Monte Carlo Simulation of THz Radiation Detection in GaN MOSFET n⁺nn⁺ Channel with Uncentered Gate in n-region

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Abstract. Electron transport and drain current noise in the wurtzite GaN MOSFET have been studied by Monte Carlo particle simulation which simultaneously solves the Boltzmann transport and pseudo-2D Poisson equations. A proper design of GaN MOSFET n⁺nn⁺ channel with uncentered gate in n-region to reach the maximum detection sensitivity is proposed. It is shown that the main role in formation of longitudinal transport asymmetry and THz radiation detection is played by optical phonon emission process. It is found that the detection current at 300 K is maximal in frequency range from 0.5 to 7 THz. At higher frequencies the detection current rapidly decreases due to the inertia of electron motion.

1. Introduction

To detect the microwave power semiconductor diodes with asymmetric current-voltage relation (CVR) are widely used. Usually, such an asymmetry is obtained by forming various barriers (pin, Schottky, heterojunction, etc.) in the active region. Unfortunately, in going to terahertz (THz) region the sensitivity of barrier-structures rapidly decreases due to time-delay related with large values of the barrier capacitance and its resistance. In contrast, as it was experimentally demonstrated [1], these restrictions can be overcome in detector based on asymmetrically necked n+ GaAs planar structure. The detector operated in wide frequency band (30 GHz - 2.5 THz) at room temperature [1]. Also the detector based on n+nn+ GaAs diode with nonuniform doped n region for room temperature operation in 20 GHz - 3 THz frequency band is proposed and simulated by Monte Carlo particle (MCP) technique [2]. It is shown in ref.2 that upper limit of detection range depends on optical phonon emission rate. The drain current vs drain voltage relation asymmetry needed for the microwave power detection in field effect transistors can be easily controlled by the gate position on the channel. The optical phonon emission rate in GaN considerably exceeds the one in GaAs.

The aim of this article is to study the possibility of THz detection in wurtzite GaN MOSFETs at room temperature. The electron transport and noise is simulated by the Monte Carlo particle (MCP) technique coupled to a pseudo-2D Poisson solver [3]. The main attention is paid to the optimum conditions for detection in the THz frequency range by varying the MOSFET geometry and doping. The mechanism responsible for THz detection is discussed from a microscopic point of view.
2. Model
Below we present the calculations of electron transport and noise in optimized for THz detection MOSFET structure based on a 50–450–50 nm n"n+p wurtzite GaN 50 nm wide channel. A 200 nm gate is placed in the n-region 200 nm away from n" source and 50 nm from the n" drain at a distance of 25 nm from the channel. The doping concentrations are $n = 10^{17}$ cm$^{-3}$ and $n^+ = 2 \times 10^{18}$ cm$^{-3}$. For Monte Carlo simulation the wurtzite GaN band and material parameters of a spherically symmetric nonparabolic conduction band are taken from Ref. [4]. Electron scatterings by polar optical and acoustic deformation phonons, and ionized impurities are included. The common source configuration is considered. All the calculations are made for 300 K temperature an gate bias $U_g = 0$ V. The number of simulated particles, depending on the case, is varied from $10^5$ to $10^6$. The time step in all cases was 0.5 fs.

3. Steady state
The drain current - drain voltage (I-V) relation calculated in GaN MOSFET is presented in Fig. 1. For better representation of the I-V relation asymmetry the negative values of bias and current are changed to positive ones. The asymmetry of I-V relation is evident from Fig. 1 where the absolute value of drain current at negative drain bias exceed the one at positive bias. In Fig. 2 the doping and electron concentration profiles in GaN MOSFET channel at $U_d = -0.2$ and 0.2 V are shown. One can see in

![Figure 1. GaN MOSFET I-V relation at drain bias from -0.8 to 0.8 V.](image1)

![Figure 2. The doping and electron concentration profiles in MOSFET channel at $U_d = -0.2$ and 0.2 V.](image2)

Fig. 2 the typical electron depletion region (red solid line) under the gate at positive bias while at negative bias the depletion region (green broken line) is absent because the gate is too close to n" drain. This depletion region gives the lower current values as compared with drain current at negative bias (see Fig. 1). Figures from 3 to 6 demonstrate various physical quantity profiles in GaN MOSFET

![Figure 3. Electron velocity profiles in channel at different drain biases: -0.2 and 0.2 V.](image3)

![Figure 4. Optical phonon local scattering profiles in channel at different drain biases: -0.2 and 0.2 V.](image4)
channel. In Fig. 3 the electron velocity at negative drain bias (green broken line) is shown with negative sign for better comparison with the one at positive drain bias. The increased velocity over the depletion region at positive bias (red solid line) is clearly seen. The optical phonon local scattering profiles are demonstrated in Fig. 4. The optical phonon local absorption profile is flat (Fig. 4, blue dotted line) because the absorption rate do not depend on electron energy. The optical phonon local emission rate profile have two peaks (see Fig. 4). At positive drain bias there is the peak in the channel centre and another one at the drain (Fig. 4, red solid line). At negative drain bias there is the peak in the channel centre and another one at the source (Fig. 4, green broken line). The number of optical phonon local emission peaks depends on potential difference which is flight by electron.

**Figure 5.** Electron energy profiles in channel at different drain biases: -0.2 and 0.2 V.

**Figure 6.** Electric field profiles in channel at different drain biases: -0.2 and 0.2 V.

Keeping in mind that optical phonon energy in wurtzite GaN is of 91.2 meV the two optical phonon emission local peaks are possible during 0.2 V flight (see Fig. 4). The electron energy profiles are demonstrated in Fig. 5. The electron energy minima at the centre of the channel are caused by optical phonon emission (see Fig. 4). Fig. 6 shows the electric field profiles in wurtzite GaN MOSFET channel. The high electric field spikes are formed at n’n junctions of source and drain contacts.

4. THz radiation detection

The wurtzite GaN MOSFET detector drain current response to the radiation is simulated applying to the structure an alternating bias $U(t) = U_1 \cos(2\pi ft)$, where $U_1$ is voltage induced along the channel by the microwave radiation and $f$ is the radiation frequency. The long current response trajectories are simulated. The drain current value is obtained by averaging in time the stationary part of trajectory.

**Figure 7.** Drain current dependence on alternating drain bias amplitude at frequencies 1 and 6 THz.

**Figure 8.** Drain current spectrum at alternating drain bias $U_1 = 0.2$ V.

The drain current dependencies on alternating drain bias amplitude $U_1$ at frequencies $f = 1$ and 6 THz and zero drain and gate biases are demonstrated in Fig. 7. The absolute values of detected drain
currents monotonically grow with the alternating drain bias amplitude $U_1$. The detected drain current spectrum in frequency range from 0.01 to 10 THz at alternating drain bias $U_1 = 0.2$ V is presented in Fig. 8. The absolute value of detected drain current monotonically grows with frequency and approach the maximum in frequency range from 0.5 to 7 THz. To explain the frequency dependence of detected drain current the optical phonon local emission profiles in wurtzite GaN MOSFET channel at alternating drain bias $U_1 = 0.2$ V and frequencies $f = 0.1$ and 1 THz are simulated (see Fig. 9). The considerable increase of optical phonon local emission rate at 1 THz frequency as compared with rate at 0.1 THz is evident. This optical phonon local emission rate resonant increase with frequency $f$ (see Fig. 9) gives the increase of detected drain current absolute values (Fig. 8). Also the drain current noise spectral densities are calculated at constant drain biases $U_d = 0.2$ and $-0.2$ V (Fig. 10, green broken and blue dotted lines). The drain current noise spectral densities at negative and positive drain biases have two maxima each. First maximum is around 1 THz and is associated with optical phonon emission induced plasma instability and the second one around 7 THz is the result of plasma oscillations at n’n junctions of drain and source contacts. The comparison of reverse detected drain current (absolute values of Fig. 8) with spectral noise densities in Fig. 10 clearly show that enhanced detection current in frequency range of 0.5 – 7 THz are coused by optical phonon emission processes. At frequencies over 7 THz the absolute value of detected drain current rapidly decreases due to the inertia of electron motion.

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