Drift and diffusion high-field magneto-transport in GaN

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Abstract. The paper is focused on the investigation of magneto-transport phenomena in the compensated bulk-like GaN sample. Particularly, we studied the diffusion coefficient of the electrons in parallel and crossed configurations of moderate electric (\(E=1...10\) kV/cm) and magnetic (\(H=1...4\) T) fields. We found that \(E\)-field dependencies of the transverse-to-current diffusion coefficient are non-monotonic for both configurations with magnitude of the diffusion coefficient greatly controlled by the \(H\)-field. We showed that different behavior of the diffusion processes corresponds to distinct kinetics of the hot electrons. We suggest that measurements of the diffusion coefficient under \(E\)- and \(H\)-fields will allow to identify important for applications regimes of the electron kinetics.

1. Introduction
Wide bandgap semiconductor compounds, such as GaN, InN, AlN and quantum heterostructures on their basis have great perspectives for various applications in the modern high-power and high-frequency micro- and optoelectronics [1]. The unique properties of the nitrides – high low-field mobility, strong electron-optical-phonon coupling and large optical phonon energy (\(\hbar\omega_0 \approx 90\) meV for GaN) is favorable for the realization of streaming electron transport that associated with quasi-ballistic electron motion in momentum space that leads to the formation of strongly anisotropic distribution function [2, 3]. This effect is possible at low temperatures, \(k_B T_0 < \hbar\omega_0\) and small electron concentrations, where \(e-e\) scattering does not prevail and the electrons have independent individual momentum and energy budgets. Previously, it was shown for GaN structures that streaming effect can occur at electron concentration of < 10¹⁶ cm⁻³ (for bulk-like samples)[4] and < 5 x 10¹¹ cm⁻² (for quantum heterostructures with 2D electron gas)[5] at temperatures < 150 K in the range of applied electric fields of 3 – 10 kV/cm. Formation of the streaming-like electron kinetics is characterized by the emergence of the specific saturation behavior of current-voltage characteristics, anisotropy of electron conductivity and frequency ranges of negative dynamic conductivity (the effect of optical phonon transit-time (OPTT) resonance)[4, 5, 6]. OPTT resonance can be used as core mechanism for a development of electrically-pumped generators in THz frequency range. Additionally, the useful information on formation of streaming transport regime can be obtained by investigation of magnetic field effects. For example, in parallel configuration of applied electric and magnetic fields (\(\vec{E}||\vec{H}\)) it can be observed co-existence of OPTT and cyclotron resonances. Latter can be identified by strong dependencies of transmission/absorption spectra vs polarization of incident radiation[7, 8].
If the magnetic field is oriented perpendicular to the electric field, the electron dynamics can be essentially changed. Particularly, the magnetic field can destroy the streaming transport forming a vortex-like electron motion which suppresses the main energy dissipation due to optical phonon emission[9]. It can leads to the formation of population inversion and a series of galvanomagnetic effects such as a negative magneto resistance and collapse of the dissipative current [10, 11]. The aim of the paper is the study of the magnetic field effect on diffusion processes of hot electron in coordinate space.

2. Diffusion coefficients in $\vec{E}||\vec{H}$ configuration

Diffusion coefficient is calculated using Monte Carlo simulation [12] of semiclassical magneto–transport in bulk-like GaN sample. In contrast of previous studies of diffusion coefficients in nitrides [13] we restrict ourself by the case of moderate applied electric fields when the effect of inter-valley transitions is negligibly small. To exclude the quenching effect on the streaming regime by $e-e$ scattering, in the transport model the sample is supposed to be compensated, the electron concentration $n_e$ is less than impurity one, $N_i$. In the simulation we take into account the three main scattering mechanisms: scattering by ionized impurities, acoustic phonons and polar optical phonons. The details of transport model is given in refs.[7, 11]. The magnetic field is treated as a classical one.

In this section the geometry of the applied fields is following: both $\vec{E}$ and $\vec{H}$ are oriented along $z-$axis. Early, we found that at magnetic fields of a moderate strength ($H < 10$ T), the steady-state characteristics such as the distribution function of hot-electrons, the drift velocity, $V_d (E)$, and the average energy, $< \epsilon > (E)$ practically are independent of the magnetic field [7]. 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. However, the electron diffusion process in coordinate space demonstrates the essential dependence vs values of $H$. Electric field dependences of transversal component of the diffusion coefficient, $D_{xx}(E)$, calculated at three given magnitudes of $H$ are shown in Fig.1(a) by solid lines. As seen, the dependence of $D_{xx}(E)$ has non-monotonic

![Figure 1](image)

**Figure 1.** Panel (a): dependences of $D_{xx}(E)$ (solid lines) and $D_{xx}^{(a)}(E)$ (dots). Panel (b): dependences of $\mu_{xx}(E)$ (solid lines) and $\epsilon_{\perp}(E)$ (dash-dotted line). Calculations performed at $N_i = 10^{16}$ cm$^{-3}$, $n_e = 10^{15}$ cm$^{-3}$ and $T_0 = 30$ K.

behavior and electron diffusion in the perpendicular direction to the applied fields is essentially suppressed with increasing of $H$. Such behavior of $D_{xx}(E)$ is correlated with field dependences of transversal component of low-field mobility $\mu_{xx}$ (shown in Fig.1(b) by solid lines). We found that field dependencies of $D_{xx}(E)$ can be approximately described by the phenomenological Einstein relationship, $D_{xx}^{(a)} = \langle \epsilon_{\perp} \rangle \mu_{xx}/e$, where $\langle \epsilon_{\perp} \rangle$ is the part of the average electron energy.
corresponding to the electron motion in perpendicular plane. In the frames of the assumed transport model this quantity is the independent on $H$ and decreases in the range of electric fields corresponding to the formation of developed streaming transport regime (see dashed-dotted line in Fig.1(b)). The results of the diffusion coefficient approximation by the Einstein relationship (dots in Fig. 1(a)) are in the good agreement with exact calculations.

3. Diffusion coefficients in $\vec{E} \bot \vec{H}$ configuration

In this section we assume that $\vec{E}$ and $\vec{H}$ are oriented along $z$–axis and $y$–axis, respectively. In such geometry of the crossed electric and magnetic fields the electron kinetics is much more complicated. The presence of magnetic field can essentially affect on the form of both steady-state distribution function and transport characteristics[11]. Depending on the ratio between magnitudes of the electric and magnetic fields, it can be realized three typical situations. In the case (I) of the weak magnetic field ($H < H_1 \equiv m^* c E/P_0$, where $P_0 = \sqrt{2m^*/\hbar \omega_0}$, $c$ is the light velocity) electron trajectories in the momentum space are weakly bent and the streaming motion is maintained. The form of distribution function remains strongly-anisotropic and elongated along $z$–axis. In the case (II) of the intermediate magnetic fields ($H_1 < H < 2H_1$) there are two groups of electrons. In the former group, the electrons execute a streaming cyclic motion over bent trajectories. In the latter group, the electrons rotate over the Larmor orbits and do not interact with optical phonons. The effect of accumulation of the essential part of electrons on the Larmor orbits stipulates the formation of the complicated topological structure of distribution function. In the case (III) of strong magnetic fields ($H > 2H_1$) most of the electrons are captured on the Larmor orbits. As a result the optical phonon emission is strongly suppressed, distribution function becomes quasi-isotropic and acquires the axial symmetry. This leads to the decreasing of the Ohmic and Hall components of current [11].

We analysis the field dependencies of diffusion coefficient components in transversal directions to $\vec{E}$. Electric field dependences of $D_{xx}(E)$ are shown in Fig.2(a). As seen, the increasing of magnetic field is considerably suppressed electron diffusion in the $x$– direction. The quantity $D_{xx}(E)$ at finite $H$ as well at $H = 0$ exhibits a non-monotonic behavior with the maximum. At higher magnetic fields the maximum shifts to the region of higher electric fields. The positions of the maxima are marked in Fig.2(b) by circles. All circles lie in the region of $E - H$ corresponding to the case (II) of the co-existence of two electron groups.

![Figure 2](image_url)

**Figure 2.** Panel (a): dependences of $D_{xx}(E)$. Other parameters are the same as in Fig.1. Panel (b): Diagram of $E - H$ regions corresponding to the (I), (II), (III) cases of electron kinetics in crossed fields. Shadow demarcates the electric fields of developed streaming regime.

The field dependencies of the $D_{yy}$ component which describes the electron diffusion along $H$ cardinaly differ from the field dependencies of the $D_{xx}$ component. As seen in Fig.3(a) the magnetic field stimulates the growth of electron diffusion along magnetic field. The obtained
values of the $D_{yy}$ are in several times larger than values of the $D_{yy}$ at the same $H$. It should be noted that magnetic field weakly affect on the position of maximum observed in the $D_{yy}(E)$ dependencies. At such high electric fields when the case (I) occurs the $D_{yy}(E)$ tends to the constant value which is independent on both $E$ and $H$. We found that general behavior of $D_{yy}$ component of diffusion coefficient is correlated with electric field dependence of quantity $< \epsilon_y >$ that is the part of the average electron energy corresponding to the motion along $y$–direction (see Fig.3(b)).

![Figure 3](image). Panel (a): dependences of $D_{yy}(E)$. Panel (b): dependences of $< \epsilon_y > (E)$. Other parameters are the same as in Fig.1.

In summary, investigation of the diffusion processes in electric and magnetic fields can provides valuable information on kinetic regimes of hot electrons in GaN. Besides, study of the field dependencies of the diffusion coefficient are important for many applications, device modeling, characterization of noise and space-charge phenomena in hot-electron devices, etc. Also, such a study can be useful for development of novel types of magnetic field sensors, which exploit the specific features of ballistic and quasi-ballistic transport regimes[14, 15].

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