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Modeling AlGaN/GaN HEMTs degradation due to hot carrier injection in the passivation layer

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***Abstract*—We propose a modeling approach to describe the degradation of power AlGaN/GaN HEMTs under semi-on stress by hot carriers. A semi-analytical model for hot-electron injection into the passivation layer has been developed based on a detailed analysis of Monte Carlo device simulation results. The model is then incorporated into the TCAD tool Sentaurus Device using the Physical Model Interface. TCAD simulations are then employed to compute the evolution of the drain current during high drain-to-source voltage stress conditions.**

I. INTRODUCTION

THE advantage of GaN power HEMTs compared to other power transistors lies mainly in their ability to operate at high electric fields. In these conditions, typical of, e.g., the saturation regime during hard-switching commutation [1], significant hot-electron generation occurs. As we recently reported in [2], in normally-off p-GaN gate HEMTs with a single thin AlGaN barrier (Fig. 1), hot-electrons can easily diffuse across AlGaN layer, impinge onto the passivation, and get trapped therein, leading to a dynamic-$R_{DS(on)}$ increase. Accurate modelling of this phenomenon is of great importance for device design [3]. However, hot-carrier transport modeling requires the solution of the Boltzmann Transport Equation (BTE), e.g., by Monte Carlo (MC) methods. MC simulations are computationally inefficient in simulating trapping transients in electron devices, as these processes occur over orders of magnitude longer time scales than carrier scattering times.

In this work, we employ a novel semi-analytical model for hot-electron injection, validated against MC simulations, that we have implemented into a commercial TCAD simulator. This extended TCAD model allowed us to simulate the dynamic-$R_{DS(on)}$ transients of a realistic p-GaN gate GaN HEMT.

II. MODELING APPROACH

In this work, the 1D MC simulator for AlGaN/GaN devices described in [2] has been extended to handle a 2D potential profile extracted from drift-diffusion simulations. Close inspection of the MC results (carrier fluxes, electron energy distributions, concentration profiles), allowed us to develop an analytical model [4] that provides two quantities relevant for hot carrier injection: (i) the ratio, $\eta = \Phi/n_{ITF}$, between the total (i.e. integrated over energy) flux of electrons injected into the passivation and the concentration at the AlGaN/GaN interface, (ii) a correction factor, C_n , for the value of n_{ITF} provided by the TCAD to make it match the MC results (where hot electrons tend to spread across the GaN layer due to higher carrier temperature w.r.t. TCAD). The ratio η depends only on the lateral electric field profile $F_x(x)$ at the GaN/AlGaN interface, on the vertical field in the AlGaN layer $F_{z,AlGaN}(x)$ and on the energy barrier between AlGaN and passivation E_{b0}. The C_n, instead, only depends on $F_x(x)$. Examples of comparison between MC calculations and a TCAD PMI implementation of the model for uniform fields are reported in Fig.1.

The flux injected into the passivation at the position x is:

$$\Phi(x) = \eta[F_x(x), F_{z,AlGaN}(x), E_{b0}]\, C_n[F_x(x)] n_{ITF,TCAD}(x)\,. \quad (1)$$

Electron injection takes place directly from the GaN channel non-locally into the conduction band of the passivation layer, similarly to the approach adopted in Fiegna's model [5]. Some electrons get trapped via a SRH mechanism into acceptor-like traps. Most of the others return to the AlGaN layer due to the strong repulsive field in the passivation.

III. RESULTS

The test case device of this work is sketched in Fig.2. Fig.3 compares the flux provided by (1) and by the MC (left) as well as the n_{ITF} from TCAD (with and without correction by C_n) to that from MC (right). Good agreement is observed all throughout the drift region.

We then perform TCAD simulations applying a stress of V_{DS}=100V with V_{GS}=2V. A simple description of trapping is adopted, assuming a single level located 0.5eV below the conduction band of the passivation, with a concentration of $5\cdot10^{19}$cm^3. Fig.4 shows the evolution of the vertical band diagram at a representative point in the drift region during stress: the trapped charge in the passivation increases the repulsive vertical field in the AlGaN and lowers the attractive vertical field in the GaN. Both effects reduce the injected flux as stress time proceeds (Fig.5, bottom). The repulsive vertical field in the passivation is reduced too, so charges are trapped deeper into the layer. The lateral field profile changes as well (Fig.5, top), shifting the peak of hot carrier injection toward the drain.

As visible in Fig.6, the reduction of the two-dimensional electron gas density in GaN associated to trapping into the

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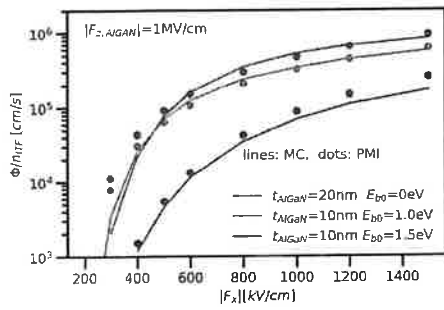

Fig. 1. Ratio between the flux injected into the passivation and the interface concentration at the AlGaN/GaN interface Φ/n_{ITF} for an infinitely long drift region with uniform electric field F_x.

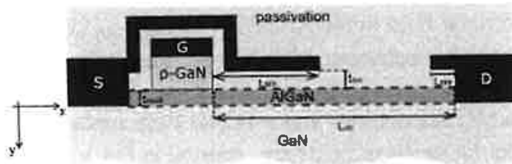

Fig. 2. Device geometry and indication of the main geometrical parameters. L_{GD}=2μm, t_{AlGaN}=10nm, L_{SFP}=0.25μm, L_{DFP}=0.1μm

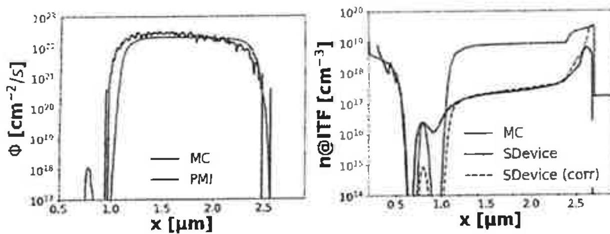

Fig. 3. Comparison between MC results and the PMI implemented in SDevice. Left: flux injected in the passivation (Φ); Right: electron concentration at the interface between GaN and AlGaN (n_{ITF}). The dashed line is the SDevice concentration multiplied by the factor C_n. Same device as in Fig.2.

passivation leads to a reduction of the on-state drain current. This is strongly related to the AlGaN thickness T_{AlGaN} and to E_{b0}. Increasing the former by 10 nm is approximately equivalent to increasing the latter by 0.5eV; both options result in a retarded drain current collapse.

Conclusion

A semi analytical hot-electron injection model, calibrated against MC simulations, is implemented in TCAD via the Sentaurus Device Physical Model Interface. The resulting framework enables the simulation of long-term hot-electron-induced degradation in AlGaN/GaN HEMTs, which would be computationally prohibitive using full Monte Carlo approaches. To the authors' knowledge, this represents the first MC-calibrated TCAD hot-electron model for GaN HEMTs. Future work will extend the model to include more detailed trap distributions and interface-related trapping mechanisms.

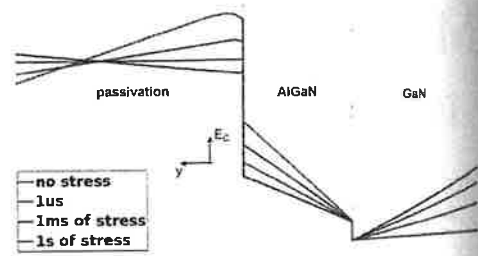

Fig. 4. Evolution (during stress with V_{DS}=100V and V_{GS}=2V) of the vertical conduction band profile for a section at the center of the drift region. The energy reference is taken at the AlGaN/GaN interface.

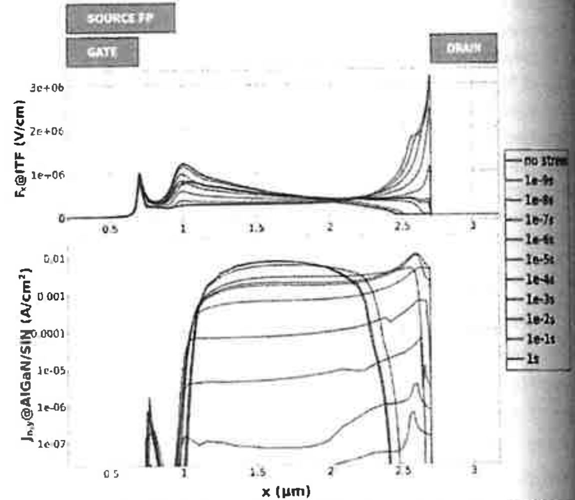

Fig. 5. Evolution during stress of (top) the lateral electric field and (bottom) injected current (flux from Eq.1 multiplied by q).

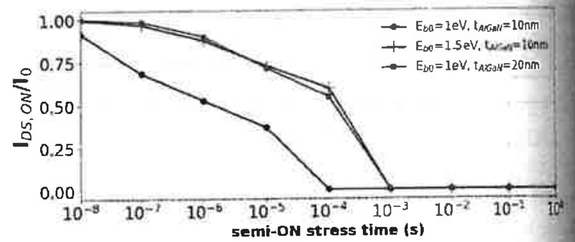

Fig. 6. Drain current (extracted at V_{DS}=50mV and V_{GS}=5V) vs stress time for different values of the AlGaN layer thickness and of the energy barrier between AlGaN and passivation.

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