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TCAD simulation capabilities towards gate leakage current analysis of advanced AlGaN/GaN HEMT devices

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ABSTRACT

2D TCAD Sentaurus simulations based on Drift-Diffusion transport are performed to identify the modeling parameters that crucially affect the reliability characteristics of AlGaN/GaN HEMT devices, demonstrated by their effects on the gate leakage characteristic. The behavioural nature and impact of each parameter on the leakage performance is discussed. Schottky gate tunneling and trapping effects within the structure are two major reliability issues that modulate the leakage characteristic. Hence, their contributions are precisely modeled. A simulation methodology is presented to recognize the relative control of individual parameters on distinct regions of the leakage characteristic. This modeling approach is demonstrated for a GaN HEMT technology and can be further applied to facilitate reliability comparisons across different device technologies. This validates TCAD simulation to be an effective aiding tool in reviewing and interpreting GaN HEMT reliability performance and design choices.

1. Introduction

Technology Computer Aided Design (TCAD) simulation has emerged as an advantageous tool to investigate various reliability concerns of AlGaN/GaN HEMTs such as current collapse [1], gate lag and drain lag [2]. However, simulating the unique III-N HEMT with its polarization charges is a challenge and requires further work to isolate inherent correlations within factors controlling and modulating device behaviour.

The gate leakage current describes the robustness of the pivotal gate-drain region and is linked to GaN HEMT reliability. Reverse gate leakage is often substantially higher than predicted by thermionic emission which deteriorates high voltage operation and standby power dissipation [3,4]. Significant research has been performed to interpret gate leakage mechanisms [5–10]. Many works have confirmed the contribution of tunneling through the Schottky barrier to the increased leakage [6–8]. While Poole-Frenkel emission could assist conduction at high temperatures [8,9], surface trap related hopping conduction [10] and trap assisted tunneling mechanisms [6,9,10] have also been reported. The gate leakage current still requires improved modeling, probably because it is susceptible to various degradations that could be undiscernible in other outputs. Also, the motivations behind choosing certain parameter values for modeling a particular device or technology are often unclear.

To address these issues, this work targets simulation of device parameters that majorly control the I_G-V_G characteristic. The process to recognize the physical limits and establish the correct operational ranges for these crucial parameters, and thus, to build a consistent model for a GaN based HEMT is discussed. Two critical reliability issues affecting leakage performance are carefully modeled: Gate tunneling described by the Non-Local tunneling model; trapping effects through introduction of acceptor traps within the simulated structure. A methodology is proposed to recognize the relative control of parameters on distinct regions of the I_G-V_G characteristic, aiding to identify primary parameters that are relevant to performance optimization across different operational conditions or technologies.

2. TCAD simulation approach

A physical AlGaN/GaN HEMT model is built to virtually represent internal transistor operation using the Sentaurus tool from Synopsys [11]. The model is based on the Drift-Diffusion (D-D) transport model and Fermi statistics. A doping dependence model and a high velocity saturation model, driven by a field computed as the gradient of the electron quasi-Fermi level, are defined for electron mobility. The SRH model for generation-recombination is activated. The source and the drain regions (see Fig. 1) are defined in Sentaurus as "modified ohmic" contacts [11]. This definition while reproducing the electrical behaviour of an ohmic

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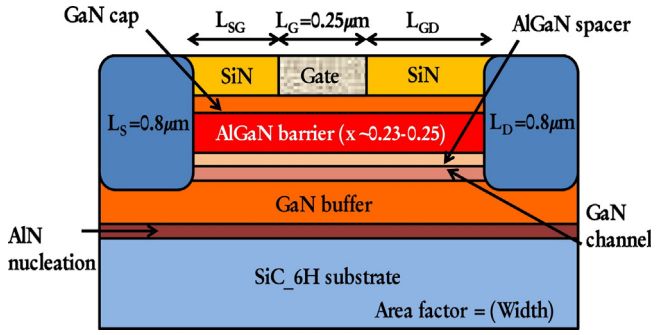

Fig. 1. Simulated 2D GaN HEMT structure details.

contact does not impose the charge neutrality condition at contact vertices, thus helping to prevent inaccurate simulations around charged depletion regions.

Defining reference values for major parameters is crucial in reproducing a characteristic GaN HEMT. Each parameter is studied individually to identify its physical range through its impact on global I_G-V_G. To enable unambiguous inferences, parameter variations are performed under ideal or degradation-free initial conditions. The activated thermionic emission (TE) model dominantly controls the gate current response in this ideal model.

2.1. 2D TCAD structure details

The simulated 2D TCAD structure in Fig. 1 is built to closely resemble the advanced GaN HEMT GH-25 process from United Monolithic Semiconductors (UMS). Except the thin 2 nm GaN cap, which is highly n-doped, the rest of the structure has minimal doping. A non-uniform mesh [11] of nodes is created to discretize the physical properties and numerically simulate the HEMT behaviour. The mesh is markedly finer at gate edges, especially for the Gate-Drain, and all semiconductor interfaces, to ensure both robust and efficient simulation.

2.2. Simulation of gate Schottky contact

An essential step to develop a complete HEMT model is physical simulation of the gate Schottky contact. The Schottky barrier Φ_B at the surface is theoretically defined as the difference of the gate metal work function and the electron affinity of the semiconductor. Standard thermionic emission theory can however be applied to extract the effective Schottky barrier height $\Phi_{B,eff}$ directly from the device forward gate characteristics I_{Forw} using:

$$I_0 = AA^*T^2 \exp\left(\frac{\Phi_{B,eff}}{\eta k_B T}\right), \quad (1)$$

where I_0 is the saturation current obtained as the zero-bias intercept through extrapolation of the linear region of I_{Forw}. A is the contact area, A^* is the effective Richardson's constant, T is the absolute temperature and η is the ideality factor.

It is a preferable simulation technique to choose Φ_{ms} as a parameter instead of directly specifying Φ_B for Schottky contacts on semiconductors such that the $\Phi_{B,eff}$ is calculated internally. An $\Phi_{B,eff}$ ~ 0.9 eV has been previously extracted from UMS GH-25 measurements in [12], and also reported in other works [2,13–15]. For the mole fraction range of $x = 0.235–0.25$, a χ_{AlGaN} of 3.425–3.45 eV and a $\chi_{GaN} =$ 3.9 eV is considered in Sentaurus material parameter files [11]. A gate contact with $\Phi_{ms} = 4.4$ eV well approximates the measured I_{Forw} current levels, resulting in an effective gate to channel barrier of ~1 eV. Hence, it's chosen as the reference value.

A distributed gate resistance (R_G) is the other major parameter defining a Schottky gate. As observed in Fig. 2, an increase in R_G reduces

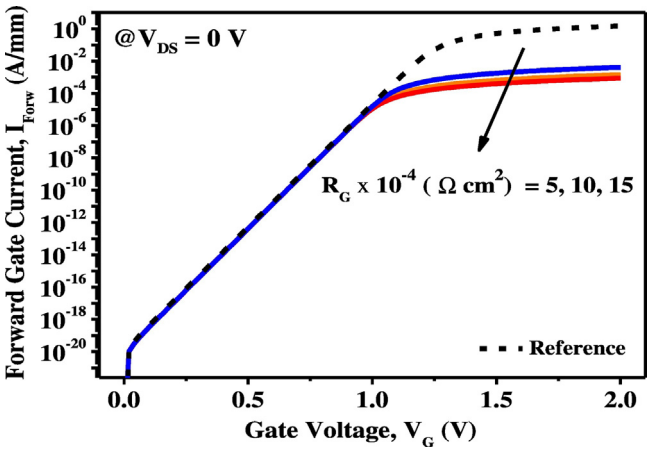

Fig. 2. Forward I_G-V_G characteristics for varying R_G.

the I_{Forw} in the high current regime ($V_G > 1$ V). However, as can be expected, the activation of R_G has no influence on reverse gate characteristics (I_{Rev}). No reference R_G is defined to better isolate the effects of parameters described in the following sections.

2.3. Effect of surface donors

The GaN HEMT is singular because of the piezoelectric and spontaneous polarization charges at device interfaces, which require detailed modeling. The "Piezoelectric Polarization" model in Sentaurus [11] internally calculates these interface charges, and is activated in our simulations as a function of strain. Surface-Donors (S-D) at the top SiN/GaN cap interface support and control the 2-dimensional electron gas (2DEG) concentration formed in the quantum well at the AlGaN/GaN hetero-interface. Hence, they are both inevitable and indispensable in the GaN HEMT system. Both S-D density (N_{S-D} in cm^{-2}) and energy (E_{S-D} in eV) need careful optimization for a given structure to sustain the complete activation of 2DEG, and thereby achieve maximal device performance. Works on simulation of GaN HEMTs [13,14] generally choose S-D definitions based on fits to experiments, or previous literature. However, reasons for which specific N_{S-D} or E_{S-D} values might be physically more suitable than others remain abstruse. I_G-V_G characteristics offer a coherent approach towards interpreting the physical origin of changes due to variations in N_{S-D} or E_{S-D}.

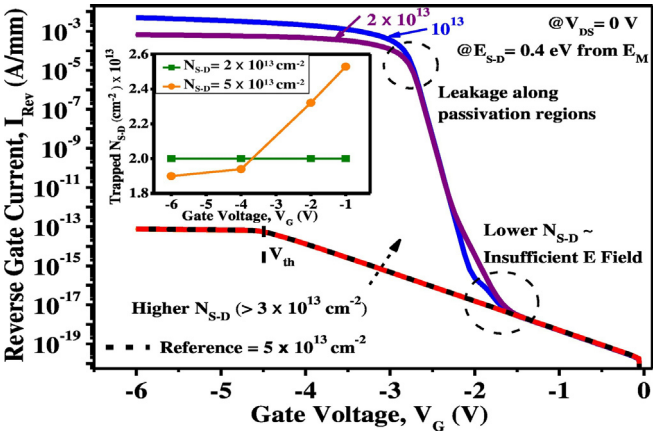

Fig. 3. I_{Rev} characteristics for varying N_{S-D}; inset: Trapped N_{S-D} as a function of reverse V_G bias.

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