High-frequency response of GaN in moderate electric and magnetic fields: interplay between cyclotron and optical phonon transient time resonances

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Received 26 October 2012, in final form 27 December 2012
Published 4 February 2013
Online at stacks.iop.org/SST/28/035007

Abstract
We have studied the high-frequency properties of the non-equilibrium electron gas in GaN samples subjected to electric and magnetic fields. Spectra of the complex tensor of the dynamical mobility have been calculated for the THz frequency range. For the compensated GaN and low temperatures, in the intervals of electric fields of a few kV cm\(^{-1}\) and magnetic fields of a few T the existence of the cyclotron and optical phonon transit-time resonances has been identified. We have shown that interplay of two resonances gives rise to specific spectra of THz transmission and absorption (or gain). We suggest that experimental investigation of these effects will facilitate elaboration of field-controlled devices for THz optoelectronics.

1. Introduction
Progress in the technology of group-III nitrides, discovery of unique material properties and perspectives of high-power, and high-frequency applications [1] have inspired studies of high-field transport regimes in these materials [2–4], including the high-frequency phenomena [5–7]. Most of these studies were focused on very high electric fields (10...200 kV cm\(^{-1}\)), where the intervalley electron transfer and the Gunn effects are expected. Also, there is a necessity of understanding of hot electron kinetics in the range of moderate electric fields (1...10 kV cm\(^{-1}\)), because of the fundamental and practical importance of such a case. Indeed, it is believed (see recent review [8]) that in polar nitride materials subjected to a moderately high electric field, strong inelastic optical phonon scattering can provide the so-called streaming transport regime. The latter is characterized by considerable anisotropy of electron distribution in the momentum space, quasi-saturation of the current-field dependence, negative dynamic conductivity and other useful effects.

In general, the following conditions are favorable to realize the streaming regime: (i) strong electron-optical phonon coupling, (ii) low temperatures which provide optical phonon emission as the dominant scattering mechanism of hot electrons and (iii) relatively low electron concentrations, when e–e scattering is negligible. According to the analysis given in a number of the works [8], these conditions can be met in the nitride materials, as well as in the nitride heterostructures [9, 10]. At the streaming regime, the electron motion is nearly periodic: in an appropriate range of the dc electric field, an electron accelerates quasiballistically until it reaches the optical phonon energy, then the electron loses its energy by emitting an optical phonon and starts the next period of acceleration\(^1\). Such a mechanism of the nearly periodic electron motion leads to electric field-induced resonances in high-frequency conductivity (the so-called optical phonon transient time resonance (OPTTR)) [13]. The OPTTR provides an operating principle for electrically pumped semiconductor sub-THz and THz sources [13], that has been practically realized in n-InP crystals [14].

Experimental observation of the OPTTR in the nitrides and its further device implementation is impeded by the deficit of electron transport data for the range of moderate electric fields, including high-frequency properties.

Additional useful information on properties of the nitrides can be obtained by investigation of magnetic field effects

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\(^1\) Note, this simplified picture can be traced back to papers by Shockley [11] and Price [12].
on charge carriers, for example, investigation of the electron cyclotron resonance (CR). It is well known, that exploitation of the CR is a powerful spectroscopic method that allows us to determine important parameters of the band structure and carrier dynamics (for a detailed review see [15]). Monitoring the CR in an electric field, one can study intrainband dynamic processes of nonequilibrium carriers. For example, the CR technique was successfully used to study hot electrons and holes in Ge [16], Si [17], InSb [18], GaAs [15] and other important semiconductor materials. As a result, the detailed features of hot carrier kinetics have been understood. These include: relaxation mechanisms and their parameters, character of carrier distribution in the momentum space, the dynamic conductivity, etc. Recently, the CR was observed in the nitrides at moderate and high magnetic fields (above 5 tesla). Here the resonance became apparent in the THz-frequency range [19–22], because of small sub-picoscond relaxation time characteristic for the nitrides.

In this paper by the use of the Monte Carlo method, we study GaN bulk-like material in moderate electric and magnetic fields. We focus on high-frequency response of GaN under conditions, when both resonances, the CR and the OPTTR, become apparent simultaneously. We show that overlapping of the two resonances produces specific spectra of THz transmission and reflection, as well as characteristic polarization effects.

2. Model of electron transport

We consider a bulk GaN sample of the cubic modification with a given concentration of ionized impurity, $N_i$. To exclude the quenching effect on the OPTTR by electron–electron scattering we suppose that the sample is compensated, thus the electron concentration $n_e < N_i$. At electric fields of a moderate strength, all electrons remain in the $\Gamma$ valley and can be characterized by the parabolic dispersion law with the effective mass, $m^*$. The dc electric field, $F$, and the magnetic field, $B$, are assumed to be parallel. Let both fields be directed along $OZ$ axis, $F \parallel B \parallel OZ$. The magnetic field is treated as a classical one. The ac electric field is supposed to be harmonic, $F_{ac} \exp(-i\omega t)$, with $\omega$ being the frequency. To find the small-signal response, the ac field is considered as a small perturbation, $|F_{ac}| \ll |F|$.

To calculate electron transport characteristics and, particularly, frequency-dependent dynamic mobility, $\mu_{\omega}$, we use the single-particle algorithm of the Monte Carlo procedure [23, 25]. For the simulation of the electron transport we take into account the main three scattering mechanisms: scattering by ionized impurities, acoustic phonons and polar-optical phonons. For ionized impurity scattering, we exploit the ‘mixed’ scattering model that unifies both Brooks–Herring and Conwell–Weisskopf approaches. This approach is more appropriate for the analysis of compensated materials. The formulae of electron scattering probabilities for these mechanisms can be found in [23].

In the limit of a classical magnetic field, the scattering probabilities do not depend on this field. However, the magnetic field determines the Lorentz force, so that electron dynamics between sequential collisions is described by the equation

$$m^* \ddot{v} = -e \left[ F + F_{ac} \exp(-i\omega t) + \frac{1}{c} [v \times B] \right]. \quad (1)$$

where $v$ is the electron velocity, $e$ is the elementary charge, $c$ is the light velocity. To avoid cumbersome expressions for $v(t)$ during free flight between collisions we present here only velocity modulation by the ac field, $F_{ac}$:

$$\ddot{v}_i(t) = -\frac{eF_{ac}}{m^*} \omega \sin(\omega t) \sin(\omega_i \Delta t) - \left(\frac{eF_{ac}}{m^*} \omega \cos(\omega t) + \frac{eF_{ac}}{m^*} \omega \sin(\omega t) \sin(\omega_i \Delta t) + \frac{eF_{ac}}{m^*} \omega \cos(\omega t) \cos(\omega_i \Delta t) - \frac{eF_{ac}}{m^*} \omega \cos(\omega t) \sin(\omega_i \Delta t) \right),$$

$$\ddot{v}_e(t) = \frac{eF_{ac}}{m^*} \sin(\omega t) \sin(\omega_0 \Delta t) + \frac{eF_{ac}}{m^*} \sin(\omega t) \sin(\omega_0 \Delta t) + \frac{eF_{ac}}{m^*} \sin(\omega t) \sin(\omega_0 \Delta t) - \frac{eF_{ac}}{m^*} \sin(\omega t) \sin(\omega_0 \Delta t), \quad (2)$$

where $\omega_0$ is an initial moment, $\Delta t = t - \omega_0$ and $\omega_i = \epsilon B/cm^*$ is the cyclotron frequency. We used equations (1) and (2) to apply the Monte Carlo procedure to the steady-state kinetics and high-frequency response of the electron gas subjected to both electric and magnetic fields [23].

First, we studied the steady-state distribution function of hot-electrons, the drift velocity, $V_d(F)$, the average energy, $\bar{E}(F)$, and other stationary electron characteristics in a wide range of applied dc electric fields, when the magnetic field, $B$, is present. In figure 1 we show an example of calculations of $V_d(F)$, $\bar{E}(F)$ and distribution function. These results are discussed below in more detail.

For the magnetic fields of a moderate strength ($B < 10$ T), we found that these characteristics practically are independent of the magnetic field. This is a consequence of two main factors: (i) for the parabolic electron dispersion and the parallel configuration of electric and magnetic fields, electron motion along fields direction and that in perpendicular plane are uncoupled; (ii) the magnetic field does not affect the energy balance of the electron system. Detailed analysis of the steady-state transport characteristics in compensated GaN can be found in [24].

In the presence of steady-state electric and magnetic fields, the high-frequency response can be characterized by the dynamical mobility, which is the tensor, $\tilde{\mu}_{\omega}$. The dynamic mobility tensor defines the ac electric current induced by the ac field, $J_{ac} = \mu_{\omega} \hat{F}_{ac}$. For the considered configuration of the fields, this tensor has five non-zero components:

$$\tilde{\mu}_{\omega} = \begin{pmatrix} \mu_{\omega,xx} & \mu_{\omega,xy} & 0 \\ \mu_{\omega,xy} & \mu_{\omega,yy} & 0 \\ 0 & 0 & \mu_{\omega,zz} \end{pmatrix}, \quad (3)$$

where only three components, $\mu_{\omega,xx}$, $\mu_{\omega,xy}$ and $\mu_{\omega,zz}$, are linearly independent. Other components are $\mu_{\omega,yy} = \mu_{\omega,xx}$, $\mu_{\omega,zy} = -\mu_{\omega,yy}$. Note, at $B = 0$ nondiagonal components are equal to zero. In the next section we present the analysis of spectra of all components of $\tilde{\mu}_{\omega}$ and their dependences on the electric and magnetic fields.
remains symmetric, while the longitudinal one shows strong asymmetry: the electrons have momenta mainly directed along the applied force. The streaming distribution leads to the effect of the OPTTR in the frequency range 0.2–2 THz [8].

Classical treatment of electron motion in the magnetic field requires the condition \( \hbar \omega_c \ll E \). For the above range of the electric field, the average hot electron energy in GaN is estimated to be \( E < 30 \text{ meV} \). Then, the latter inequality gives limitations: \( \omega_c \ll 45 \text{ THz} \) and \( B < 50 \text{ T} \). In what follows, we restricted ourself to the analysis of moderate magnetic fields, \( 1 \ldots 5 \text{ T} \), which correspond to the cyclotron frequency \( \omega_c/2\pi \approx 0.1 \ldots 0.7 \text{ THz} \).

3. Calculation of the dynamic mobility

Prior to discussion of results on the hot-electron dynamical mobility, \( \hat{\mu}_{\omega} \), we shall estimate ranges of the parameters favorable for observation of the OPTTR and the CR effects in GaN.

For concentrations of the electrons and ionized impurities we set \( n_e = 10^{15} \text{ cm}^{-3} \) and \( n_i = 10^{16} \text{ cm}^{-3} \). The lattice temperature is assumed to be 30 K. For the GaN material parameters, such as effective mass, dielectric constants, deformation potential, etc, we used the database from [26]. The low field mobility was calculated to be \( \approx 5000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \), which is well correlated with the measured mobility in GaN samples of low dislocation density [27]. For these parameters, the streaming transport regime and the OPTTR are the most pronounced in the range of the characteristic velocity, \( v_d \), electric fields and the OPTTR are the most pronounced in the range of

![Figure 1](image1.png)

**Figure 1.** Panel (a) shows the field dependencies of the drift velocity, \( V_d (E) \), and averaged energy, \( \bar{E} (E) \). Panels (b) and (c) show the longitudinal and transversal profiles of electron distribution function at \( p_z = 0 \) and at \( p_x = 0 \), respectively, at \( E = 3 \text{ kV cm}^{-1} \). Characteristic velocity, \( v_d = 4 \times 10^7 \text{ cm s}^{-1} \), optical phonon energy \( \hbar \omega_0 = 92 \text{ meV} \), \( p_0 = \sqrt{2m^* \hbar \omega_0} \) is the characteristic momentum.

3.1. General properties of \( \hat{\mu}_{\omega} \) tensor

A representative example of the dynamic mobility of hot electrons under the developed streaming regime (\( F = 3 \text{kV cm}^{-1} \)) is given in figure 2. The magnetic field is set to be \( B = 4.5 \text{T} \). In this figure, three independent tensor components, \( \mu_{\omega,xx}, \mu_{\omega,zz}, \mu_{\omega,xy} \), are shown as functions of the frequency, \( \omega \).

The ‘longitudinal’ (with respect to the applied fields) component, \( \mu_{\omega,zz} \), is practically independent of the magnetic field and demonstrates all signs of the OPTTR effect: an oscillation behavior of both \( \text{Re}[\mu_{\omega,zz}] \) and \( \text{Im}[\mu_{\omega,zz}] \), and a frequency ‘window’, where the real part of the dynamic mobility is negative, \( \text{Re}[\mu_{\omega,zz}] < 0 \). Minimum of \( \text{Re}[\mu_{\omega,zz}] \) reaches the value \( \approx -200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \) at \( \omega/2\pi = 0.63 \text{ THz} \). Note, absolute values of \( \text{Re}[\mu_{\omega,zz}] \) including the case \( \omega \to 0 \) are much smaller than the low field mobility. This is a consequence of above-mentioned quasi-saturation of the velocity–field characteristics.

The ‘transverse’ component, \( \mu_{\omega,xx} \), and off-diagonal component, \( \mu_{\omega,xy} \), are dependent on both \( F, B \) fields and demonstrate features proper to the CR. The maximum of

![Figure 2](image2.png)

**Figure 2.** (a), (b) and (c): real (solid lines) and imaginary (dashed lines) parts of the components \( \mu_{\omega,xx}, \mu_{\omega,zz} \) and \( \mu_{\omega,xy} \) as functions of the frequency for \( F = 3 \text{kV cm}^{-1} \) and \( B = 4.5 \text{T} \). Thin lines are fitting curves defined by equation (4).
Re[μ_{ω,xx}] and zero of Im[μ_{ω,zz}] occur at ω → ω₁, ω₂/2π ≈ 0.63 THz for the used parameters. In the vicinity of ω₁, we find that Re[μ_{ω,xx}] is considerably larger than (|Re[μ_{ω,zz}]|). This is because all electrons contribute to the CR, while exclusively streaming electrons contribute to the OPTTR effect.

We found that spectral dependencies of two tensor components, μ_{ω,xx}, μ_{ω,zz}, can be approximately described by the simple Drude–Lorentz model that takes into account the electron motion in a magnetic field. For this model, the components are

\[
\begin{align*}
\mu^{(DL)}_{\omega,xx} &= \frac{\epsilon \tau^*}{m^*} \frac{1 - i \omega \tau^*}{(1 - i \omega \tau^*)^2 + (\omega_0 \tau^*)^2}, \\
\mu^{(DL)}_{\omega,zz} &= -\frac{\epsilon \tau^*}{m^*} \frac{\omega_0 \tau^*}{(1 - i \omega \tau^*)^2 + (\omega_0 \tau^*)^2},
\end{align*}
\]

(4)

where τ* is an effective relaxation time. As seen from figures 2(b) and (c), equations (4) give a good fitting to the Monte Carlo result for τ* = 0.6 ps. Herewith, the CR is well pronounced, because ω₀τ* ≈ 2.4.

3.2. Electric-field dependence of the cyclotron resonance

For the analyzed configuration of F and B fields, the electric field does not affect the cyclotron motion of the electrons in the \{x, y\}-plane. Instead, this field modifies the electron distribution and alters relaxation processes, and, consequently, the effective relaxation time, τ*.

The results presented in figure 3 illustrate the electric field effect on the CR. One can see that when the F field varies, the frequency of the resonance remains equal to ω₁, while the sharpness of the resonance degrades considerably with increase of the F field magnitude. For example, at B = 2.2 T (ω₀/2π = 0.32 THz) the cyclotron peak in Re[μ_{ω,xx}] practically disappears when F ≥ 5 kV cm⁻¹ (see figure 3(a)). This is, obviously, due to an intensification of scattering processes. For the larger magnetic field, B = 4.5 T, the CR remains observable for the range F = 1 . . . 5 kV cm⁻¹, as shown in figure 3(b). Therein we present also the F field dependence of the effective relaxation time, τ*, found by fitting equation 4 to the Monte Carlo results. It is interesting that for the F field range, 1 . . . 5 kV cm⁻¹, when the streaming regime is formed, τ*(F) dependence qualitatively correlates with the transit-time, τ_tr, during which a ballistically accelerated electron reaches the optical phonon energy, ℏω_0, i.e. τ_tr = \sqrt{2m^*ℏω_0/|eF|}. Thus under a very fast process of optical phonon emission, the width of the CR is determined rather by the dynamic characteristic, τ_tr.

4. Coexistence and interplay of the CR and the OPTTR

To measure microwave/optical effects in a magnetic field one uses, typically, the Faraday and/or Voigt configurations of an incident wave and a magnetic field. The CR can be observed for both configurations, while the OPTTR can be measured only for the Voigt configuration (if F and B fields are parallel).

To study coexistence and interplay of both resonant effects, we will focus on the Voigt configuration.

For certainty, we set that the incident electromagnetic wave propagates along the OY axis and the high-frequency electric field, E₀, lies in the \{x, z\}-plane. The incident wave is supposed to be linearly polarized. Then, for the wave polarization along the OX axis (E₀||OX) the CR is observable, but the OPTTR is absent. Contrary to this, for the wave polarization along the AZ axis (E₀||AZ) the CR is missed, but the OPTTR appears. For other polarizations, both resonances coexist and affect each other.

Interplay of the two resonances becomes apparent, for example, in transmission spectra. These spectra comprise two contributions from electron and lattice subsystems. In addition, the spectra vary with the sample thickness because of reflection and interference effects. In figure 4(a), we show the transmission spectra of a GaN sample in the THz frequency range, where the CR and the OPTTR appear. The electron parameters and magnitudes of the F, B fields are the same as in figure 2. The sample thickness is set 10 μm, the dielectric permittivity is 8.9. For comparison, the contribution of the lattice subsystem is shown separately. In accordance with the above-mentioned, the transmission spectra depend on the polarization of the incident wave. For the polarization parallel to the F, B fields, the CR is absent; however, due to the OPTTR the electron contribution leads to an increase in the transmission coefficient (curve 1). For the perpendicular polarization, the CR decreases the transmission (curve 3), while there is no OPTTR contribution. The transmission spectra for an intermediate polarization are illustrated by curve 3.

In figure 4(b), we present frequency dependencies of the loss/gain coefficients which append the data in figure 4(a). The loss/gain coefficient defines decrease/increase of the electromagnetic wave energy per unit time due to interaction with the electrons in the GaN sample. One can see that characteristic for the CR decrease in the transmission
coefficient is due to cyclotron absorption, while sample ‘bleaching’ under the OPTTR is relevant to a gain of the electromagnetic wave.

The loss/gain effects and their dependences on the wave polarization can be analyzed as follows. Let \( \theta \) be an angle between the electric vector \( \mathbf{E} \) and the \( OZ \) axis. Then, the time-averaged ac power density that is received by electrons from the electromagnetic wave, reads

\[
P_\omega(\theta) = \frac{1}{2} \epsilon_0 c_0 [\mu_{xx,xx} \sin^2(\theta) + \mu_{xx,zz} \cos^2(\theta)] |\mathbf{E}_0|^2.
\]  

A negative value of \( P_\omega \) indicates that an energy is transferred from the electrons to the electromagnetic field and vice-versa; a positive \( P_\omega \) means that the energy of the wave is absorbed by the electron subsystem.

In the frequency window, where \( \text{Re}[\mu_{xx,zz}] < 0 \), the function \( P_\omega(\theta) \) can be negative in some interval of the polarization angles \( \theta \). The condition \( P_\omega(\theta) = 0 \) restricts the parameters \( \theta \), \( \omega \), where the gain due to the OPTTR occurs. The actual space of these parameters can be illustrated in the \( [\theta, \omega] \)-plane, as presented in figure 5 for different values of the \( B \) field. From this figure it is seen that for \( B = 0 \) the gain occurs in the sufficiently wide angle sector, \( |\theta| < 35^\circ \). With increasing \( B \) this angle sector becomes narrow. For example, at \( H = 4.5 \) T the gain is possible only at \( |\theta| < 15^\circ \). Thus, polarization dependences of the gain effect are strongly affected by the CR.

5. Summary

In this paper, we have investigated bulk-like GaN subjected to electric and magnetic fields of moderate magnitudes, \( 1 \ldots 5 \) kV cm\(^{-1} \) and \( 1 \ldots 5 \) T, respectively. The parallel configuration of the electric and magnetic fields has been assumed. With the use of the Monte Carlo method, we have calculated steady-state and high-frequency characteristics of the compensated GaN at low temperatures. Particularly, we have focused on the situation, when two resonances, the CR and the OPTTR, become apparent simultaneously. We have calculated spectral dependences of all components of the tensor of dynamical mobility in the THz frequency range for different magnitudes of the electric and magnetic fields.

We have studied the CR for hot electrons, particularly, the electric field dependence of the CR broadening. For the analyzed range of the electric fields, where the streaming transport regime and the OPTTR effect are realized, we have found that the effective relaxation time, \( \tau^* (F) \), determining the broadening, correlates with the transit-time, \( \tau_{tr} \), during which a ballistically accelerated electron reaches the energy of the optical phonon. That is, at a very fast process of optical phonon emission, the CR broadening is determined rather by the dynamic characteristic, \( \tau_{tr} \).

We have determined spectral and field dependences of the OPTTR. Then, we have found that at electric fields of a few kV cm\(^{-1} \) and magnetic fields of a few T, well-developed cyclotron effect and optical phonon transient-time effects may coexist in the frequency range of 0.5 \ldots 1 THz: they can be observed simultaneously for the Voigt configuration of the incident THz wave and the fields. We have shown that interplay of two resonances gives rise to specific spectra of THz transmission and absorption (or gain), as well as characteristic polarization effects.

It is important to make a few remarks on experimental observation of the discussed effects in the THz frequency range. The spectral measurements in the THz range can be performed by using recently developed detection methods for ultrashort electric signals and generation techniques for sub-picosecond transients of electric fields. The advanced ultrafast detection methods mainly relay on two techniques: photoconductive sampling [28] and electro-optic sampling [29, 30]. By the use of femtosecond laser pulses with high repetition rates, these techniques allow for the direct measurement of electric transients with sub-picosecond time resolution. As for the generation techniques of sub-picosecond electric field transients, the most studied are THz pulses.
emitted by transient photocurrents in a photoconductive switch and THz emission generated by nonlinear optical processes (optical rectification, four-wave mixing, etc). Additionally, time-resolved THz polarization and ellipsometry methods are available. The techniques of generation and detection of sub-picosecond electric field transients were applied to GaN films to measure real and imaginary parts of the small signal conductivity under equilibrium conditions [5–7]. Apparently, the discussed THz techniques are generally compatible with high-field measurement set-ups for magnetotransport in GaN films/plates. Particularly, these techniques can be applied to study the CR and OPTTR for the most interesting Voigt configuration of the fields.

Concluding, the presented results show that low-temperature investigation of GaN samples in moderate electric and magnetic fields can provide useful information on hot electron dynamics and relaxation, as well as revealing novel high-frequency effects. We suggest that the experimental investigation of these effects would facilitate elaboration of field-controlled devices for THz optoelectronics, including THz emitters, amplifiers, electro-optical modulators [31], etc.

Acknowledgments

The authors acknowledge the support of bilateral cooperation by the NASU/CNRS (grant no 24019) and Ukrainian State Fund for Fundamental Researches (project no. F40.2/057).

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