Performance Study of Nitride-Based Gunn Diodes

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ABSTRACT

In this work, the performance of InN and GaN Gunn diodes is assessed by means of two-dimensional mixed-mode device/circuit simulation. A proprietary hydrodynamic high-field mobility model is used, calibrated against Monte Carlo simulation data, which properly accounts for the negative differential mobility effect. Available theoretical results for GaN-based Gunn diodes are verified. The simulation results predict superior performance of GaN below 200 GHz while InN Gunn diodes show promising potential for the higher frequency range.

Keywords: simulation, Gunn diodes, Indium Nitride, Gallium Nitride

1 INTRODUCTION

Low-power microwave transmitters require nanoscale devices operated in terahertz regime. This can be achieved by using transferred-electron devices based on Gunn oscillations (Gunn oscillators). Such devices exhibit favorable characteristics, like low FM noise, which makes them suitable for applications like injection-locked oscillators and amplifiers [1]. Negative differential mobility (NDM) is a requirement for the occurrence of the Gunn effect, which has been already extensively studied in GaAs. The frequency of oscillation of a Gunn device is determined by the time taken for a Gunn domain to form and complete the transit between the cathode and anode contacts [2]. For this reason, it would be desirable to minimize the transit time of Gunn domains, in order to achieve higher frequencies. This can be realized through a higher electron drift velocity. The wide bandgap group III-Nitride materials have several advantages, which include a large bandgap, a high breakdown field, and a high electron drift velocity. From this group, GaN drew attention recently, since it exhibits favorable velocity-field characteristics [3] and can offer higher operation frequency than GaAs [4]. In recent work [5], bias oscillations could be observed for a GaN Gunn diode realized on a n^+-GaN substrate. A material with even more favorable velocity-field characteristics is InN. This material offers both about fifteen times higher NDM as well as about six times higher low-field mobility than GaN. However, InN did not attract much interest so far, most probably due to its narrower bandgap than that of GaAs. In this work, we evaluate and compare the performance of GaN and InN devices.

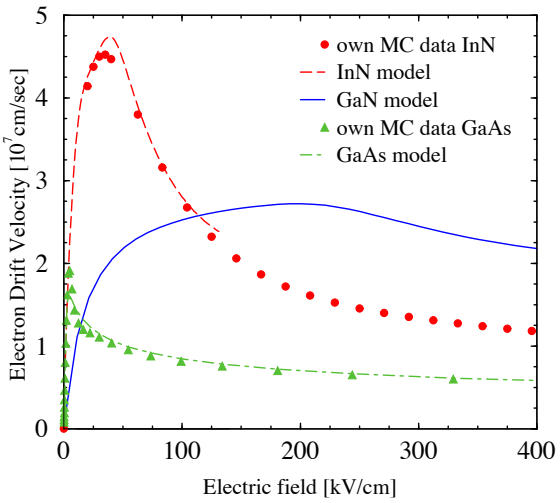

Figure 1: Electron drift velocity vs. electric field.

2 PHYSICAL MODELING

Novel emerging devices based on the Nitride material system require physics-based models to properly describe their electrical and thermal behavior. Basic parameter for expressing the currents in a semiconductor device is the carrier mobility. In recent work we proposed new mobility models for electrons suitable for the drift-diffusion and the hydrodynamic transport models [6,7]. These models were calibrated against Monte Carlo simulation results and experimental data for GaN, AlN, and InN [8]. Specific effects are accounted for, such as the negative differential mobility observed at high electric fields (see Fig. 1), which is a reason for occurring of Gunn oscillations [9]. The models and the model parameters values were implemented in our two-dimensional device/circuit simulator [10] and were verified against measured transistor characteristics and allow simulation of various III-Nitride semiconductor devices.

Table 1: Physical parameters and design constraints for GaN, InN, and GaAs devices.

Material	GaN	InN	GaAs
μ_0 [cm^2/Vs]	1600	10200	8000
D_s [cm^2/s]	40	270	180
ε_r	8.9	11	12.9
ν [cm/s]	2.5×10^7	4.8×10^7	1.5×10^7
F_{th} [kV/cm]	200	40	4
μ_{NDR} [cm^2/Vs]	40	650	1000
$N \times L$ [cm^{-2}]	1.6×10^{13}	2.1×10^{12}	3×10^{15}
N_{crit} [cm^{-3}]	4×10^{18}	5×10^{17}	5×10^{11}

3 DESIGN CRITERIA

Gunn oscillators typically employ of n-i-n diode structures, which must fulfill specific design criteria [9]. One of them is the so-called Kroemer criterion:

$$N_0 \times L > \frac{3\varepsilon_r\varepsilon_0\nu}{q \mid \mu_{NDR} \mid}. \quad (1)$$

Here, N_0 denotes the doping concentration in the intrinsic layer, L is its length, $\varepsilon_r\varepsilon_0$ is the material's dielectric permittivity, ν is the velocity of the Gunn domain, and μ_{NDR} is the negative differential mobility. This criterion must be fulfilled in order Gunn domains to occur. Another condition must be fulfilled to secure stable amplification regime:

$$N_0 < N_{crit} = \frac{\varepsilon_r\varepsilon_0\mu_0 F_{th}^2}{qD_s} \quad (2)$$

μ_0 is the low-field mobility, F_{th} is the threshold field for inter-valley transfer, and D_s is diffusion coefficient. The parameter values are summarized in Table 1 together with the resulting values for N_{crit} and $N_0 \times L$. As can be seen in Table 1 the higher F_{th} leads to some orders of magnitude higher N_{crit}. On the other hand, the lower limit for the $N_0 \times L$ product is higher for Nitrides due to higher electron velocity and lower NDM.

The simulated devices have a homogeneously-doped active layer of 1 μm or 3 μm length and two highly-doped (10^{19} cm^{-3}) regions of 0.1 μm each. The donor concentration in the active layer is chosen so that the critical doping concentration for GaN [11] and InN is not exceeded for both devices. In this way, the formation of static Gunn domains in the anode is avoided and the device's operation in the NDM regime is ensured.

4 SIMULATION RESULTS

In order to obtain much higher efficiency, the device is placed into a microwave LCR-cavity as depicted in Fig. 2. This is a parallel resonant circuit which needs to be matched for each geometry, doping and material (see Table 2).

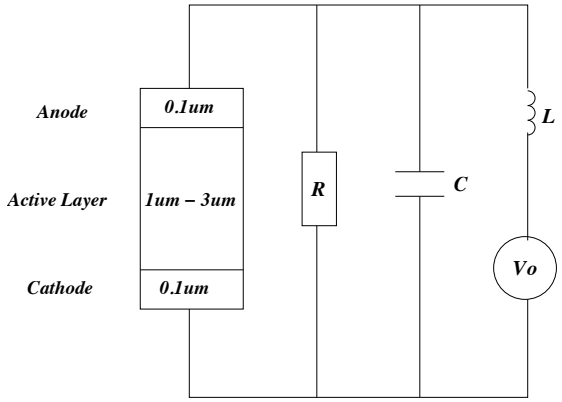

Figure 2: Schematic of the Gunn diode and resonant cavity.

As the first step, our model was verified against results from [4] for a GaN Gunn diode with $L = 3\mu$m, $N_0 = 10^{17}$cm^{-3}, and device area of 2000μm^2. Using the same LCR-circuit identical results were obtained (see Table 2). Fig. 3 shows snapshots of the evolution of the electron concentrations in the GaN diode, which are taken in subsequent time instances with interval of 1 ps. As can be seen in the Fig 3, stable domains of high electron concentration occur, which lead to inhomogeneities in the electric field distribution, illustrated in Fig. 4. Accordingly, the electron concentration and electric field for InN diode is depicted in Fig. 5 and Fig. 6 . As the devices are biased over the threshold field F_{th} (≈200 kV/cm for GaN against ≈40 kV/cm for InN), the formation of a first stable Gunn domain near the cathode at t_0 is observed. At the next time instances, the Gunn domains propagate in the direction of the anode, where they are annihilated. The formation of Gunn domains will continue as long as the mean electric field is above the threshold field F_{th}. A comparison between Fig. 3 and Fig. 5 shows that the Gunn domains propagate much faster in the InN diode. This is due to the considerably higher electron velocity in this material.

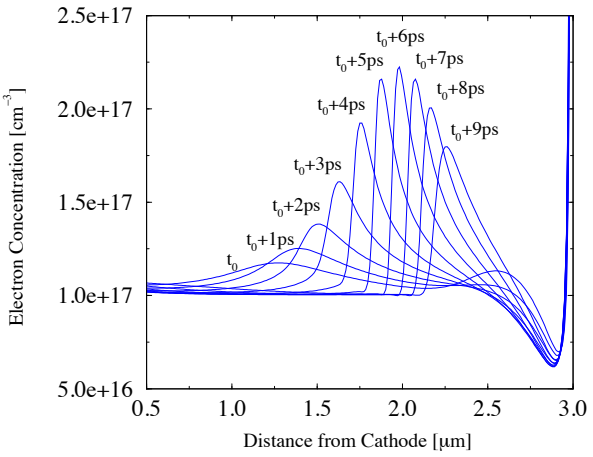

Figure 3: Electron domains in the GaN diode with time step Δ t = 1 ps (t$_0$=40 ps).

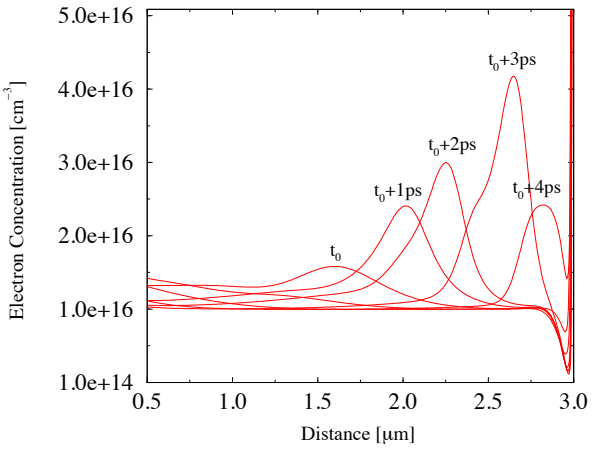

Figure 5: Electron domains in the InN diode with time step Δ t = 1 ps (t$_0$=40 ps).

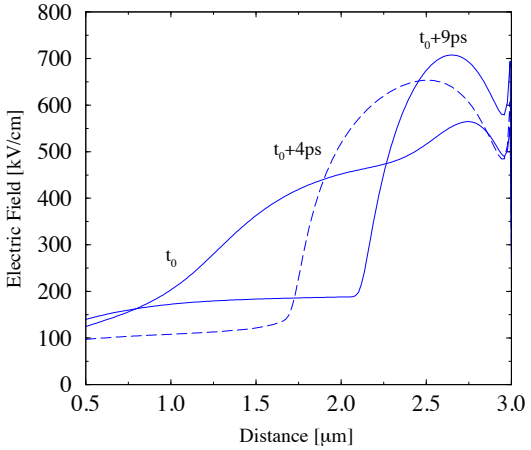

Figure 4: Electric field in the GaN diode at time steps t = 4 ps, 9 ps (t$_0$=40 ps).

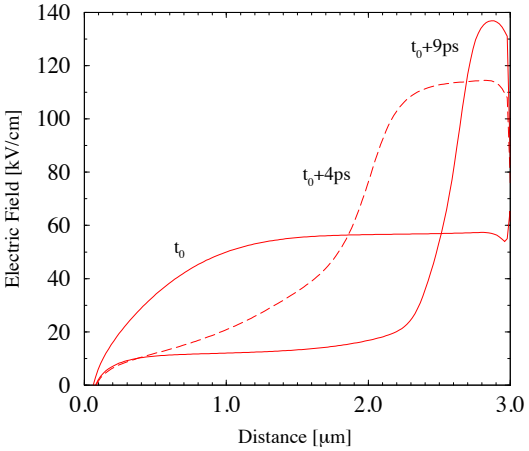

Figure 6: Electric field in the InN diode at time steps t = 4 ps, 9 ps (t$_0$=40 ps).

Using the mixed-mode device/circuit transient hydrodynamic simulation the output waveforms of the devices are obtained (see e.g. Fig. 7 and Fig. 8). These waveforms are used to extract the oscillation frequency and the output power. Input parameters and the corresponding simulation results for the 3 μm devices of GaN, InN, and GaAs are summarized in Table 2.

Using the same simulation approach, the performance of GaN, InN and GaAs devices with an active length of 1 μm was investigated. For the geometry given and taking into consideration the design constraints, the doping concentrations, the bias voltage, and the LCR-cavity parameters were tuned for maximal device performance (see Table 3).

The simulation results predict superior high-frequency and power performance for both Nitride compounds compared to GaAs. While GaN significantly outperforms other materials in terms of power density at frequencies below 200 GHz, InN shows comparable performance at about 200 GHz.

5 CONCLUSION

In this paper, we present simulation results of Nitride-based Gunn diodes. Our investigations show that both GaN and InN outperform GaAs in microwave applications. In addition, Nitride-based Gunn diodes are suitable for integration in upcoming Nitride technologies. Although GaN has attracted much interest recently, InN also offers potential advantages. Due to higher NDM, InN devices would easier fulfill the criteria for operation in the Gunn-regime, which gives them a good chance of experimental realization.

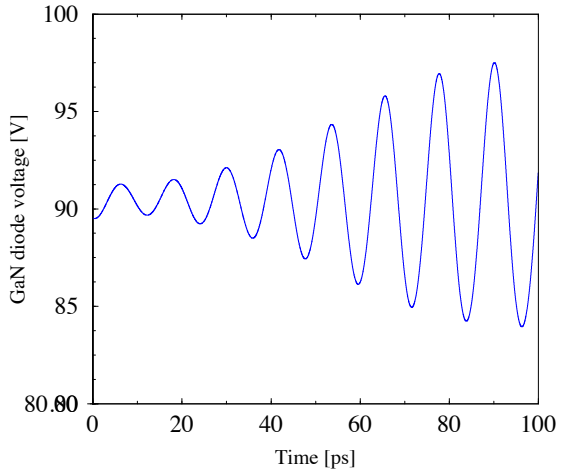

Figure 7: Voltage waveforms for the 3 μm GaN diode.

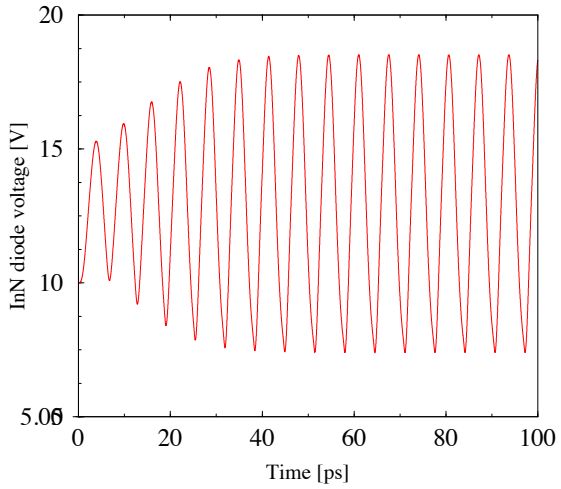

Figure 8: Voltage waveforms for the 3 μm InN diode.

6 ACNKOWLEDGEMENTS

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Table 2: Device and setup parameters for the 3 μm devices.

Material	GaN*	GaN	InN	GaAs
N_0 [cm^{-3}]	10^{17}	10^{16}	10^{16}	10^{16}
V_0 [V]	90	90	13	2
L [pH]	17.5	17.5	8	0.1
C [pF]	0.1	0.1	0.01	25
R [Ω]	50	50	90	50
f [GHz]	70	85	150	97
Power [W/cm^2]	3×10^5	3×10^4	3×10^2	1.6

Table 3: Device and setup parameters for the 1 μm devices.

Material	GaN	InN	GaAs
N_0 [cm^{-3}]	5×10^{17}	5×10^{17}	10^{16}
V_0 [V]	45	8	2
L [pH]	1.0	0.08	0.1
C [pF]	0.2	5.0	25
R [Ω]	150	150	150
f [GHz]	200	213	103
Power [W/cm^2]	6×10^4	4.5×10^4	1.0

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