Influence of Accurate Electron Drift Velocity Modelling on the Electrical Characteristics in GaN-on-Si HEMTs

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***Abstract*—The influence of an accurate electron velocity-field relationship modelling on pulsed IV and small-signal RF characteristics in GaN-on-Si HEMTs is discussed and compared to measurements. We show by technology computer-aided design (TCAD) simulation and measurements that not only the low-field mobility and saturation velocity are of great importance, but also the transition behaviour in between has to be modelled accurately. Experimentally, we extract the velocity-field relationship using device simulation and measured data with ultra short pulse lengths. To the best of our knowledge, this is the first study on the velocity-field relationship in GaN-on-Si devices.**

***Index Terms*—Gallium nitride, saturation velocity, velocity field curve, GaN-on-Si, TCAD**

I. Introduction

Gallium nitride based devices gained a lot of attention in the last years for power as well as RF-power applications due to the inherent advantages of the III-nitride material system. In combination with silicon as substrate, the advantages of the III-nitrides can be offered for cost sensitive applications. However, optimizing GaN High-Electron-Mobility-Transistors (HEMTs) remains challenging. Virtual prototyping based on technology computer aided design (TCAD) is hence a valuable guidance for device design. Compared to already successfully established silicon device simulations, TCAD simulations of III-nitrides are so far not as predictive. A major reason is the lack of well-calibrated empirical models supporting the simulations. Special focus should be put on the correct modelling of the electron velocity-field relationship, since high electric fields are commonly present in GaN based devices. Several studies extracting the velocity-field relationship for GaN-on-Sapphire and GaN-on-SiC are available in literature [1]–[6]. However, the increased density of dislocations in GaN-on-Si devices [7] compared to GaN-on-Sapphire or GaN-on-SiC affects the coulomb scattering mechanisms [8] and thus is expected to influence also the velocity-field curve [9]. Furthermore, studies extracting the full velocity-field relationship based on an analytical model that can be used for TCAD based simulations are barely available [10]. Hence, common practice in TCAD studies is to model low-field mobility and saturation velocity only, whereas different models for the full velocity-field curve are used [11]–[14]. In this study, we extract the full GaN-on-Si velocity-field relationship including an analytical representation that can be easily used in TCAD simulations. We show that in particular the transition regime has a big impact on the modelled characteristics and needs to be taken into account carefully. To our best knowledges, this is the first report discussing the full velocity-field relationship of GaN-on-Si devices.

II. Experimental Methods and Simulation Setup

A. GaN-on-Si Technology and Fabrication

AlGaN/GaN heterostructures grown on high resistivity (4000 Ωcm) silicon (111) substrate by metal-organic chemical vapour deposition (MOCVD) are investigated. The epitaxial layers consist of a nucleation layer, a stress mitigation buffer, a GaN channel and a 21 nm thick $Al_{0.20}Ga_{0.80}N$ barrier layer. Test structures for velocity-field relationship measurements and AlGaN/GaN HEMTs with 450 nm gate length as well as gate and source connected field-plates were fabricated and passivated by SiN. The specially designed test structure for the velocity-field relationship characterization is shown in Fig. 1. The ohmic contact length l was chosen to be much bigger than the contact transfer length $l > 2L_T$.

B. Electrical Characterization

For characterizing the velocity field relationship and pulsed transistor curves we use a four point Kelvin TLP method [15]. The force and sense pads were connected with GGB picoprobes each to eliminate possible errors from non-zero contact resistance of the probes at high currents. An ultra short pulse width of 5.0 ns and a rise time of 0.3 ns were used to avoid unintentional self-heating during the characterization of the velocity field relationship. Similarly, the transfer and output characteristics of the fabricated GaN HEMTs were measured with short pulses. Small-signal RF measurements were performed on an Agilent N5230A vector network analyzer (VNA) by measuring the s-parameters. For calibration an off-chip SOLT standard as well as short and open on-wafer de-embedding was used.

C. TCAD Simulation

Two-dimensional TCAD drift and diffusion simulations based on Fermi statistics are performed using the commercial tool Synopsis Sentaurus. The geometric dimension of the test and device structure were obtained from layout as well as scanning electron microscope (SEM) pictures. The buffer above the substrate is simplified by using AlGaN layers with various concentrations for the carbon doping. The doped layers are modelled by an auto compensation model using shallow donors and deep acceptors [16]. The 2DEG density of $7{\cdot}10^{12}$ cm^{-2} as well as the low-field mobility were fitted according to Hall-measurements. For the low-field mobility the constant-mobility model was used after [17]. The ohmic contact resistances were carefully determined with TLM measurements [18] and accordingly used during simulation. For the surface physics a simplified Fermi-level pinning model based on surface donors is used [19]. The piezoelectric charge is taken into account according to the built in model of the simulator following [20]. For high-field saturation the Farahmand-Model [1] is used and fitted according to own measurements as discussed below.

III. Results

A. Extraction of Velocity-Field Relation

To characterize the velocity-field relationship experimentally, we measure the pulsed I-V characteristics of the specially designed test structure and extract the parameters for the Farahmand model by comparing to simulations of the same structure. This procedure has the advantage of taking non-

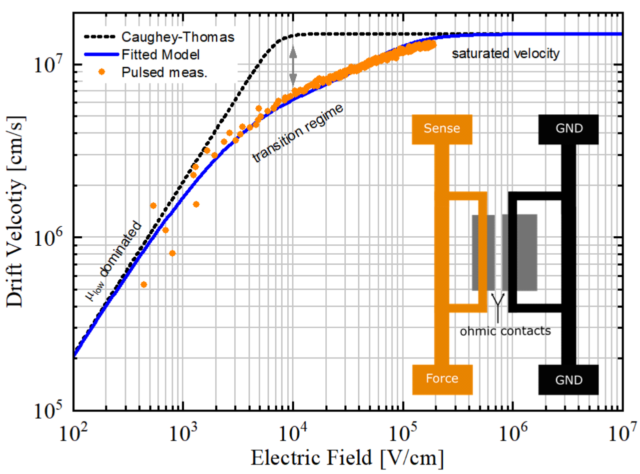


Fig. 1: Velocity-field relationship comparison between the measured values, the fitted Farahmand and the Caughey-Thomas model.

uniform carrier concentration and electric field variations into account as well as not using the approximation $v_d = I/qn_S$. The fitted Farahmand model, given by Eq. 1

$$v_d = \frac{\mu_0 E + v_{sat}\left(\frac{E}{E_0}\right)^{n_1}}{1+\alpha\left(\frac{E}{E_0}\right)^{n_2} + \left(\frac{E}{E_0}\right)^{n_1}}, \tag{1}$$

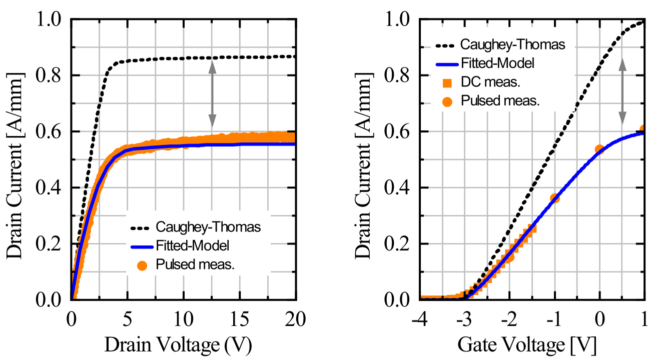
together with the measured data is shown in in Fig. 1. The low field mobility is denoted by μ_0 and the saturation velocity by v_{sat}. The parameters used are given in Tab. I.

TABLE I: Extracted parameters for the fitted Farahmand velocity-field model.

Extracted parameter	Value
v_{sat} $[cm/s]$	1.50 10^7
E_0 $[V/cm]$	2.4550 10^4
α	6.187
n_1	2.912
n_2	1.025

B. Impact of Accurate Velocity-Field Relation Modelling

The importance of accurately modelling the full velocity-field relationship is discussed in the following. Two velocity-field models are plotted in Fig. 1, were we compare our fitted model to the often used Caughey-Thomas model [21] given by $v_d = \mu_0 E / \left(1 + (\mu_0 E / v_{sat})^{\beta}\right)^{1/\beta}$. The major difference for the two models can bee seen for electric fields between 10^3 V/cm and 10^5 V/cm. Our fitted model exhibits much lower drift velocities in the transition regime compared to the Caughey-Thomas model. Comparing to device simulations of the fabricated GaN-on-Si HEMTs, this difference directly translates into a much lower saturation current and transconductance as shown in Fig. 2a and Fig. 2b. Only by using an accurate modelling of the transition regime results in a good agreement with measurements.



(a) (b)

Fig. 2: Comparison of simulated and measured transistor characteristics under pulsed and DC conditions. In (a) the IdVd curve for $V_{gs} = 0\ V$, and in (b) the IdVg curve for $V_{ds} = 5\ V$ is shown.

To further discuss this difference between the two models used we compare the simulated drift velocity and electric field parallel to the channel between the drain side edge of the gate and the drain contact as shown in Fig. 3. The electric

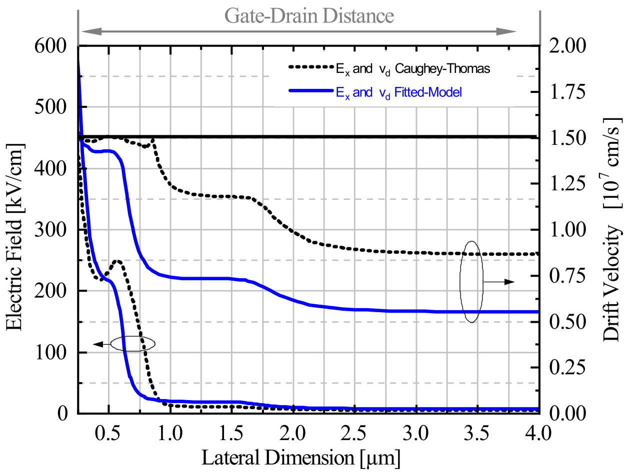


Fig. 3: Drift velocity (dashed lines) and electric field along the channel (solid lines) for the two different velocity-field relationships at $V_{gs} = 0\ V$ and $V_{ds} = 20\ V$. The Caughey-Thomas velocity-field relationship overestimates the drift velocity inside the device.

fields along the channel are qualitatively comparable for both models with a peak electric field at the gate edge and a second lower field peak at the gate field plate corner. However, for the Caughey-Thomas model the region where the drift velocity remains at the saturated value is much bigger and shows an overall higher value throughout the whole gate-drain region. This difference in drift velocity between the Caughey-Thomas model and the fitted model explains the significant difference in the simulated characteristics.

Finally, we compare the simulated h_{21} RF characteristic to measurements, as shown in Fig. 4. There, the current gain h_{21} for a fixed drain current and drain voltage of 20 V is shown. The higher drift velocity for the Caughey-Thomas model leads to an increased h_{21} and to an overestimated f_t compared to the measured values, whereas the simulations based on the fitted velocity-field relationship matches the measurements well.

IV. Conclusion

We have experimentally characterized the velocity-field relationship in GaN-on-Si devices at room temperature and presented an analytical model that can be easily used in TCAD simulations. We discussed the influence of the velocity-field relationship on the device characteristics and concluded that not only modelling the low-field mobility and saturation velocity is of great importance, but also the full velocity-field relationship has to be modelled accurately in order to match experimental obtain DC and RF characteristics of GaN-on-Si transistors. To the best of our knowledge this is the first report discussing the velocity-field relationship in GaN-on-Si based transistors.

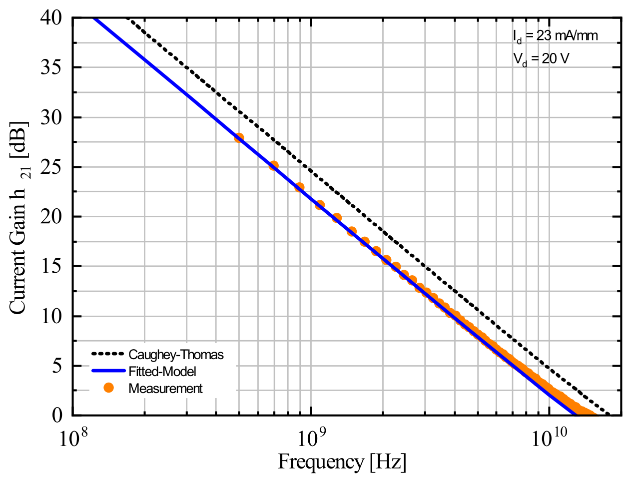


Fig. 4: Current gain h_{21} for fixed drain current and voltage. The measurements are compared with two different velocity-field relations, where only the fitted model matches the measured results.

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