Advanced TCAD Simulation Techniques

For Wide Bandgap Power Devices

With a Focus on GaN HEMTs
Contents

Power Electronics and Future Trend of Power Devices
- Introduction to Power Electronics
- History of Power Devices
- Wide Bandgap Devices

Wide Bandgap Power Devices Simulation, an Introduction
- Simulation Procedures
- Simple Examples of GaN HEMTs
- Simple Examples of SiC SBD and MESFET

Advanced Physical Models
- Polarization and 2DEG
- Electron Mobility Model for GaN
- Impact Ionization Model
- Convergence: Tips and Tricks
- Self-consistent Schrödinger Equation Solver
- Trap assisted QM Tunneling

Reference
Power Electronics: An Enabling Green Technology

- Battery
- Charger
- Fuel Storage
- Lightweighting Materials
- Electric Motor
- Engine
- Radiator

Optional Obstruction Light
- Nacelle Cover
- Power Converter & System Controller
- Mainframe
- Yaw Assembly (below Mainframe)
- Service Platform
- Tower

Meteorological Instruments ("Met Mast")
- Blade
- Generator
- Rotor Hub
- Mechanical Brake (behind generator)

Power supply and driver electronics
- LED package array
- Optical diffuser
- Integrated trim and heat sink

CROSGLIGHT
Power Electronics: The Basics

Diagram showing the basic components of power electronics:
- **Rectifier**: Converts AC to DC
- **AC/AC Converter**: Converts AC to AC
- **DC/DC Converter**: Converts DC to DC
- **Inverter**: Converts DC to AC

Diagram illustrating the control circuitry:
- **Power input**
- **Power output**
- **Feed-forward**
- **Control input**
- **Feed-back**
- **Reference**

Diagram of a simple topology:
- **Topography**
- **Controller**
- **Power Elements**

Diagram of a power electronics system:
- **Power MOSFET**
- **PWM controller**
- **Simple Flyback Converter Topology**
- **PWM IC**
### Power Devices: History of Evolutions

<table>
<thead>
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<tr>
<td>Device</td>
<td>Power Diode Germanium</td>
<td>Thyristor Silicon</td>
<td>Power Bipolar Silicon</td>
<td>Power MOSFET Silicon</td>
<td>IGBT Silicon</td>
<td>Schottky diode Silicon Carbide</td>
<td>Power HEMT GaN</td>
</tr>
</tbody>
</table>

- **Power Diode**
- **Thyristor**
- **Power Bipolar Silicon**
- **Power MOSFET Silicon**
- **IGBT Silicon**
- **Schottky diode Silicon Carbide**
- **Power HEMT GaN**
It’s time to move on…

- Bipolar
- VFET
- HEXFET
- TrenchFET
- Super Junction
- Next Gen Si
- Silicon Maturation
- GaN / SiC Power Devices

FOM

Year

1978 2003 2009

Si

WBG

Figure of Merit (FOM)
## Material Properties Comparison

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Silicon</th>
<th>SiC-4H</th>
<th>GaN</th>
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</thead>
<tbody>
<tr>
<td>Band-gap (eV)</td>
<td>1.1</td>
<td>3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Critical Field (1E+6V/cm)</td>
<td>0.3</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Electron Mobility (cm²/V-Sec.)</td>
<td>1450</td>
<td>900</td>
<td>2000</td>
</tr>
<tr>
<td>Electron Saturation Velocity (1E+6 cm/Sec.)</td>
<td>10</td>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm²K)</td>
<td>1.5</td>
<td>3.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Baliga Figure of Merit (FOM) = $\varepsilon_s \mu E_c^3$</td>
<td>1</td>
<td>675</td>
<td>3000</td>
</tr>
</tbody>
</table>
WBG Power Devices: Applications

- Consumer Electronics
  - Power Supplies
  - UPS
- Automotive
  - DC/AC Inverter
  - DC/DC Converter
- Industrial
  - Motor Control
  - Wind Turbine

< 5KW  30 – 350 KW  100 KW – 1 MW

GaN and SiC in Competition  SiC Only

Reference: Jian-Jang Huang, NTU, “GaN/Si HEMT power devices” III-V Nitride Material and Device Modeling workshop, Taiwan, 2014
# Substrate Materials for GaN HEMT

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Si substrate</th>
<th>SiC substrate</th>
<th>GaN substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect density (cm(^{-2}))</td>
<td>1E+9</td>
<td>5E+8</td>
<td>1E+3 to 1E+5</td>
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<tr>
<td>Lattice mismatch (%)</td>
<td>17</td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm-k at 25 °C)</td>
<td>1.5</td>
<td>3.0~3.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Coefficients of thermal expansions (%)</td>
<td>54</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Off-state leakage</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Reliability and yield</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Lateral or Vertical device</td>
<td>lateral</td>
<td>lateral</td>
<td>lateral or vertical</td>
</tr>
<tr>
<td>Integration possibility</td>
<td>Very high</td>
<td>Moderate</td>
<td>-</td>
</tr>
<tr>
<td>Substrate size (mm) (as of 2012)</td>
<td>300</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Substrate cost (relative)</td>
<td>Low</td>
<td>high</td>
<td>Very high</td>
</tr>
</tbody>
</table>
Global Research Activities for GaN HEMTs

* Due to limited space, this diagram is by far not showing the complete companies and institutions that are active in GaN HEMT research.
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Reference
Simulation Steps

- Process Simulation
- Create Device Structure
- Contact Definition

Device Simulation
- Potential, Electric Field, Impact Ionization, Electron Density, Current Magnitude, etc.
- Post Process (GUI)

Post Process (Script)
- I-V Curves, Band Diagrams, Capacitance, Inductance, S Parameter, Smith Chart, etc.
**GaN Single Layer**

Single GaN layer simulation with polarization and band diagram plots

(a) Simulated GaN material polarization effect

(b) Band diagram plot of GaN material (cut line from top to bottom)

*Polarization model should be activated, otherwise the band diagram will be flat*
GaN + AlGaN Layers

\[ \text{Al}_{0.3}\text{Ga}_{0.7}\text{N} \]

\[ \text{GaN} \]

**Band Diagram**

**Net Fix Charge Plot**
GaN + AlGaN Layers: AlGaN Layer Thickness

Band diagram at equilibrium of GaN-AlGaN structure with various AlGaN layer thickness

(a) Band diagram plot of GaN-AlGaN structure with Al$_{0.3}$Ga$_{0.7}$N layer thickness of 15 nm

(b) Band diagram plot of GaN-AlGaN structure with Al$_{0.3}$Ga$_{0.7}$N layer thickness of 20 nm

(c) Band diagram plot of GaN-AlGaN structure with Al$_{0.3}$Ga$_{0.7}$N layer thickness of 35 nm

(d) Band diagram plot of GaN-AlGaN structure with Al$_{0.3}$Ga$_{0.7}$N layer thickness of 45 nm
**GaN + AlGaN Layers: Al Mole Fraction in AlGaN**

Band diagram at equilibrium of GaN-AlGaN structure with various Al mole fraction.

(a) Band diagram plot of GaN-AlGaN structure with $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ layer thickness of 30 nm

(b) Band diagram plot of GaN-AlGaN structure with $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layer thickness of 30 nm

(c) Band diagram plot of GaN-AlGaN structure with $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ layer thickness of 30 nm

(d) Band diagram plot of GaN-AlGaN structure with $\text{Al}_{0.45}\text{Ga}_{0.55}\text{N}$ layer thickness of 30 nm
A Schottky contact (work function = 5.1 eV) is applied to the top of AlGaN layer while an Ohmic contact is applied to the bottom of GaN layer. -5V is applied to the top Schottky contact with bottom Ohmic contact grounded.
**P Type of Traps in the GaN Layer**

Traps are placed in the GaN layer to model a semi-insulating substrate and prevent leakage current under the 2DEG channel.

- **(a) Without traps** (Al$_{0.3}$Ga$_{0.7}$N layer: 30 nm thick)
- **(b) With acceptor type traps:** $P = 1 \times 10^{16}$ cm$^{-3}$
- **(c) With acceptor type traps:** $P = 3 \times 10^{16}$ cm$^{-3}$
- **(d) With acceptor type traps:** $P = 3 \times 10^{17}$ cm$^{-3}$
A Simple GaN Power HEMT Example

Silicon Substrate

AlN Nucleation Layer

GaN Buffer Layer

Al$_{0.3}$Ga$_{0.7}$N

2DEG Channel

Field Plate

SiN

5.5 µm

0.8 µm

0.7 µm

S

G

D

5 µm

20 nm

4 µm

30 nm

Silicon Substrate
Simulation Setup:

- Intrinsic stress can be applied in the SiN layer to simulate the stress effect
- Polarization charge model is applied with a screening factor
- Interface charges/traps can be placed to simulate the surface states
- P type traps are placed in the GaN buffer layer to make it semi-insulating
Device Simulation: Band Diagram and $I_d$-$V_d$ Curves

Band Diagram @ Equilibrium Close to 2DEG

I-V Family of Curves

Electron Conc. Close to 2DEG
**Device Simulation:** Self-Heating

- **Heat Sink**
- **R_{TH}**
- **Field Plate**
- **SiN**
- **0.8 μm**
- **5.5 μm**
- **S**
- **D**
- **30 nm**
- **4 μm**
- **20 nm**
- **5 μm**
- **Al\(_{0.3}\)Ga\(_{0.7}\)N**
- **2DEG Channel**
- **GaN Buffer Layer**
- **AlN Nucleation Layer**
- **Silicon Substrate**

**I_d-V_d Curves**

- **I_d-V_d Curve**
- **I_d-V_d Curve with Self-heating**

**Graph Details:**
- **X-axis:** Drain Voltage (V)
- **Y-axis:** Drain Current (A/m)
- **Range:**
  - Drain Voltage: 0 to 8 V
  - Drain Current: 0 to 300 A/m
Device Simulation: Breakdown

Potential plot

Electric Field

I-V Curve @ Vg = -7V
BV > 600 V

Drain edge

Gate edge

E. Field close to barrier top
2DEG Mobility and AC Simulation

Electron Mobility Close to 2DEG

I-V Curves

$C_{gd}$ and $C_{gs}$
At large positive drain bias, electrons from the gate may leak to the trap states in the un gated surface, creating a “virtual gate” and modulate the depletion region.
**Current Collapse:**  Transient Simulation

**Graph 1:**
- **Y-axis:** Drain/Gate Voltage (V)
- **X-axis:** Time (Ps)

**Graph 2:**
- **Y-axis:** Drain Current (A/m)
- **X-axis:** Drain Voltage (V)

**Graph 3:**
- **Y-axis:** Drain Voltage (V)
- **X-axis:** Time (Ps)

**Graph 4:**
- **Y-axis:** Drain Current (A/m)
- **X-axis:** Time (Ps)
Threshold Voltage and Stress Simulation

In addition to stress caused by material lattice mismatch, the intrinsic stress from SiN layer can be defined in the process simulation. The stress profile can be used by the device simulator to calculate the piezoelectric polarization.

Stress engineering may help to achieve enhancement mode?
A Simple SiC Power SBD Example

- **Substrate**: 200 um SiC, N type with Dop. Con. = $1E+18$ cm$^{-3}$
- **Drift region**: 10 um SiC, N type with Dop. Con. = $7E+15$ cm$^{-3}$
- **Titanium / SiC Schottky contact** (Ti thickness: 1.3 um)

**Note**: Substrate is not shown in this plot to enlarge the top portion
A Simple SiC Power MESFET Example

Material Plot

- Nickel
- 4H-SiC
- s.i.SiC

Net Doping

- (Nitrogena/)
- Signed_Log10

Potential

- Gate voltage = -2V
- Drain voltage = 40V

Differential Potential

- 0 to 40
SiC MESFET Breakdown

SiC MESFET I-V Curves

Current Mag.
$V_{gs} = -2\text{V}$
$V_{ds} = 40\text{V}$
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Reference
Polarization: *Spontaneous Polarization*

- The bond between Ga atom and N atom is polar
- Direction of the polarization is from N atom to Ga atom
- Intrinsic asymmetry of the bonding in the equilibrium crystal structure
- Integrate all the micro dipoles -> spontaneous polarization
Polarization: Piezoelectric Polarization

Besides spontaneous polarization, applying mechanical stress to the material distorts the crystal structure, resulting in further polarization: Piezoelectric Polarization $P_{PE}$

$$P_{PE} = 2 \frac{a - a_0}{a_0} \left( e_{31} - e_{33} \frac{C_{13}}{C_{33}} \right)$$
Two-Dimensional Electron Gas (2DEG)

The Origin of 2DEG

- Due to polarization of AlGaN and GaN, there is large negative bound charge at the AlGaN surface.

- Nowadays, it is widely accepted that surface donor-like traps, could be the source of both the channel electrons (2DEG) and the positive charge screening the large negative polarization-induced bound charge.
Electron Mobility Models for GaN

- **FMCT Model:**
  Proposed by Farahmand etc. in 2001, but fail at high temperature
  \[ v = \frac{\mu_0 F + v_{sat}(F/F_C)^n_1}{1 + a(F/F_C)^n_2 + (F/F_C)^n_1} \]

- **YHT Model:**
  Proposed by Yang, etc., modified FMCT model with temperature effect.
  \[ \gamma = \gamma_0(\gamma_1 + \gamma_2(T/300) + \gamma_3(T/300)^2) \]

- **V. O. Turin Model:**
  Proposed by V. O. Turin, etc., considered the kink effect in low field region.
  \[ v_{MTE} = \frac{F(E) + v_{sat}(E/E_{MT})^{\beta_T}}{1 + (E/E_{MT})^{\beta_T}} \]

Different electron mobility models for GaN at T=300K and doping concentration=10^{17} \text{cm}^{-3}

References:

Impact Ionization Parameters for GaN

**Chynoweth’s Law** is generally used in TCAD simulation. For electrons, the impact ionization coefficient $\alpha_n(E)$:

$$\alpha_n(E) = a_n \cdot e^{-\frac{b_n}{E}}$$

where $a_n$ and $b_n$ are fitting parameters for electrons, $E$ is the electric field strength. For holes, $\alpha_p(E)$:

$$\alpha_p(E) = a_p \cdot e^{-\frac{b_p}{E}}$$

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$a_n$ for electrons</td>
<td>2.00E+6 cm$^{-1}$</td>
<td>2.6E+8 cm$^{-1}$</td>
<td>2.90E+8 cm$^{-1}$</td>
</tr>
<tr>
<td>$b_n$ for electrons</td>
<td>3.00E+7 V/cm</td>
<td>3.40E+7 V/cm</td>
<td>3.40E+7 V/cm</td>
</tr>
<tr>
<td>$a_p$ for holes</td>
<td>1.34E+8 cm$^{-1}$</td>
<td>4.98E+6 cm$^{-1}$</td>
<td>1.34E+8 cm$^{-1}$</td>
</tr>
<tr>
<td>$b_p$ for holes</td>
<td>2.03E+7 V/cm</td>
<td>2.03E+7 V/cm</td>
<td>2.03E+7 V/cm</td>
</tr>
</tbody>
</table>

*Note that Crosslight’s parameter has two ranges, the parameter shown here is the first range*
Impact Ionization Parameters for SiC

Chynoweth’s Law is generally used in TCAD simulation. For electrons, the impact ionization coefficient $\alpha_n(E)$:

$$\alpha_n(E) = a_n \cdot e^{(-\frac{b_n}{E})}$$

where $a_n$ and $b_n$ are fitting parameters for electrons, $E$ is the electric field strength. For holes, $\alpha_p(E)$:

$$\alpha_p(E) = a_p \cdot e^{(-\frac{b_p}{E})}$$

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<tr>
<td>$a_n$ for electrons</td>
<td>4.60E+5 cm$^{-1}$</td>
<td>1.76E+8 cm$^{-1}$</td>
<td>2.10E+7 cm$^{-1}$</td>
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<tr>
<td>$b_n$ for electrons</td>
<td>1.78E+9 V/cm</td>
<td>3.30E+7 V/cm</td>
<td>1.70E+7 V/cm</td>
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<tr>
<td>$a_p$ for holes</td>
<td>1.16E+7 cm$^{-1}$</td>
<td>3.41E+7 cm$^{-1}$</td>
<td>2.96E+7 cm$^{-1}$</td>
</tr>
<tr>
<td>$b_p$ for holes</td>
<td>1.72E+7 V/cm</td>
<td>2.50E+7 V/cm</td>
<td>1.60E+7 V/cm</td>
</tr>
</tbody>
</table>
Convergence: Tips and Tricks

- The choice of voltage or current bias affects the convergence and stability of the Newton solver.

- In order to guarantee convergence, small changes in the applied bias should always result in small changes in the overall solution. Here are two typical examples:

  - For BV simulation where the total amount of current flowing in the device is very small, the actual current amount may fluctuate due to lack of numerical precision, making it difficult to use current bias. This situation can be detected by observing the net current over all the electrodes: if the sum is not zero, then Kirchhoff’s Current Law is violated and the current is too low to use as a control variable.

  - In a forward-biased diode example, the solver can enter a non-convergent state if the applied (anode) voltage bias is much higher than the turn-on voltage. Since the conductivity increases exponentially with bias in a typical diode, seemingly small changes in voltage can result in very large changes of the solution.
Convergence: *Tips and Tricks*

This leads us to a simple general rule:

- Use voltage bias for devices with high resistance
- Use current bias for devices with low resistance

For example, a typical diode under forward bias has low resistance past its turn-on point but high resistance at lower bias or under reverse bias conditions. With these two extremes in mind, the following general strategy is recommended when setting up a simulation under forward bias:

1. Solve for equilibrium solution
2. Apply voltage until 80-90% of the built-in bias value is reached. Some software tools also allow the possibility of terminating the voltage increase once certain current conditions have been met
3. Verify that Kirchhoff’s Current Law is satisfied at this bias point
4. Apply current bias until desired value is reached
**Convergence: Parameter Scan**

- Convergence is usually easy at high current.
- Basic idea is to artificially change a parameter, such as bandgap, temperature, polarization charge, near equilibrium to make it easier to converge.

**Steps:**

1. Change a parameter.
2. Ramp up the voltage until desired value (such as break down)
3. Hold the high current while recovering the changed parameter (bandgap, etc.)
4. Ramp down the voltage to get desired I-V
Self-consistent Carrier Density Model

\[ n_{2D}(x, y) = \sum_j g_n^j(y) \rho_j^0 kT \ln \left[ 1 + \exp \left( \frac{E_{fn}(x, y) - E_j(x, y)}{kT} \right) \right] \]
Self-consistent Carrier Density Model

I-V Curves

Elec. Conc. Plots

Band-Diagram Plot with Self-Consistent QM Model
Incorporating QM Tunneling in TCAD

A. Tunneling current at top of barrier

\[ J = J_{dd,m} + J_{tun} = (1 + \alpha_m)J_{dd,m} \]

\[ J_{tun} = qvn_m(kT)^{-1} \int_{U_0}^{U_m} \exp \left( \frac{U_m - E}{kT} \right) D_T(E) dE \]

\[(1 + \alpha_m) = \text{Barrier-Peak tunneling enhancement factor}\]
Incorporating QM Tunneling in TCAD

B. Tunneling current at an arbitrary point

- Distribution function:
  \[ n_E(x) = n_{Ex} \exp\left(\frac{U(x) - E}{kT}\right) \]

- Tunneling current may be used to compute local current (local current model)

  \[ J_{tun} = qvn(x)(kT)^{-1} \exp\left(\frac{U(x) - U_m}{kT}\right) \int_{U_0}^{U_m} \exp\left(\frac{U_m - E}{kT}\right) D_T(E)dE \]

- Mesh points away from the barrier-peak have lower tunneling current

- Basis for local transport model
C. Total or average tunneling current

- At the edge of the tunneling region, \( U(x) = U_0 \)

\[
J_{tun} = f_{aT} J_{dd} = J_{dd} (kT)^{-1} \int_{U_0}^{U_m} \exp \left( \frac{U_0 - E}{kT} \right) D_T(E) dE
\]

- A simple average with a Boltzmann distribution function

- \( f_{aT} = \) average tunneling factor, or total tunneling coefficient

- Basis for non-local transport model
Incorporating QM Tunneling in TCAD

D. Local vs. non-local transport model

Local model:

- **Pros**: better self-consistency, smooth distribution of current and densities.
- **Cons**: convergence maybe difficult. Cannot handle pure insulator regions (lack of local current).

Non-local model:

- **Pros**: better convergence, suitable for wide bandgap and insulators.
- **Cons**: inconsistency with local model, may cause unphysical back-diffusion
Propagation Matrix For QM Tunneling

The purpose is to compute tunneling transparency for tunneling transmission

For QM wave propagating in z-direction:

\[
\frac{-\hbar^2}{2m(z)} \frac{d}{dz} \left[ \frac{1}{m(z)} \frac{d}{dz} \phi(z) \right] + V(z) \phi(z) = E \phi(z)
\]

Make Piece-wise constant assumption for V(z) and m(z) to obtain general solution:

\[
\phi_n(z) = A_n e^{ik_n(z-z_n)} + B_n e^{-ik_n(z-z_n)} \quad \text{for } z_{n-1} \leq z \leq z_n
\]

where

\[
k_z = \sqrt{\frac{2m_n}{\hbar^2}} (E - V_n)
\]

which can take real or imaginary value depending on the sign of \((E - V_n)\)
Propagation Matrix For QM Tunneling

We apply continuity boundary condition for \( \phi(z) \) and \((1/m(z))d\phi(z)/dz\) (continuity in probability and probability flux) at \( z = z_n \) to obtain propagation matrix:

\[
\begin{bmatrix}
A_{n+1} \\
B_{n+1}
\end{bmatrix} = T_{n+1,n} \begin{bmatrix}
A_n \\
B_n
\end{bmatrix}
\]

define

\[
P_{n+1,n} = \frac{m_n k_{n+1}}{m_{n+1} k_n}
\]

where the propagation matrix is given by:

\[
T_{n+1,n} = \frac{1}{2} \begin{bmatrix}
(1 + P_{n+1,n})e^{ik_{n+1}h_{n+1,n}} (1 - P_{n+1,n})e^{ik_{n+1}h_{n+1,n}} \\
(1 - P_{n+1,n})e^{-ik_{n+1}h_{n+1,n}} (1 + P_{n+1,n})e^{-ik_{n+1}h_{n+1,n}}
\end{bmatrix}
\]
Propagat**on Matrix For QM Tunneling**

Repeating the matrix equation to relate the incident and transmitting waves:

$$
\begin{bmatrix}
A_n \\
B_n
\end{bmatrix} = G_{N,0} \begin{bmatrix}
A_0 \\
B_0
\end{bmatrix}
$$

QM transmittance ($|t|^2$) and reflectivity ($|r|^2$) can be obtained by setting:

$$
\begin{bmatrix}
A_0 \\
B_0
\end{bmatrix} = \begin{bmatrix} 1 \\ r \end{bmatrix}
$$

And

$$
\begin{bmatrix}
A_n \\
B_n
\end{bmatrix} = \begin{bmatrix} t \\ 0 \end{bmatrix}
$$
QM Tunneling Model for HEMT Gate Leakage

Standard Barrier HEMT

<table>
<thead>
<tr>
<th>Layer Structure</th>
<th>Width (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300Å $\text{Al}<em>{0.25}\text{Ga}</em>{0.75}\text{N}$ - uid</td>
<td>25</td>
</tr>
<tr>
<td>3 μm $\text{GaN}$ - uid</td>
<td></td>
</tr>
<tr>
<td>sapphire substrate</td>
<td></td>
</tr>
</tbody>
</table>

Enhanced-Barrier HEMT

<table>
<thead>
<tr>
<th>Layer Structure</th>
<th>Width (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75Å $\text{GaN}$ - uid</td>
<td>25</td>
</tr>
<tr>
<td>225Å $\text{Al}<em>{0.25}\text{Ga}</em>{0.75}\text{N}$ - uid</td>
<td></td>
</tr>
<tr>
<td>3 μm $\text{GaN}$ - uid</td>
<td>50</td>
</tr>
<tr>
<td>sapphire substrate</td>
<td></td>
</tr>
</tbody>
</table>

E.J. Miller et.al., JAP, v.88, p5951(2000)
QM Tunneling Model for HEMT Gate Leakage

A 2D Problem

For reverse gate bias:

1) Depletion of 2DEG under gate. No change in barrier shape

2) Lateral voltage pull-down by the S/D contact, causing thinning of barrier and increase of $I_g$

3) Further S/D voltage pull down causing voltage drop between G and S/D, $I_g$ increase slows down
QM Tunneling Model for HEMT Gate Leakage

Critical Modeling Parameters

- Polarization fraction at 2DEG and AlGaN/GaN interface. (0.7-1)
- Polarization fraction on top (passivated) surface (< 0.1)
- Gate metal work function (5.2-5.4).
- Deep donor traps for UID barriers (1.e17-1.e18/cm³)
- Deep acceptor traps for substrate GaN (1.e17/cm³)
QM Tunneling Model for HEMT Gate Leakage

Traps Affect Barrier Height
QM Tunneling Model for HEMT Gate Leakage

SB-HEMT vs. EB-HEMT
Compact Trap Assisted Tunneling Model

Trap Assisted Tunneling (TAT) assumes current from trap emission

\[ J = q \int_{0}^{t_{bar}} \frac{N_{\text{trap}}}{\tau} dx \]

Field dependent rate with temperature dependent factor:

\[ \frac{1}{\tau} = S_{\text{tat}}(F)f_{\text{temp}} \]

\[ f_{\text{temp}} = \exp\left(\frac{E_{t0}}{k300} - \frac{E_{t}}{kT}\right) \]

A. Linear model

\[ S_{\text{tat}}(F) = S_{\text{tat}}(0) + \left(\frac{dS_{\text{tat}}}{dF}\right)F \]

\[ J = qN_{\text{trap}}f_{\text{temp}}\left(\frac{dS_{\text{tat}}}{dF}\right)\Delta V \]

Compact Trap Assisted Tunneling Model

B. Poole-Frenkel Model

Field dependence comes from factor $\exp\left(\frac{E_t}{k_{300}}\right)$ with $E_t$ shifted by field within a Coulomb potential:

$$\Delta E_t = \sqrt{\frac{qF}{\pi \epsilon_0 \epsilon}}$$

C. Hopping model

Trap level $E_t$ shifted by field in a rectangle potential well of size $d_{hop}$:

$$\Delta E_t = F d_{hop}$$
Compact Trap Assisted Tunneling Model

T. Huang et al, IEEE EDL Vol. 33 Issue 8
Reference


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