High-field electron transport in GaN under crossed electric and magnetic fields

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Abstract. High-field electron transport studied in crossed electric and magnetic fields in bulk GaN with doping of $10^{16}$ cm$^{-3}$, compensation around 90% at the low lattice temperature (30 K). It was found the range of the magnetic and electric fields where the non-equilibrium electron distribution function has a complicated topological structure in the momentum space with a tendency to the formation of the inversion population. Field dependences of dissipative and Hall components of the drift velocity were calculated for the samples with short- and open-circuit Hall contacts in wide ranges of applied electric (0–20 kV/cm) and magnetic (1–10 T) fields. For former sample, field dependences of dissipative and Hall components of the drift velocity have a non-monotonic behavior. The dissipative component has the inflection point which corresponds to the maximum point of the Hall component. For latter sample, the drift velocity demonstrate a usual sub-linear growth without any critical points. We found that GaN samples with controlled resistance of the Hall circuit can be utilized as a electronic high-power switch.

1. Introduction

Semiconductor compounds of group-III nitrides, in particularly GaN, InN and AlN, are the base elements of the modern high-power and high-frequency micro- and optoelectronics. The strong electron-optical-phonon coupling, large optical phonon energy, sufficiently high electron mobility make them perspective for the development of the electrical pumping THz sources. The basic physical mechanism underlying of such devices is the quasiballistic electron motion associated with a emission of the optical phonon arising at sufficiently strong applied electric field. In literature this mechanism is widely discussed for nitride quantum heterostructures [1, 2, 3, 4] and short $n^+ - n - n^+$ diodes [5]. In the case of the unlimited sample this transport regime leads to the formation of the strongly-anisotropic distribution function in momentum space and the dynamic negative differential conductivity in the specific frequency ranges.

The application of an external magnetic field, $\vec{H}$, transverse to the direction of the electric field, $\vec{E}$, can essentially affect on the dynamic of the quasiballistic (streaming) electrons and their distribution function. A qualitative analysis of the possible transport regimes in crossed electric and magnetic fields have been done in the pioneer paper [6]. In particularly, it was predicted two effects: a formation of the inverted electron distribution and a suppression of dissipative transport with optical phonon emission. The first effect can be realized in the magnetic fields satisfying inequality $m^*cE/P_0 < H < 2m^*cE/P_0$ (I), where $P_0 = \sqrt{2m^*\hbar\omega_0}$ is the electron momentum corresponding to the optical phonon energy, $\hbar\omega_0$, $m^*$ is the electron effective mass.
and $c$ is the light velocity and the second effect can be realized at magnetic fields $H > 2m^*cE/P_0$ (II).

Transport phenomena in crossed electric and magnetic fields at low temperature and at dominant inelastic scattering have been intensively studied in the past both theoretically and experimentally. These investigations were aimed to reveal conditions of the formation of an inversion population necessary for a development of high-frequency generators. These ideas were realized in $p-$Ge where the inversion population between light- and heavy-hole bands and emission of the high-frequency radiation were observed under the conditions of the deep cooling [7]. However, in conventional polar semiconductors (n-GaAs, n-InSb, n-InP), in spite of many theoretical predictions [8, 9], the emergence of the electron inverted distribution associated with electron-optical phonon interaction was not found experimentally.

Here we present a theoretical analysis of steady-state electron magneto-transport in bulk GaN in which the strong electron-optical interaction and the large optical phonon energy promote favorable conditions for the observation of the above-mentioned effects. We focus on the study of the distribution function and current-voltage characteristics for different schemes of the external electrical circuits.

2. Transport model and analysis of the non-equilibrium distribution function

Analysis of the magneto transport was carried out for bulk-like sample of the compensated GaN. Compensation process allows to reduce free electron concentrations and avoid the undesirable influence of the non-elastic $e-e$ scattering [2] on the formation of the streaming transport regime. Calculations were performed in the frames of the numerical solution of Boltzmann transport equation by single-particle Monte-Carlo method [10]. In calculations we assumed the low ambient temperature of, 30 K, impurity and electron concentrations of $N_i = 10^{16}$cm$^{-3}$ and $10^{15}$cm$^{-3}$, respectively. We took into account the main three scattering mechanisms: scattering by ionized impurities, acoustic phonons and polar optical phonons. For similar parameters it was found that electron streaming effect at zero magnetic field occurs in the range of electric fields 3$-$10 kV/cm [11]. Under the study of the hot magneto transport we considered the range of the applied magnetic fields of a few tesla when the quantization effects can be neglected.

![Figure 1](image_url)

**Figure 1.** (a): Distribution function $f(\epsilon)$ for different magnetic fields. (b) and (c): The contour plots of the distribution function $f(P_x, P_y)$, at $H = 2.3$ T and $H = 5.7$ T, respectively. The white dashed circle separates the passive ($\epsilon < \hbar\omega_0$) and active ($\epsilon > \hbar\omega_0$) energy regions. The sign $\times$ indicates the maximum of the distribution. $E = 5$ kV/cm. $E$ and $H$ are applied along the $x-$ and $z-$axis, respectively.

Figs. 1 demonstrate behavior of the electron distribution function in the energy, $f(\epsilon)$, and in the momentum, $f(P_x, P_y)$, spaces for several magnetic fields. For magnetic field, $H = 2.3$ T satisfying inequality (I) the streaming distribution (dashed-doted curve) is strongly modified. The effect of accumulation of high-energy electrons in the energy interval $[0.5, 0.9] \times \hbar\omega_0$ is
clear seen. The corresponding distribution in the momentum space acquires the complicated topological structure (b) stipulated by the coexistence of two groups of carriers: electrons executing streaming motion (interacting with optical phonons) and electrons moving on cyclotron orbits closed in the passive regions (non-interacting with optical phonons). The center of \( f(P_x, P_y) \) is essentially shifted along both dissipative \((x)\) and Hall \((y)\) directions. However, for assumed parameters of GaN the inverted distribution function is still not formed due to the intensive scattering on the ionized impurities. Such distribution can be obtained only in the limit of the small impurity concentration, \( N_i \sim 10^{14} \text{ cm}^{-3} \). For \( H > 5 \text{ T} \) satisfying inequality (II) most of electrons move along the cyclotron trajectories closed in the passive region and interaction with optical phonons is strongly suppressed. The distribution function in the energy space is localized in the passive region and have axial symmetry in the momentum space. The discussed evolution of the distribution function is reflected in the specific behavior of the transport characteristics.

3. Current-voltage characteristics

In generally, the results of measurements of the transport characteristics in the magnetic field depend on the configuration of the external electrical circuit. There are two typical schemes of measurements: scheme with short-circuited Hall contacts \((R_h = 0)\) and scheme with open-circuited Hall contacts \((R_h = \infty)\). In the case of \( R_h = 0 \), the effect of the charge accumulation at Hall contacts can be neglected and component of the electric field in the Hall direction, \( E_h^{(0)} \), is equal to zero. In turn, both components of the drift velocity: dissipative, \( V_d^{(0)} \), (describes the current between Ohmic contact) and Hall, \( V_h^{(0)} \), (describes the current between Hall contacts) are nonzero. The developed Monte Carlo procedure allows to calculate both components of the drift velocity, simultaneously.

In case of the sample with \( R_h = \infty \), only dissipative component, \( V_d^{(\infty)} \), is the nonzero. In turn, due to the charge accumulation on Hall contacts, electric field acting on electron has two nonzero components: dissipative, \( E_d^{(\infty)} \), (applied field) and Hall, \( E_h^{(\infty)} \). If the sample is so long in the Hall direction that spatial inhomogeneity of the electric field near the Hall contacts can be neglected, electrical characteristics \( V_d^{(\infty)} \) and \( E_h^{(\infty)} \) can be easily obtained using results for the case of the sample with \( R_h = 0 \). From simple geometrical considerations, it follows: \( V_d^{(\infty)} = \sqrt{V_d^{(0)^2} + V_h^{(0)^2}} \), \( E_d^{(\infty)} = E_d^{(0)} \cos \theta \) and \( E_h^{(\infty)} = E_d^{(0)} \sin \theta \) where \( \theta \) is the Hall angle and defined as \( \tan \theta = V_h^{(0)}/V_d^{(0)} \).

![Figure 2](image_url)

**Figure 2.** (a): Dependencies of the dissipative (solid lines) and Hall (dashed lines) components of the drift velocity vs applied electric field for sample with \( R_h = 0 \). (b): dissipative components vs applied electric field for sample with \( R_h = \infty \). (c): Comparison of the dissipative components of the drift velocity for the samples with short- and open-circuited Hall contacts. The characteristic velocity \( V_0 = 4 \times 10^7 \text{ cm/s} \).

Typical electric fields dependences of the nonzero components of the drift velocity for the
electrical circuits with $R_h = 0$ and $R_h = \infty$ are shown in Figs. 2(a) and (b), respectively. As seen, $V_d^{(0)}(E_d^{(0)})$ and $V_h^{(0)}(E_d^{(0)})$ have three specific intervals. For example, for $H = 3.4$ T (green pair of curves in (a)) in the interval of applied electric fields of $0 - 5$ kV/cm the Hall current dominates over the dissipative one. The dependence $V_h^{(0)}(E_d^{(0)})$ shows superlinear growth, while $V_h^{(0)}(E_d^{(0)})$ remains almost linear. This situation corresponds to the electron distribution with axial symmetry (see Fig.1(c)) and amplitudes of the applied fields have to satisfy the inequality (II). With further increasing of the electric fields when inequality (I) is already satisfied, dissipative and Hall currents become of the same order. At this, the dependence $V_d^{(0)}(E_d^{(0)})$ contains the inflection point which corresponds to the maximum point in the dependence of $V_h^{(0)}(E_d^{(0)})$. Electron distribution have the form close to the one depicted in Fig.1(b). At electric fields $> 15$ kV/cm, Hall current is suppressed and dissipative current tends to the curve obtained at zero magnetic field. At stronger applied magnetic field (red pair of curves in (a)) the inflection and maximum points are shifted to the range of stronger electric fields and dissipative current is negligibly small up to 10 kV/cm (it is observed the collapse of the dissipative current).

For the electrical circuit with $R_h = \infty$, electric-field dependences of the drift velocity (b) have monotonic behavior and in contrast to the sample with $R_h = 0$ there is no inflection point. Note that the drift velocity under applied magnetic fields can exceed its value at zero magnetic field. The similar result was obtained and discussed in ref.[9] relating to n-GaAs and n-InP samples.

In summary, we compare dissipative currents calculated for the circuits with $R_h = 0$ and $R_h = \infty$ (see Fig.2(c)). Apparently, for the Hall circuit with the finite values of the $R_h$ dissipative current-applied electric field characteristic is placed between the solid and dashed curves. Thus, changing the resistance of the Hall circuit one can control the dissipative current between Ohmic contacts (analysis of such circuit will be published elsewhere). We suggest, that peculiarities of the high-field electron magneto transport in GaN can be used for the development of the four-terminal devices, in particularly, high power electronic switches.

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