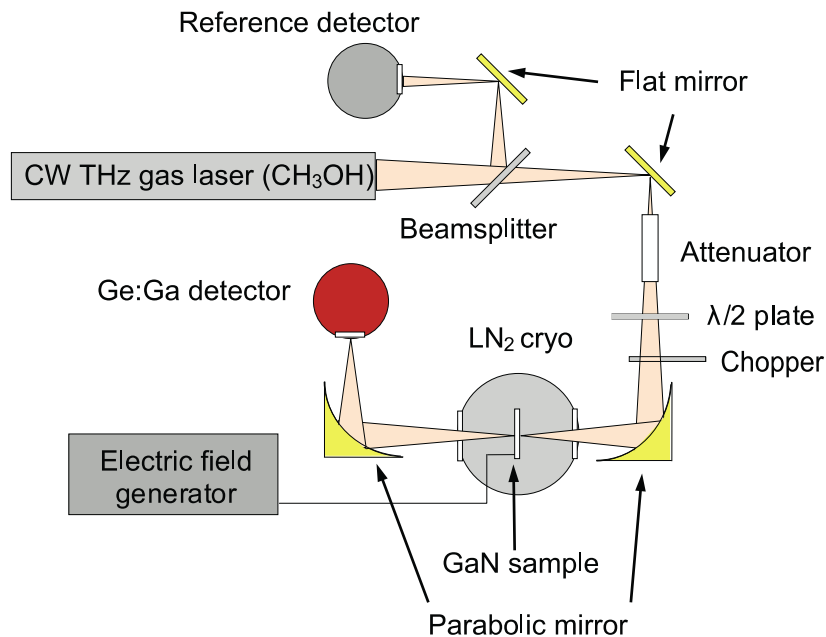

Figure 1. Optical experimental setup scheme.

3. Results and discussion

The dependencies of the absorption modulation on the lateral electric field **E** at λ = 118 μm are shown in figure 2. Solid red circles correspond to the absorption modulation for radiation polarized perpendicular to the electric field (**e**$_\omega \perp$ **E**, **e**$_\omega$ is radiation polarization vector). Empty black circles correspond to the absorption modulation for radiation polarized along the electric field (**e**$_\omega \|$**E**). The negative modulation M (which corresponds to the decrease of radiation intensity detected by a photodetector) means an increase of absorption ($\Delta\alpha > 0$) . Modulation for both radiation polarizations demonstrates similar behavior in electric fields up to $E = 3000$ V/cm. There is a significant difference in the absorption modulation for different polarizations at high lateral electric fields ($E > 4000$ V/cm). In this range for polarization **e**$_\omega \perp$ **E**, the absorption modulation monotonically increases with electric field. Absorption modulation field dependence drastically differs for polarization **e**$_\omega \|$**E**. In the fields exceeding 4000 V/cm modulation is almost constant.

In order to understand the peculiarities of optical modulation we additionally measured current-voltage characteristic (CVC) in wide range of the electric fields (see figure 3). The general behavior of the obtained CVC can be explained qualitatively in the following way. The superlinear increase of the current in the field range $E = 200 – 2000$ V/cm can be attributed to the impurity breakdown and the sublinear increase of current in the fields exceeding 4000 V/cm is the result of mobility decrease due to the electron heating [4].
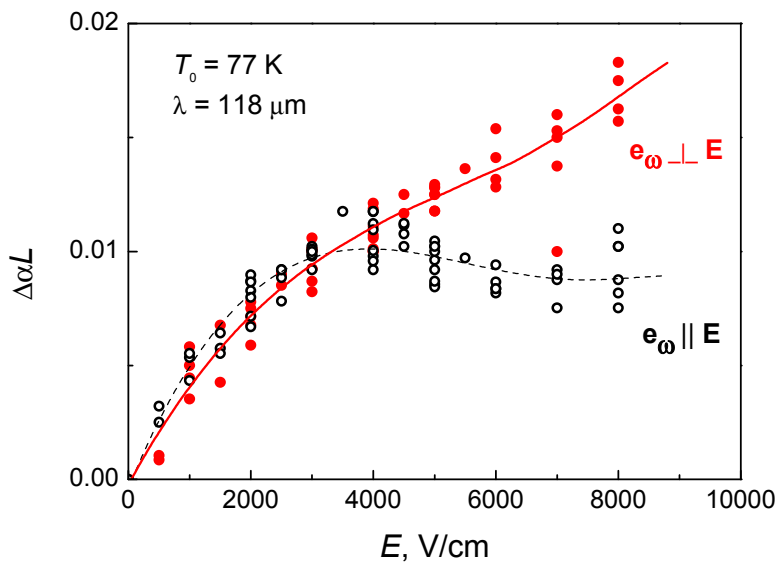
Figure 2. Dependences of the absorption modulation on the lateral electric field E for radiation polarized parallel (empty black circles) and perpendicular (solid red circles) to the electric field. $T_0 = 77$ K, λ = 118 μm. The solid and dashed lines are guides for the eyes.

The following model was considered to describe the abovementioned experimental results on absorption modulation and CVC. Variation of the absorption coefficient of GaN epitaxial layer in electric field can be described as $\Delta\alpha(E) = \alpha(E) – \alpha_0$, where α_0 and $\alpha(E)$ are equilibrium and nonequilibrium absorption coefficients, respectively. The latter quantity can be expressed as $\alpha(E) = s(E) \cdot n(E)$ where $s(E)$ and $n(E)$ are nonequilibrium absorption cross-section and electron concentration in electric field E. The equilibrium absorption coefficient $\alpha_0 = s_0 \cdot n_0$ where s_0 and n_0 are equilibrium absorption cross-section and equilibrium electron concentration at $T_0 = 77$ K. CVC allows us to find

field dependence of conductivity $\sigma(E) = e \cdot \mu(E) \cdot n(E)$ which is determined by nonequilibrium electron concentration as well as electron mobility in electric field $\mu(E)$.
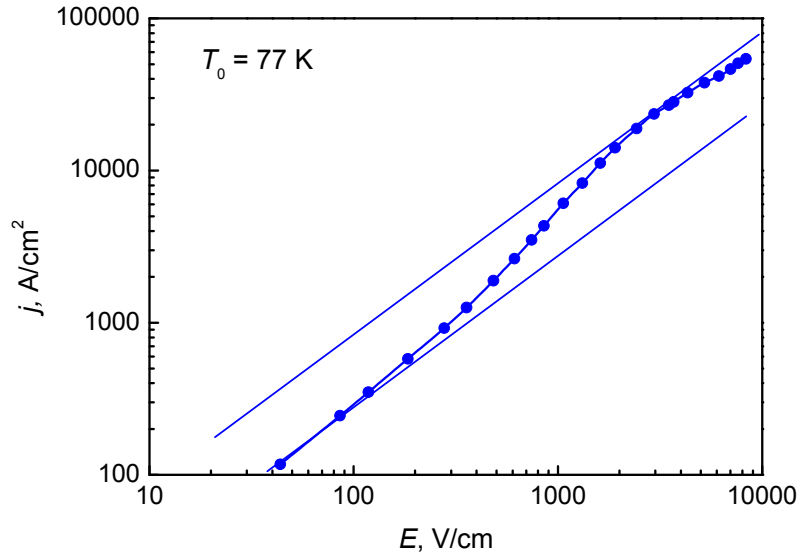

Figure 3. Current-voltage characteristic at temperature $T_0 = 77$ K. Straight lines correspond to linear dependence.

The field dependencies of μ, s and n uniquely determine the behavior of the dependencies $\Delta\alpha(E)$ and $\sigma(E)$ but not vice versa. Nevertheless the problem of determination of $\mu(E)$, $s(E)$ and $n(E)$ can be solved on the base of experimental results on $\Delta\alpha(E)$ and $\sigma(E)$ if there is some additional coupling equation. Such an equation can be derived from the Drude model of free carrier absorption. In the framework of the model, electron absorption cross-section and mobility are coupled by inverse proportion: $s(E) \propto \lambda^2/\mu(E)$.

Using abovementioned relations, we performed joint analysis of the experimental data on absorption modulation for polarization $\mathbf{e}_\omega \perp \mathbf{E}$ and CVC. The results are presented in figures 4 and 5. Free electron concentration monotonically increases with electric field that can be attributed to the process of impurity breakdown [4]. Total increase of the electron concentration is rather large (3.6 times) because in equilibrium at $T_0 = 77$ K the major part of electrons is frozen-out. At electric fields exceeding 4000 V/cm, one can notice simultaneous significant decrease of electron mobility (see figure 4) and increase of absorption cross-section (see figure 5). Maximum deviation of these quantities from their equilibrium values is close to 40%. The decrease of the electron mobility is caused by electron heating under applied electric field, and it results in an increase of the absorption cross-section in accordance with Drude model. It should be noted that equilibrium value of the absorption cross-section $s_0 = (2.0 \pm 0.15) \cdot 10^{16}$ cm^{-3} was found from the experimental data on absorption modulation under relatively low fields (~ 1000 V/cm) when decrease of the mobility due to electron heating is negligibly small (see figure 4). Consequently, $\alpha_0 \approx 10$ cm^{-1} and the equilibrium optical transmission of the GaN epitaxial layer $\exp(-\alpha_0 L) \approx 0.996$. This result proves the statement from Introduction concerning the impossibility of the direct measurements of equilibrium absorption coefficient.

After that using the obtained dependencies $n(E)$ and $\mu(E)$, we analyzed the experimental data on absorption modulation for polarization $\mathbf{e}_\omega \| \mathbf{E}$ and found corresponding absorption cross-section. Dependence $s(E)$ for this polarization (see dashed curve in figure 5) demonstrates non-monotonic behaviour and can not be understood in the framework of Drude model.
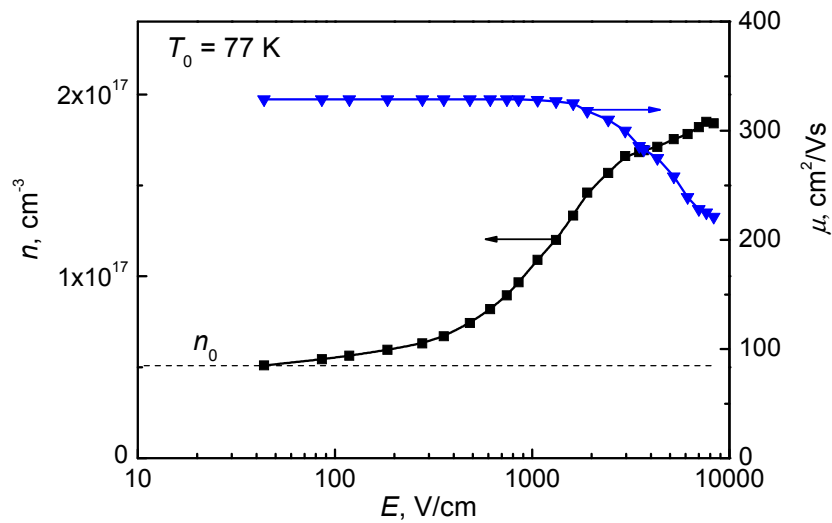
Figure 4. Field dependencies of electron concentration (left axis) and electron mobility (right axis) at $T_0 = 77$ K. Dashed line shows the equilibrium electron concentration value at the named temperature.

Microscopic mechanism of the observed polarization dependence of absorption modulation remains to be discovered. It can be related to anisotropy of the hot electron distribution function which arises in high electric fields [5, 6]. In particular, scattering on nonequilibrium optical phonons can have a significant influence on electron distribution.
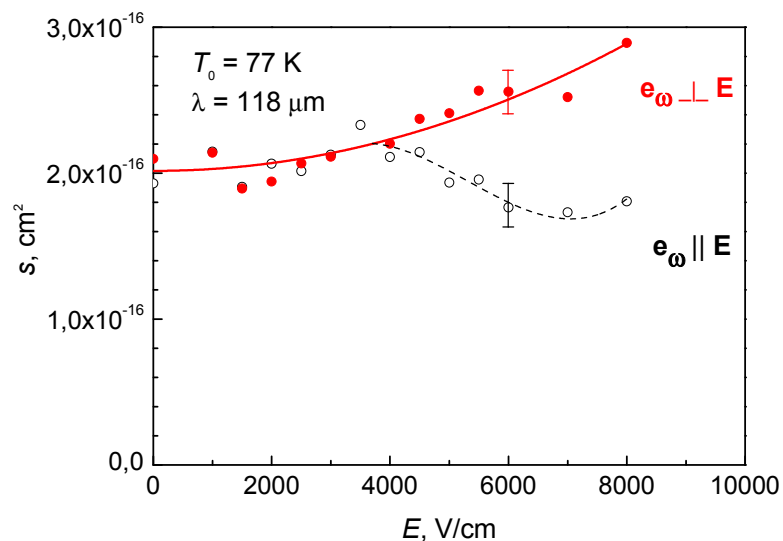
Figure 5. Absorption cross-section field dependence. Terahertz radiation is polarized parallel (empty black circles) and perpendicular (solid red circles) to the electric field. $T_0 = 77$ K, $\lambda = 118$ μm. The solid and dashed lines are guides for the eyes.

4. Summary

In this work, modulation of absorption in GaN epitaxial layers under electric field was investigated in terahertz spectral range. Joint analysis of optical and electrical measurements resulted in a determination of field dependencies of mobility, electron concentration and absorption cross-section. Experimental and analytical results in case of the terahertz radiation polarized perpendicular to electric field are consistent with Drude model of free electron absorption. A surprising polarization dependence was observed for absorption cross-section. The microscopic mechanism of this phenomenon for now is unclear and will be further studied.

Acknowledgments

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