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# Hydrodynamic modelling of terahertz rectification in AlGaN/GaN high electron mobility transistors

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**Abstract.** We report on the numerical modelling of rectification in a gated two-dimensional electron gas. We demonstrate that drift-diffusion-based and energy-relaxation-based models predict different features of rectified terahertz radiation as a function of gate bias. Whereas the widely accepted mechanism for rectification is considered to be plasmonic-based, there are conditions when diffusion currents originating by non-local carrier heating can dominate the response. Moreover, diffusive contributions can substantially enhance the response becoming an important phenomenon, which has to be considered in future designs of efficient transistor-based terahertz rectifiers.

The prediction of plasma wave-resonances [1] in sub-micrometer-long channel field-effect transistors, (FETs) triggered a strong interest in applied aspects of plasmonic effects, which promise the extension of otherwise standard device operation beyond the conventional cut-off frequency limits. The plasmons, relating to a wave-like propagation of charge carriers, can manifest already at microwaves, yet they become increasingly pronounced in the terahertz (THz) frequency range. By now, it has been numerously reported in experimental [2, 3] and theoretic [4, 5] studies that plasmonic rectification can be employed for efficient detection of THz radiation. Despite such progress, there are many unresolved questions left regarding the validity of predictions from existing hydrodynamic models when applied for the modeling of practical devices (rectifiers or detectors).

In this contribution, we present numerical modeling results of THz rectification in sub-micrometer size AlGaN/GaN high electron mobility transistors (HEMT). For our numerical calculations, we employ a commercial SYNOPSIS TCAD package allowing to solve coupled Poisson, drift-diffusion, continuity and energy relaxation equations in multi-dimensional (2D or 3D) geometries. These equations form the basis for the so-called quasi-hydrodynamic or energy-transport model, which differs from a full-hydrodynamic approach by the omission of momentum relaxation [6]. For the reference calculations (excluding carrier heating) we employ simple drift-diffusion equations, which are analogous to a distributed RC transmission line model [7].

Figure 1 presents the 2D profile of the structure. All numerical simulations are performed in 2D assuming homogeneous properties in lateral dimension set to be 1 µm wide. The 2D-electon gas is formed between the 25nm-thick $Al_{0.2}Ga_{0.8}N$ layer and the undoped (intrinsic) GaN substrate. The gate length is set to 300 nm whereas the ungated parts are selected to be slightly asymmetric: 300-nm-long at the source side and 500-nm-long at the drain side. The ungated regions are covered with a 25-nm-thick $Si_3N_4$ passivation layer. At the SiN/AlGaN interface we include $5 \cdot 10^{13}$ $cm^{-2}$ donors located 0.4 eV

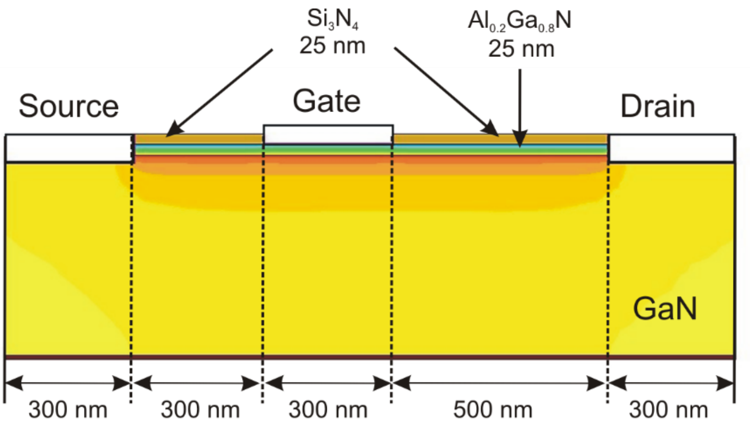

**Figure 1.** The structure of AlGaN/GaN HEMT employed for numerical simulations of THz rectification.

from the center of forbidden energy gap. Figure 2a shows the calculated static resistance as a function of gate bias. The knowledge of the static resistance allows estimation of the current responsivity in quasi-static conditions as it is usually performed for rectifying diodes [8]. $\mathfrak{R}_{I,QS} = 1/(2\sigma)d\sigma/dU_G = -1/(2R)dR/dU_G$. For the selected structure, the quasi-static current responsivity (presented in figure 2) peaks at -3.52 V reaching 5.47 A/W.

In order to calculate the rectification of THz radiation, we applied an oscillating voltage with an amplitude of 50 mV to the drain terminal placing the source terminal on ground. A fixed gate voltage implies that the gate terminal is equivalently shorted for all oscillating signals except of *DC*. Such a connection ensures asymmetric boundary conditions which are necessary for efficient rectification. We monitor the drain current in time domain which, after performing a Fast Fourier Transformation, allows obtaining the complex device impedance. The rectified signal is obtained from transient data by calculating the average current over one oscillation period after omitting the first 2 periods.

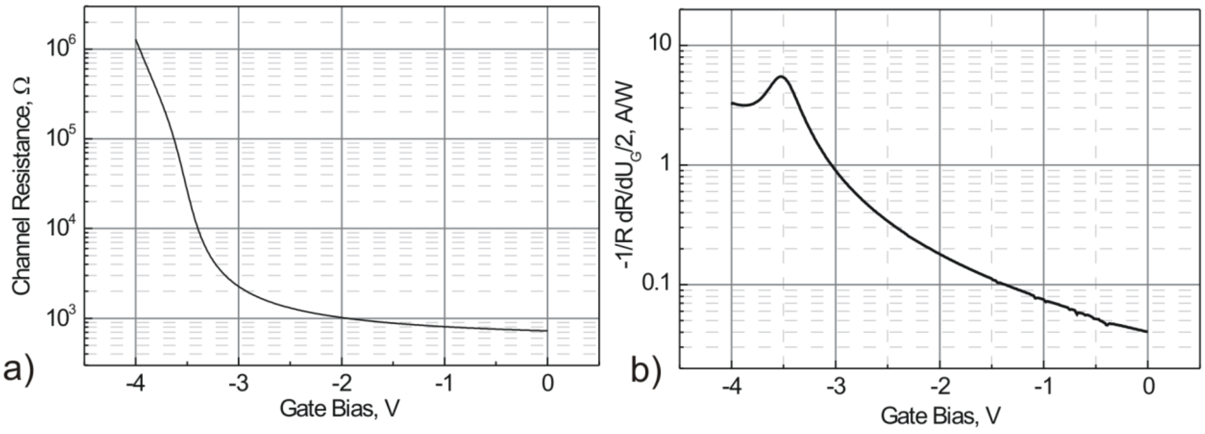

**Figure 2.** a) Modelled static resistance of the channel as a function of gate bias; b) static current responsivity as a function of the gate bias.

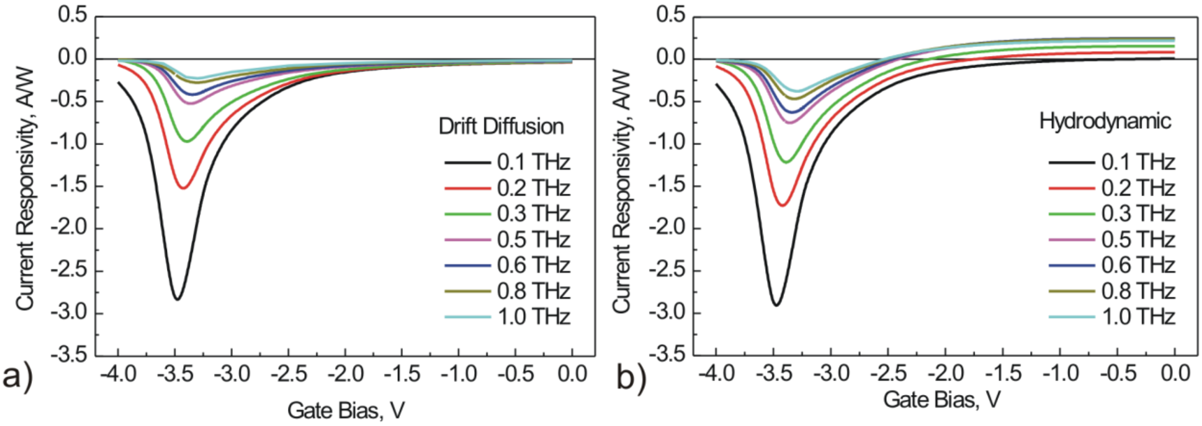

**Figure 3.** a) Current responsivity as a function of gate bias for various frequencies calculated with drift diffusion model, and b) calculated using hydrodynamic model.

We estimate the current responsivity by calculating the ratio between detected current and *AC* power absorbed by the device. Figure 3 presents the main simulation results. Since the oscillating signal is applied at the drain side, the current has negative sign. The left panel (a) presents the simulated responsivity using a drift-diffusion transport description whereas the right panel (b) presents modelling results when using the energy-transport hydrodynamic model. For comparatively low frequencies (100 GHz) both models predict similar rectification with a peak responsivity of about 2.8 A/W. With increasing frequency, the absolute value of the current responsivity decreases. Although intrinsic rectification in a distributed *RC* model should not be frequency dependent, such decrease originates from increasingly important power loss on the ungated parts at higher frequencies. It is important to note, that a hydrodynamic model predicts a reversal in the direction of the rectified current for large gate bias (in respect to threshold voltage) which cannot be explained by plasmon-based models. These predictions are supported with experimental data [9] of THz detection using AlGaN/GaN HEMTs with integrated broadband antennas.

Our experiments did not show this strong crossover between plasmonic mixing and diffusion of “warm” carriers, which might indicate that the omitted momentum relaxation terms lead to an overestimation of diffusive contributions. Moreover, the current responsivity at the maximum of the

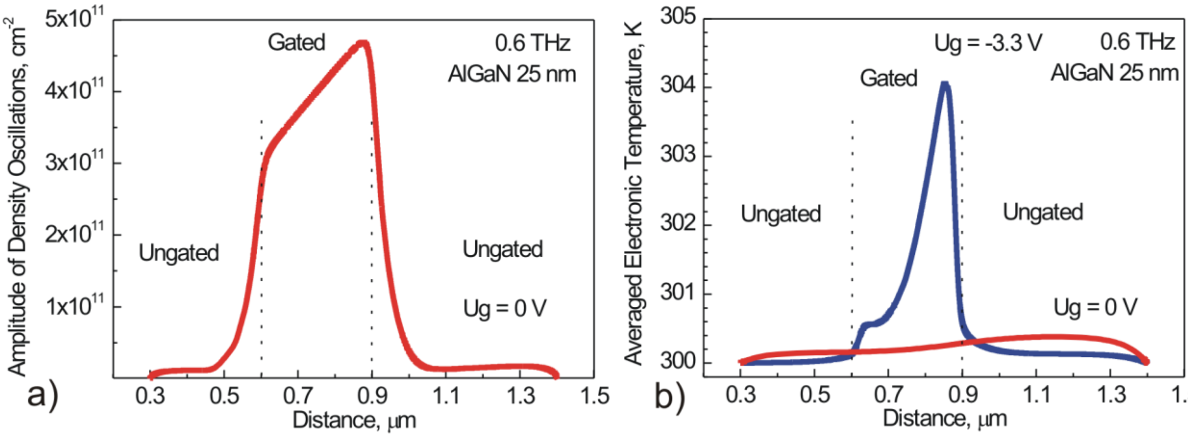

**Figure 4.** a) The lateral distribution of the amplitude of density oscillations using 600 GHz excitation for zero gate bias; b) Lateral distribution of averaged electronic temperature for two gate voltages.

absolute value of response is substantially increasing over drift-diffusion simulations at THz frequencies indicating the importance for thorough simulations of non-equilibrium carriers [10].

Figure 4 (a) demonstrates the distribution of the amplitude of the oscillating charge carriers for zero gate bias conditions, whereas the right panel (b) presents the distribution of average electronic temperature at zero gate bias and at gate bias resulting to the maximum of absolute current responsivity. Therefore, even if the carrier temperature does not change much, its lateral distribution results in an additional diffusion current, which at zero gate bias dominates the response with respect to plasmonic detection, whereas close to the threshold, the plasmonic detection is enhanced.

In summary, we show that heating of charge carriers by the coupled high-frequency radiation plays an important role in the modelled response of field-effect transistor-based THz detectors.

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