Steady-state and high-frequency electron transport in GaN nanowires

V. V. Korotyeyev¹, V.A. Kochelap¹, S. Vitusevich², V. Sydoruk² and L. Varani³

¹Department of Theoretical Physics, Institute of Semiconductor Physics, Kyiv 03028, Ukraine
²Peter Grunberg Institute, Forschungszentrum Julich, Germany
³Institut d’Electronique du Sud, CNRS UMR 5214, University Montpellier 2, France
E-mail: koroteev@ukr.net

Abstract. The results of experimental and theoretical researches of steady-state and high-frequency electric characteristics of planar AlGaN/GaN heterostructure nanowires are presented. A strong depletion effect associated with electron trapping on the edge states is observed for narrow nanowires with widths \( \sim 200 \) – 400 nm. The spatial distributions of the electron concentration and electrostatic potential are calculated. At small applied voltages \((2-10 \, \text{V})\) for nanowires of length equal to 600 \( \mu \text{m} \) we found non-linear current-voltage characteristics related to a space-charge limited transport regime. We found that for narrow wires transversal transport is essentially ballistic: this dramatically modifies the high-frequency properties of the electron gas, in particular, leading to a resonant absorption of THz radiation.

1. Introduction
Currently, different types of semiconductor nanowires (NW), for example, Si, GaAs, InAs, GaN, ZnO are intensively studied with the aims of nano-electronic, optoelectronic, and sensor applications. In particular, they show promises as single photon detectors [1], low-power consumption nanoscale light-emitting diodes [2] and transistors [3]. The latter are widely used as sensors for various chemical and bio objects [4]. However, many fundamental physical questions about the internal electronic structure, effects of large surface, and size dependent transport phenomena remain unanswered up to now. Recent investigations of the electrical characteristics of different kinds of vertically-grown nanowires (whiskers) reveal common specific properties, in particular, the formation of depletion [5] or accumulation layers [6] at the NW interfaces and super-linear current voltage characteristics associated with the space-charge limited (SCL) transport regime [7]. Similar effects were found experimentally for planar heterostructure AlGaN/GaN NWs and will be discussed in this paper. Also, we will present an electrostatic model of the depletion layers and a kinetic theory of transversal high-frequency transport in NW.

2. Samples and experimental results
Our samples consist of long, spatially ordered ribbons (Fig.1(a)) with a 2D electron gas (2DEG). They were fabricated from AlGaN/GaN HEMT-heterostructures by Ar⁺ ion beam etching (see details of fabrication in ref. [8]). Each set consists of 160 wires in parallel with length,
$L = 620 \mu m$ with different widths, $W$, from 185 nm to 1110 nm for different NW sets. The initial characterization of the AlGaN/GaN quantum heterostructure (before NWs fabrication) gives a 2DEG concentration $n_0 = 2.2 \times 10^{12} \text{ cm}^{-2}$, which remains almost constant in the temperature range $T = 77\sim 300 \text{ K}$. The electron mobility, $\mu$, varies from 4500 (77 K) to 1500 cm$^2$/Vs (300 K).

The dependencies of the sample conductance vs the geometrical width of the NWs, extracted from the slope of the low-field current-voltage (I-V) characteristics, are shown in Fig. 1(b). These dependencies are almost linear and simultaneously show a zero conductance at a critical width, $W_0 \sim 200 \text{ nm}$ which does not depend on the temperature. The slopes of the fitting lines in Fig.1(b) agree with the measured mobility $\mu(T)$. Assuming that for the wide NWs the depletion effect is negligibly small, we can estimate the resistance of the sample as $R_0 = L/160\mu n_0 dW$, where $e$ is the elementary charge. For example, for a sample with $W = 1100 \text{ nm}$ the estimation gives $R_0 \sim 2.2 \text{ k}\Omega$ that almost coincides with the experimental value of 2.3 k$\Omega$. This means that the contact resistance is much smaller than the resistance of the NWs.

The depletion effect, which is well-pronounced for the narrower NWs, is the result of the electron trapping on the edge states. Apparently, these states are quite deep because they are not activated by the temperature. The measured I-V characteristics of the different NWs (Fig.1(c)) show a linear behavior up to voltages near 1 V and a superlinear behavior at higher voltages, approaching a dependence of the type $I \sim U^{2+l}$. According to the theory of the SCL transport in the presence of charge traps [9], $I \sim V^{2+l}$ where the parameter $l > 0$. In our case $l \approx 0.5$, thus additionally proving the existence of sufficiently deep traps.

3. Electrostatic model of the depletion layers in a planar single nanowire

The effect of the electron trapping on the edge states induces a strong redistribution of the electron concentration across the NWs and gives rise to electrostatic fields both inside and around the NW. At equilibrium, the electrostatic model should include 3 equations: the 2D Poisson equation for the electrostatic potential $\varphi$, the relation between electron concentration and electrostatic potential and the charge conservation law:

$$\begin{align*}
\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial z^2} &= -\frac{4\pi e}{\kappa_0} \delta(z) \left[ N_D - n(x) - N_s [\delta(x - W/2) + \delta(x + W/2)] \right]; \\
n(x) &= \frac{m^*k_B T}{\pi e^2} \log \left[ 1 + \exp \left( \frac{\varepsilon_F + \varepsilon(x,0)}{k_B T} \right) \right]; \\
N_D &= 1/W \times \int_{-W/2}^{W/2} n(x) dx.
\end{align*}$$

where $N_D$ and $n(x)$ are the 2D concentrations of the positive charges (ionized donors) and mobile electrons, respectively, $N_s$ is the 1D concentration of the negative charge accumulated on an edge of the NW, $\kappa_0$, $\varepsilon_F$ and $m^*$ are the effective dielectric constant, Fermi level and electron effective mass, respectively. Using the Green function method [10], the system (1) is reduced to a non-linear integral equation that was solved numerically. The results of the calculations for different NWs are shown in Fig. 2 where, for the parameter $N_s$, we have used the values extracted from the conductance measurements of Fig. 1(b). Having the values of the estimated
conductance $G_0 = 1/R_0$ and measured conductance, $G$, we can restore the percentage of trapped electrons, $\delta = (1 - G/G_0)/2$ and calculate the parameter $N_s = n_0 W \delta$. For the three considered samples, $\delta$ are equal to 0.35, 0.28 and 0.21 (for one edge).

**Figure 2.** (a) and (b) Distributions of $n(x)$ and $\varphi(x,0)$, respectively, at $T = 290$ K. The dash-dotted lines show the Fermi levels. (c) Distribution of the electrostatic energy around a NW with $W = 360$ nm. The vertical lines indicate the geometrical sizes of the NW.

As can be seen, wide depletion regions occur near the edges and the free electrons are mainly concentrated in the middle of the NW (see Fig. 2(a)). In turn, the self-consistent electrostatic potential (see Fig. 2(b)) sharply increases at the edges due to the repulsive action of the trapped electrons while it is almost flat in the middle due to the screening effect of free electrons. Such redistribution of the charges inside the NW forms a strongly inhomogeneous electrostatic field that spreads to distances of the order of 1 $\mu$m around the NW (see Fig. 2(c)).

4. High-frequency transport in the nanowires: geometrical resonance

The submicron transversal size of the considered NWs (comparable with the electron mean free path) makes them a good candidate for the observation of geometrical resonances (GR) that manifests themselves in the resonant absorption of electromagnetic waves polarized across NW. The physical reason of this resonance is a regular, oscillating dynamics of the electrons between the walls created by the confinement potentials, $\varphi(x,0)$. The resonance frequencies and the shape of the resonance lines depend on the form of the built-in potential, temperature, electron mobility, etc. The GR was studied in the framework of the small-signal response, by solving the Boltzmann transport equation:

$$-i\omega \tilde{f}(\vec{p}, x) + \frac{p_x}{m} \frac{\partial \tilde{f}(\vec{p}, x)}{\partial x} - \frac{e\varphi(x,0)}{m} \frac{\partial \tilde{f}(\vec{p}, x)}{\partial p_x} - e\tilde{E} \frac{\partial f_0(\vec{p}, x)}{\partial p_x} = \tilde{I}\{\tilde{f}\},$$

(2)

where $f_0$ and $\tilde{f}$ are the steady-state (dc) and the high-frequency (ac) parts of the distribution functions, $E$ and $\omega$ are the amplitude and frequency of the ac signal, respectively. Analytical solutions of Eq.(2) were found in the limit of ballistic electron motion between the walls of confinement potentials ($\tilde{I}\{\tilde{f}\} = 0$) by applying the method of characteristics and appropriate boundary conditions in the turning points (details of the solutions will be published elsewhere). Having the distribution function $f(\vec{p}, x)$ we calculated the ac current $\tilde{J}_\omega(x)$ in each point $x$ and the specific ac mobility, defined as follows: $\langle \mu_\omega \rangle = 1/\epsilon_{\text{eff}} E W \times \int_{-W/2}^{W/2} dx \tilde{J}_\omega(x)$. Here we consider the case of a rectangular potential that is approximately realized for planar NWs with charged edges. For a Boltzmann distribution $f_0$, the spectra of the real and imaginary parts of $\langle \mu_\omega \rangle$ are:

$$Re[\langle \mu_\omega \rangle] = \mu_0 \frac{16}{\pi^2} \sum_{k=1}^\infty \Omega^2 \frac{1}{(2k-1)^2} \exp\left(-\frac{\Omega^2}{\pi^2(2k-1)^2}\right)$$

$$Im[\langle \mu_\omega \rangle] = \mu_0 \frac{1}{17} \left[1 - \frac{1}{\sqrt{\pi}} \mathcal{P} \int_0^{\infty} \rho^2 \exp(-\rho^2) \tan\left(\frac{\pi}{2}\right) d\rho \right],$$

(3)

where $\mu_0 = eW/m^* u_T$, $\Omega = \omega W/u_T$, $u_T$ is the thermal velocity, the symbol $\mathcal{P}$ denotes Cauchy’s principal values of the integral. The real part of $\langle \mu_\omega \rangle$ that is responsible for the absorption of
an \(ac\) signal, has a maximum at frequency \(\omega/2\pi = v_T/2W\) which corresponds to the electron oscillation period with thermal velocity between the walls of the potential well. The imaginary part of \(\langle \mu_\omega \rangle\) changes its sign when real part reaches the maximum. These behaviors are illustrated in Fig. 3. For GaN NWs with \(W = 50 - 200\) nm, effects of the GR can be observed in the sub-THz frequency range. With increasing temperature (see Fig. 3(a)) or decreasing NW width (see Fig. 3(b)), the resonance frequency is shifted to higher frequencies together with a broadening of the absorption line. It is important to stress that the resonance absorption arises for ballistic (collisionless) electrons which execute a regular, oscillating motion in the potential well. Obviously, the scattering processes will destroy the regular electron motion that will lead to the additional broadening of GR resonance. When the characteristic sizes of confinement potential will be much greater than electron mean free path, the GR resonance vanishes and electron response on \(ac\) perturbation will be described by standard Drude-Lorentz model. It should be noted, that GR can be experimentally studied using the propagation loss spectroscopy of the single NW embedded to the THz-waveguide or THz- transmission lines [11].

In summary, we have found that the existence of edge traps in planar AlGaN/GaN NWs leads to the formation of wide depletion regions, large electrostatic fields outside the samples and strongly non-linear current-voltage characteristics. We have also found that the transversal ballistic transport that may take place in narrow wires dramatically modifies the high-frequency properties of the wire structures, leading to new resonance effects. These phenomena could also be important for devices based on NWs: indeed, similar effects have been reported for self-switching GaN diodes [12]. We suggest that the large electrostatic fields outside the NWs can be useful for bio-sensing applications, particularly, for mobilization and separation of ions, polar molecules and cells.

Acknowledgments
Authors thanks to Federal Ministry of Education and Research (Germany), BMBF Project 01DK13016 and CNRS (France)- NASU (Ukraine) Project 26206 for support this work.

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