Drain - Bulk Leakage Current mechanisms and model for Power GaN HEMT on Si Substrate

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Introduction: AlGaN/GaN high electron mobility transistors (HEMTs) fabricated on Si substrate 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 model revealing important role 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 epitaxial GaN film grown over low-doped silicon substrate. The GaN film had the parameters typical for those used as buffer in power GaN HEMTs. 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, AlGaN barrier layer is grown on GaN. Fabrication process to create structures for measuring vertical leakage started with a device isolation step followed passivation and forming of Ti/Al based Ohmic contacts at the top surface of GaN. The off-state currents have been measured in the voltage range 0 – 750 V in the temperature range between room temperature and 150 C. The experimental I-Vs are presented in Figure 1. As seen from Figure 1, the I-Vs demonstrate two distinctly different regions: low voltage (approximately below 100V) and high voltage (above 100V). Low voltage I-Vs show quasi-ohmic behavior corresponding to 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 decrease with increasing temperature at higher voltages, 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 id defined by the doping, trap type, concentration and energy depth in the GaN layer as well as by the properties of Si/GaN interface. Devices fabricated by different vendors employ different types of nucleation layer 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 effective barrier height that can be adjusted to fit the experimental results.

For simulations, we used 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.

Figures 2 illustrates our approach. 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 Schottky barrier. The effects of the traps on the barrier height modulation is shown as zoomed in conduction band profiles at different voltages. As seen from Figure 3, by adjusting the effective barrier height a broad range of bulk I-Vs with different current magnitudes and slopes can be obtained. Simulations reveal, in full accordance with the theory 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 and hence, significantly modifying the manifestation of the Poole-Frenkel effect in the bulk of GaN. As a result, the observed bulk current I-Vs are affected by both space-charge injection and bulk Poole-Frenkel effect.

We applied the developed TCAD model, to fit the room temperature experimental I-Vs of the Figure 1. Accurate fitting was achieved in the structure with deep donors (~0.4 eV below Ec) and deep acceptors (~0.6 eV above E_V). These deep level parameters are consistent with those determined in [9, 10]. The simulation results are presented in Figure 4. As seen the developed TCAD model provide accurate fitting of the experimental data.

Compact model for the HEMT on Si bulk current

We also developed the compact model (CM) for HSPICE implementing the above mechanisms. The model equations accounting for low-voltage (resistive I-V region) and high-voltage field-dependent I-V region (combined Barrier modulation and Poole-Frenkel mechanisms) are presented in the Table 1. The model input parameters have been defined in the form allowing direct parameter extraction from experimental I-Vs. The developed CM closely reproduces the experimental data in a broad current and voltage range as shown in Figure 6.

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, barrier height modulation 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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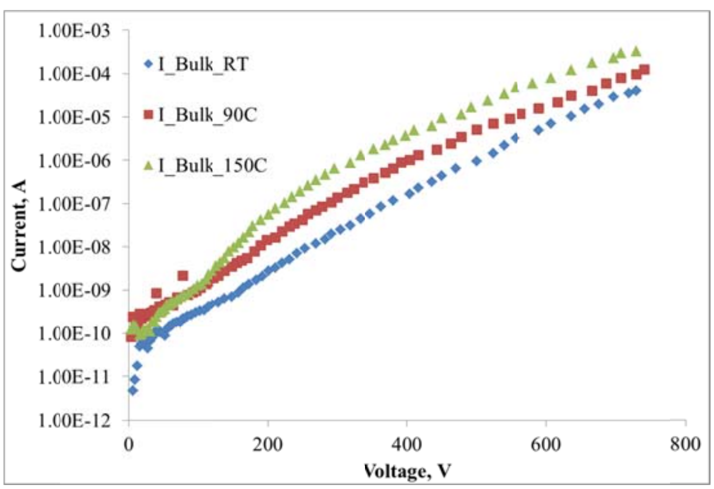

Figure 1. Experimental I-V characteristics measured at RT, 90C and 150C for two-terminal GaN on Si samples. At low voltages, the quazi-linear I-V slope corresponds to resistive current; at higher voltages the slope is proportional to exp ($V^{0.5}$) suggesting the field-dependent conductivity: Poole-Frenkel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

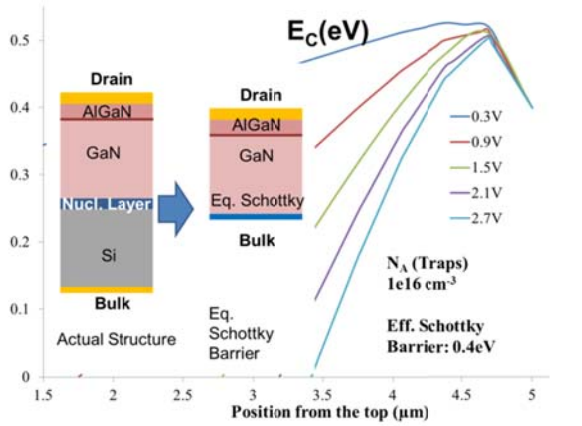

Figure 2. Effective Schottky barrier approach to simulating GaN/Si interface. E_C profiles show barrier height modulation at different voltages.

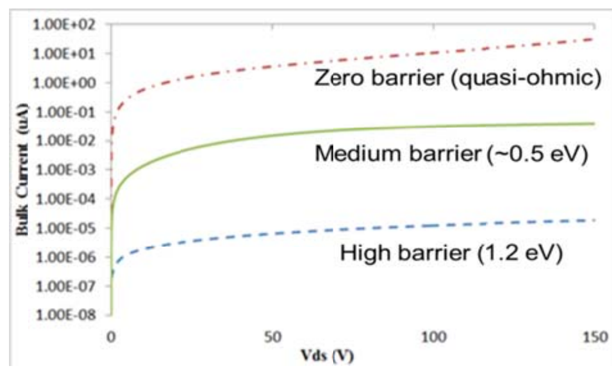

Figure 3. Bulk current for different effective barrier height in presence of deep traps.

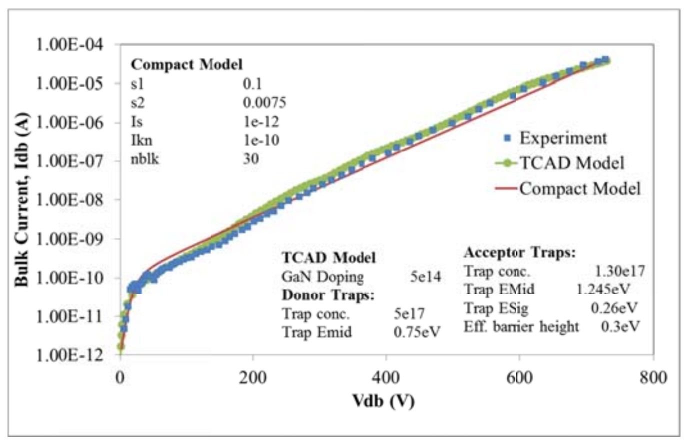

Figure 4. Fitting of the experimental I-Vs of the Figure 1 using the developed TCAD and compact model (CM)

$$I_{db} = IR + IF;$$

$$I_R = \sigma_1 V_{db} exp(-Ear/kT);$$

$$I_F = \sigma_2 V_{db} exp(-Eaf/kT) exp(\alpha V_{db}{}^{1/2}/kT);$$

σ_1, σ_2 = resistive and field − dependent conductivities

Ear, Eaf = corresponding activation energies

α – barrier modulation factor

Table 1. Compact model (CM) equations for GaN/Si HEMT bulk current accounting for resistive and field-dependent conduction components.