Drain - Bulk Current Mechanism and Model for Power GaN HEMT on Si Substrate

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INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) fabricated on Si substrates are promising as ultra-fast switching devices for power electronic systems [1 - 3]. An important factor defining the performance of GaN on Si HEMTs is the drain to substrate current in the device off-state. In spite of a number published works showing significant drain to bulk currents in power GaN HEMTs on Si substrates [4 – 6], no clear physical mechanisms that control different portions of the leakage curve have been identified. In this work, we present experimental data and TCAD modeling results revealing the important roles of boundary conditions and space charge injection in controlling drain to bulk currents; we also present a simple and accurate compact HSPICE model closely reproducing the experimental data.

EXPERIMENTAL OBSERVATIONS

Experimental samples for this study have been fabricated using an epitaxial GaN film grown over a low-doped silicon substrate. The GaN film had the parameters typical for those used as buffer in power GaN HEMTs. The epitaxial material used has a nucleation layer formed on silicon, followed by a buffer stack to accommodate thermal and lattice mismatch between GaN and silicon. Finally, an AlGaN barrier layer is grown on GaN. The fabrication process to create structures for measuring vertical leakage started with a device isolation step followed by passivation and formation of Ti/Al based Ohmic contacts at the top surface of the GaN. The off-state currents have been measured in the voltage range of 0 – 750V and in the temperature range between root temperature and 150ºC. The experimental I-Vs are presented in Figure 1. As seen from Figure 1, the I-Vs demonstrate two distinctly different regions: low voltage (below 100V) and high voltage (above 100V). Low voltage I-Vs show quasi-ohmic behavior corresponding to a resistive type of current transport. At higher voltages, ln(J/E) vs Sqrt(E) is linear suggesting the Poole-Frenkel and/or barrier modulation current flow mechanisms. The I-V slope decreases with increasing temperature at higher voltages, and so also agrees with the above mechanisms: I ~ exp (kT^{-1}). Similar I-V characteristics have been observed in other published works on GaN on Si bulk current [6 -8].

TCAD MODELING OF THE HEMT ON SI BULK CURRENT

The drain to substrate current in high voltage GaN HEMTs is defined by the doping level, trap types, concentration and energy depth in the GaN buffer layer as well as by the properties of Si/GaN interface. Devices fabricated by different vendors employ different types of nucleation layers to obtain GaN layers of acceptable quality (see, e.g. [7]). To model various interfaces in this work, we use a new approach that does not involve the details of the nucleation layer characteristics. As a parameter characterizing Si/GaN interface we introduce an equivalent barrier height that can be adjusted to fit the experimental results. For simulations, we used the Synopsys Sentaurus device simulator. The simulated device structure included a bottom Schottky barrier with adjustable barrier height, GaN layer with variable background doping concentration, the concentration and depth of deep trapping centers, and the top ohmic contact representing the HEMT drain electrode.

Figure 2 shows how drain to bulk current is typically measured in a three-terminal device when the gate voltage is below the threshold voltage. Figure 3 illustrates our approach. For bias conditions below the threshold voltage, the channel under the gate is completely off and no current flows from drain to source, so most of the bulk current flows from drain to the substrate and the three-terminal structure can be simplified into a two-terminal structure as shown in Figure 3. By introducing the equivalent barrier height at the Si/GaN interface we can obtain a broad range of bulk currents needed to describe a variety of existing experimental data. Note that the drain voltage polarity corresponds to the reverse biased bottom equivalent Schottky barrier. The barrier height modulation in the presence of traps is seen from the plotted conduction band profiles at different voltages. As seen from Figure 4, by adjusting the equivalent barrier height, a broad range of bulk I-Vs with different current magnitudes and slopes can be obtained. Figure 5 shows bulk current at

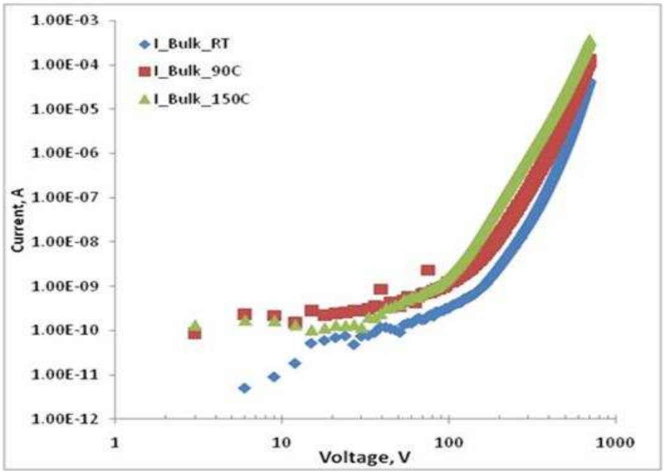

Figure 1. Experimental I-V characteristics measured at RT, 90ºC and 150ºC for two-terminal GaN on Si samples. At low voltages, the quasi-linear I-V slope corresponds to resistive current; at higher voltages the slope is proportional to exp ($V^{0.5}$) suggesting the Pool-Frenkel or barrier height modulation current flow mechanism. The I-V slope decrease with increasing temperature at higher voltages also agrees with these mechanisms: I ~ exp (kT^{-1}).

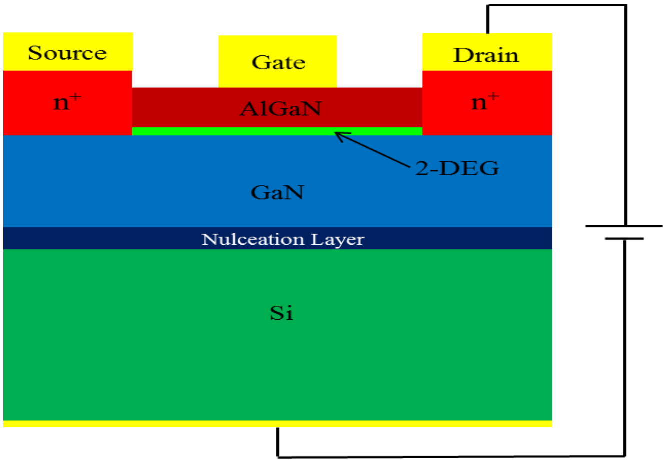

Figure 2. Measurement of bulk current in a three-terminal device when gate voltage is below threshold voltage

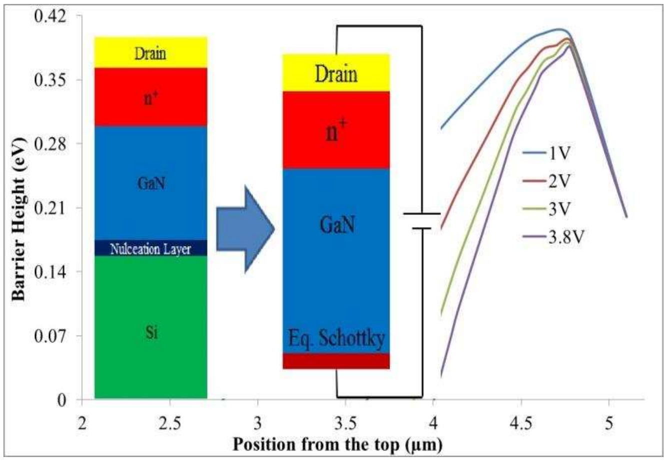

Figure 3. Equivalent Schottky barrier approach to simulating GaN/Si interface. Ec profiles show barrier height modulation at different voltages.

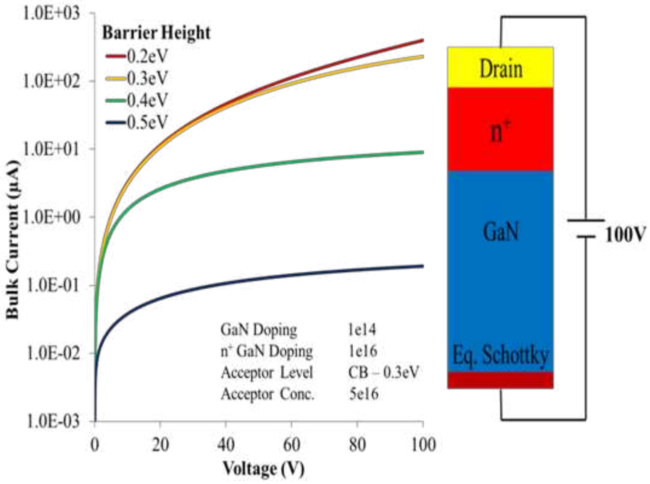

Figure 4. Bulk current at different equivalent barrier heights in the presence of deep traps.

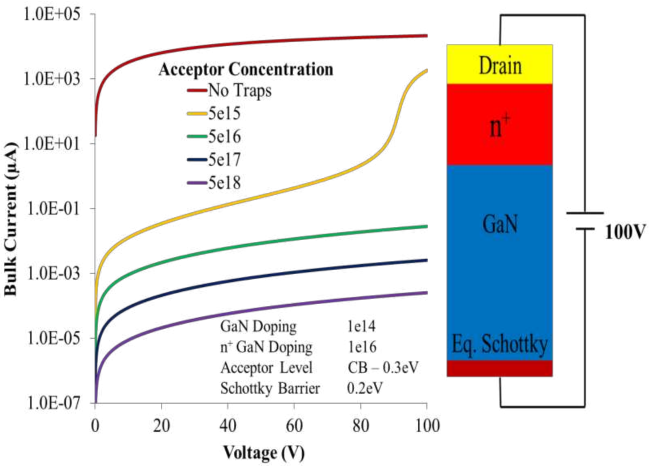

Figure 5. Bulk current at different acceptor trap concentrations.

different acceptor trap concentrations. As expected, the higher the acceptor concentration, the lower the current. When the trap concentration is relatively low, at some voltage all the acceptors are occupied and cannot capture any more electrons; beyond this voltage the current increases rapidly as suggested by the I-V curve with acceptor concentration of 5e15 cm^{-3}.

Simulations reveal, in full accordance with the physics of space-charge limited currents, that at high applied voltages the injected charge dominates over the bulk charge in GaN causing strong field non-uniformity as shown in Figures 6 and 7. The observed bulk current I-Vs are thus significantly affected by both space-charge injection and the bulk Poole-Frenkel effect. Based on our TCAD modeling results and experimental data fitting, we also developed the compact model (CM) for HSPICE implementing the above mechanisms. Given the complexity of the bulk current mechanism revealed by our TCAD modeling, the model equations (Table 1) use parameters that can be directly extracted from the experimental curves. The compact model equations account for the low-voltage (quazi-linear I-V region) and high voltage field-dependent I-V region (combined barrier modulation and Poole-Frenkel mechanisms). The developed CM closely reproduces the experimental data in a broad current and voltage range as shown in Figures 8, 9 & 10.

Table 1. The subset of the developed HSPICE Compact Model for Power GaN HEMT describing the drain to bulk current.

$$\mathrm{Idb} = \mathrm{Is} * \left[1 - \exp\left(-\frac{\mathrm{Vdb}}{\mathrm{nblk} * \mathrm{kT/q}}\right)\right] * \exp(2.3 * \mathrm{y});$$

$$\mathrm{y} = \frac{y1}{[1 + (y1/y2)^{m}]^{1/m}};$$

$$\mathrm{y1} = \mathrm{s1} * \mathrm{Vdb}; \qquad \mathrm{y2} = \mathrm{ykn} + s2 * \mathrm{Vdb}$$

I_S	Saturation current parameter of the equivalent Si/GaN barrier
nblk	Ideality factor of the equivalent Si/GaN barrier
s1	Low-voltage slope of the semilog I-V ($\log_{10}$(A)/V)
s2	High-voltage slope of the semilog I-V ($\log_{10}$(A)/V)
y	Low to high voltage region smoothing function
ykn	Knee or transition current corresponding to the low-to-high voltage region transition
m	Smoothing parameter

We applied the developed TCAD model to fit the room temperature experimental I-Vs of Figure 1. Accurate fitting was achieved in the structure with deep donors (~0.71 eV below Ec) and deep acceptors (~0.82 eV below Ec) as shown in Figure 8. These deep level parameters are consistent with those determined in [9 – 10].

Figure 9 shows our TCAD fitting of the published experimental I-V curve using only deep acceptors and both deep donors and acceptors. There is no visible change in the curve after adding donors while keeping acceptor parameters the same. This suggests that the donor concentration is not sufficient enough to generate a significant number of electrons contributing to the overall current. Applied voltage in this published work was apparently not high enough to trigger Poole-Frenkel mechanism as seen by comparing the simulation results with or without a Poole-Frenkel mechanism. Figure 10 shows our TCAD model in comparison with the experimental curve published in [8] where the currents have been measured up to much higher voltages. As seen, the high voltage portion of the curve is accurately fitted. The discrepancy at low voltages may be due to several factors such as that, even below threshold, there is some drain - to - source current as well as gate leakage current. Other reasons include spatial non-uniformity of composition and trap concentrations in the GaN buffer. Fittings with only acceptors and acceptors with donors are shown. To get accurate fitting with both deep donors and acceptors present, the acceptor concentration was increased to account for the added electrons by the donors. A curve with the "theoretical" Poole-Frenkel slope is also shown in Figure 10 for comparison. As seen, the observed I-V slope with Pool Frenkel effect is significantly different from the theoretical

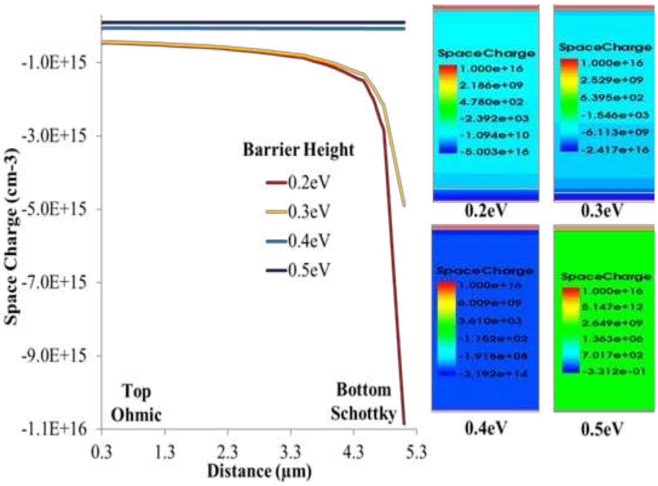

Figure 6. Space charge concentration in the bulk for different Schottky barrier height

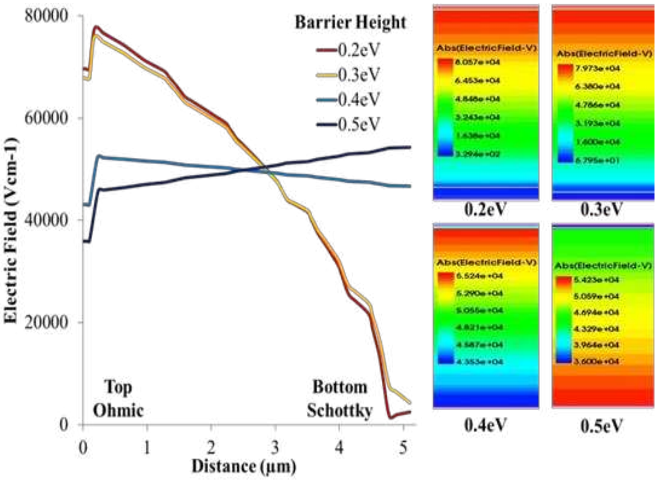

Figure 7. Electric field distribution in the bulk for different Schottky barrier height

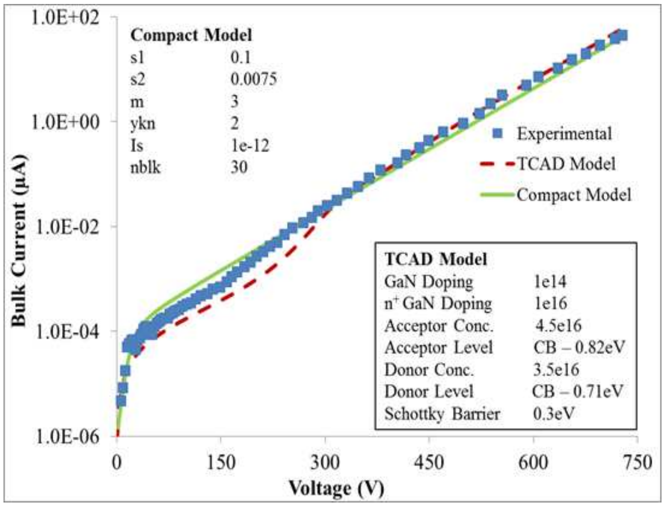

Figure 8. Fitting of the experimental I-Vs of Figure 1 using the developed TCAD and compact model (CM) according to the equations provided in the Table 1.

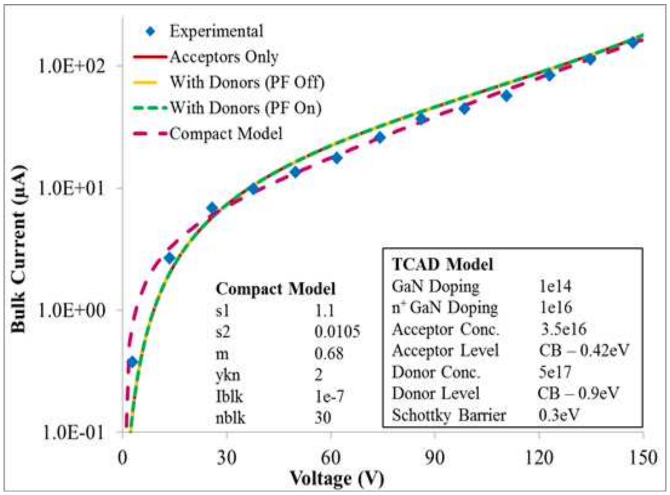

Figure 9. Fitting of the experimental I-Vs [7] using the developed TCAD and compact model (CM) according to the equations provided in the Table 1.

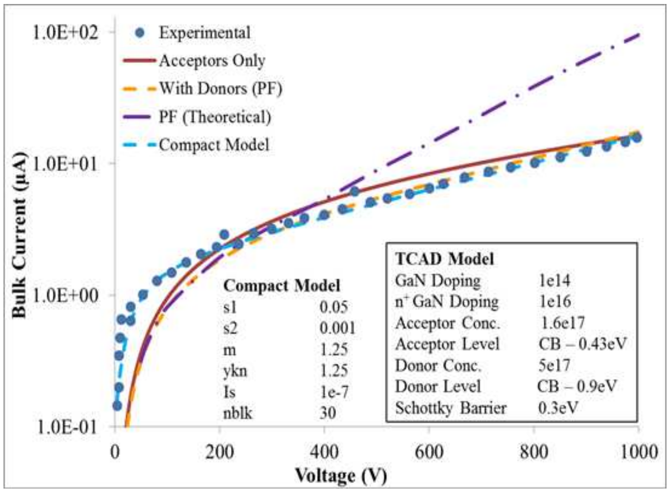

Figure 10. Fitting of the experimental I-Vs [8] using the developed TCAD and compact model (CM) according to the equations provided in the Table 1.

COMPACT MODEL FOR HEMT ON SI BULK CURRENT

slope; as we pointed out above, the difference comes from space charge injection and the non-uniformity of electric field.

CONCLUSIONS

The experimental and TCAD simulations data presented in this work establish that the dominating mechanism of the bulk current in GaN HEMT on Si device results from combined space-charge injection, carrier trapping and Poole-Frenkel effects. The developed TCAD and compact models of bulk current provide close fitting of the experimentally obtained bulk current I-V characteristics.

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