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Monte Carlo analysis of hot electron injection in the passivation layer above GaN HEMTs

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Abstract — We investigate by Monte-Carlo transport simulations the injection of hot electrons in the passivation layer above the drift region of GaN HEMTs. We find that the lateral component of the electric field in the AlGa_{0.2}N layer delivers a non-negligible kinetic energy to the electrons, thus enhancing injection in the passivation, with implications on the reliability and dynamic-Ron.

I. INTRODUCTION

Gallium-Nitride (GaN) HEMTs are strong contenders in the area of power electronics, thanks to the large breakdown field and high mobility [1]. They exploit the polarization charge at the interface between the GaN and AlGa_{0.2}N layers to induce a large electron sheet charge and achieve a low on-resistance (Ron). However, electron trapping in the carbon doped GaN buffer and in the passivation layer above the AlGa_{0.2}N induces detrimental *dynamic-Ron* effects [2] [3]. While the former effect has been analyzed in detail [4] this work focusses on the much less studied electron injection in the top passivation layer. Since the electric field in the AlGa_{0.2}N layer is repulsive, only *channel hot-electrons* can diffuse uphill and be trapped in the passivation layer. Therefore, accurate Monte Carlo

transport simulations are mandatory to overcome the quasi-equilibrium assumptions embraced by the drift-diffusion models implemented in TCAD.

II. MONTE CARLO SIMULATOR

Figure 1 sketches a GaN HEMT. We assume the electric field in the drift region to vary slowly enough along *x*, so that the electron injection can be assumed to be a function of the local electric field. We thus simulate one vertical slice assuming constant vertical and lateral fields, which are varied as parameters. Injection above an *effective barrier* E_{b0} , leads to electron trapping in the passivation.

The Monte Carlo transport model uses analytical non-parabolic bands for the Γ_1 , Γ_3 , and U valleys (the latter being 2 eV above Γ_1). Polar and non-polar, acoustic and optical phonon scattering, and alloy scattering in the Al_{0.2}Ga_{0.8}N are included. Piezo- and Coulomb scattering are implemented too, although they play a modest role in the analysis of hot-electrons. Scattering and band parameters are taken from, e.g., [5] and references therein.

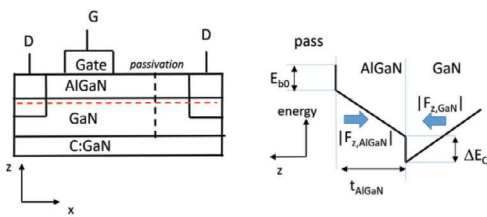


Figure 1. Sketch of a GaN/AlGa_{0.2}N HEMT (left), and conduction band diagram along the dashed line in the drift region (right).

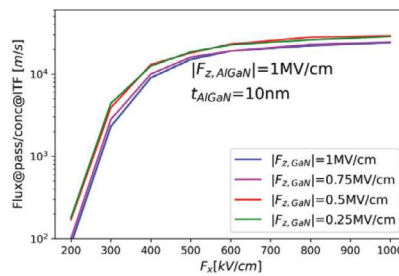


Figure 2. Flux of electrons at the AlGa_{0.2}N/passivation interface normalized to the concentration at the GaN/AlGa_{0.2}N interface vs the lateral electric field.

III. RESULTS

Figure 2 reports the electron flux at the AlGaIn/passivation interface normalized to the electron concentration at the GaN/AlGaIn interface. Remarkably, this ratio turns out to be independent of the vertical field in GaN.

To explain the flattening of the electron injection at large lateral field, F_x , Fig. 3 shows the electron occupation function at the GaN side of the AlGaIn/GaN interface. For $F_x > 500$ kV/cm the energy distribution is almost flat below 2 eV, where electrons scatter only within the Γ_1 valley, and then decreases rapidly when transfer into the U valleys becomes possible. This explains why the curves in Fig. 2 (where the total barrier for injection in the passivation is less than 2eV) flatten above that field.

Sample concentration profiles in the vertical direction are shown in Fig. 4. The concentration is highest at the AlGaIn/GaN interface, while the concentration decay above and below it depends on the vertical field (that opposes diffusion out of the electron potential well), and on the lateral field that heats the electrons.

Figure 5 compares different AlGaIn thicknesses and E_{b0} for a typical $F_{z,AlGaIn} = 1$ MV/cm, corresponding to a total barrier increase of 1 eV every 10 nm of t_{AlGaIn} . We observe that **increasing t_{AlGaIn} from 10 nm to 20 nm and 30 nm, does not decrease the injected flux as much as increasing the barrier E_{b0}** , because the electrons are heated by the lateral field when traveling in the AlGaIn, and increasing t_{AlGaIn} enhances this effect. **This suggests that engineering the passivation is expected to be more efficient than increasing the AlGaIn thickness.**

Considering as a relevant example $E_{b0} = 2$ eV, the flux/concentration ratio of ~ 10 m/s in Fig. 5 multiplied by a typical surface concentration of $\sim 10^{17}$ cm $^{-3}$

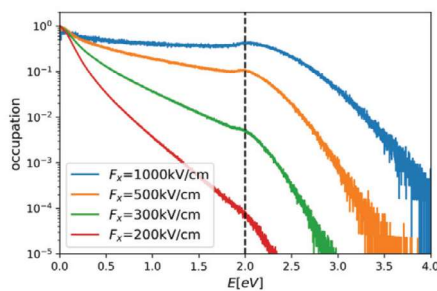


Figure 3. Distribution function at the GaN/AlGaIn interface. Dashed line: bottom of the U valleys.

gives a flux of $\sim 10^{20}$ cm $^{-2}$ s $^{-1}$. This shows that the theoretically calculated injection rates are extremely high. Thus, we conclude that to quantitatively predict the dynamic-Ron a model for the capture/release of hot electrons in the passivation, as well as full device simulations, are needed.

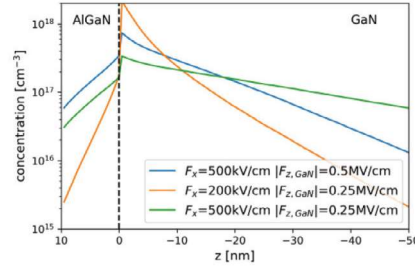


Figure 4. Electron distribution in the vertical direction for different values of the electric field in AlGaIn and GaN. We set a 2D density $= 10^{12}$ cm $^{-2}$.

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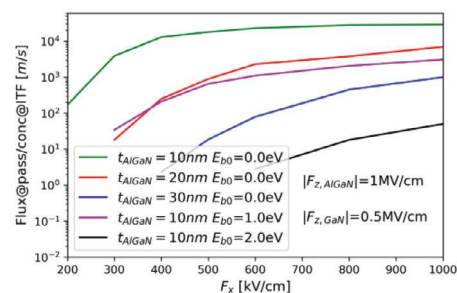


Figure 5. Electron flux at the AlGaIn/passivation interface normalized by the concentration at the GaN/AlGaIn interface.



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