Compact Models for GaN MOS devices

M. S. Shur
ECSE and Center for Broadband Data Transfer, RPI
Troy, NY

G. Simin and M. Asif Khan
Department of Electrical Engineering, Univ. of South Carolina, Columbia, SC 29208

R. Gaska
SET Inc., Columbia, SC 29209
Outline

• Nitride-based FETs - promises and problems
• New device physics of nitride-based FETs
• Modeling
  - I-Vs and C-Vs
  - Current collapse
  - Leakage current
• Conclusions
Nitride-based FETs - promises and problems

**Promises**
- 30 W/mm at 10 GHz versus 1.5 W/mm
- > 150 W per chip

**Problems**
- Reliability
- Yield

**Solutions**
- Strain energy band engineering
- MEMOCVD™
- Insulated gate designs
- Understanding and modeling

INSPEC search query:
Gallium Nitride
or Indium Nitride
or Aluminum Nitride

1000 per year level


Sensor Electronic Technology, Inc.

University of South Carolina
Electrical Engineering
Nitride Heterostructures: New Symmetry, New Physics:
Polarization Induced Electron and Hole 2D Gases

New device issues to solve:
First observation of current collapse and suggested mechanism

M. A. Khan, M. S. Shur, Q. C. Chen, and J. N. Kuznia,
High Electron Sheet Density Allows for a New Approach: AlGaN/GaN MISFET

Resolving the issues: AlGaInN, gate dielectrics, InGaN channel

Reducing the gate leakage current ($10^4 - 10^6$ times)

Reducing current collapse, Improving carrier confinement

Combining the advantages
Unified charge control model (UCCM)

MOSFETs and HFETs

\[ V_{GT} - \alpha V_F = a(n_s - n_0) + \eta V_{th} \ln\left(\frac{n_s}{n_0}\right) \]

**Approximation:**

\[ n_s \approx 2n_0 \ln\left(1 + \frac{1}{2} \exp\left(\frac{V_{GT} - \alpha V_F}{\eta V_{th}}\right)\right) \]

- \( V_{GS} \): gate-source voltage
- \( V_T \): threshold voltage
- \( V_{GT} \): \( V_{GS} - V_T \)
- \( V_F \): quasi-Fermi potential
- \( \alpha \): body effect parameter
- \( \eta \): subthreshold ideality factor
- \( V_{th} \): thermal voltage
- \( qd_i/\varepsilon_i \)
- \( d_i \): thickness of the interface layer
- \( n_0 \): \( n_s \) at threshold
HFET, MOSHFET, and MISHFET

X. Hu, A. Koudymov, G. Simin, J. Yang, M. Asif Khan, A. Tarakji, M. S. Shur and R. Gaska
HFET/MOSHFET linear channel conductance (left) and C-V

$V_{DS} = 0.5\ V$

$V_{g} (V)$

Capacitance (pF)

$\sigma_s (\text{mS})$

$V_{g} (V)$

$V_{g}, V$

$f = 1\ MHz$

Real space transfer

AlGaN barrier depleted

Real space transfer

HFET Exp.

MOSHFT Exp.

HFET Sim.

MOSHFT Sim.
MOSHFET Model Development

[Diagram showing energy levels and real space electron transfer]
Leakage current in GaN MOSHFETs

- Gate leakage current in the AlGaN / GaN HEMTs is determined by trap-assisted tunneling and thermally-assisted direct tunneling of electrons into the AlGaN layer.

- Both tunneling and temperature activation also determine gate leakage current in MOSHFETs.
Reverse Gate Leakage Modeling

Direct tunneling and trap-assisted tunneling
Comparison with Experiment
Gate Lag and Current collapse in AlGaN/GaN HFETs: Pulsed measurements of “return current”


Nearly Identical Gate Lag Current Collapse was observed in:

- \text{I-SiC/Sapphire}
- \text{Pd/Ag/Au}
- \text{GaN}
- \text{AlN}
- \text{Pd/Ag/Au}
- \text{AlGaN}
- \text{n-GaN}

\text{S G D}

\text{GaN MESFET} \quad \text{AlGaN/GaN HFET} \quad \text{AlGaN/GaN MOSHFET}

- **AlGaN cap layer is not primarily responsible for CC**
- **Only the gate edge regions contribute to the CC**
Dynamic I-V characteristics of AlGaN-GaN HFETs

Load impedance scan @ constant $V_D = 10 \text{ V} \ldots 30 \text{ V}$

A. Koudymov, G. Simin and M. Asif Khan, A. Tarakji, M. S. Shur, and R. Gaska,
Correlation between current slump and 1/f noise in GaN transistors

\[ \alpha = (0.8-2) \times 10^{-3} \]

\[ \alpha = 0.1-0.4 \]

\[ \alpha = (5-8) \times 10^{-3} \]

MOS-HFET

HFET

Longer transient - higher Hooge constant

InGaN channel DHFET Design – 2D simulations using G-PISCES

\( (V_G = -1; V_D = 20 \, V) \)

- Better 2DEG confinement and Partial strain compensation
- Significantly reduced carrier spillover
- No current collapse

Regular HFET

InGaN channel DHFET

AlGaN-InGaN-GaN DHFET:
Carrier confinement and current collapse reduction

HFET

DHFET

Pulsed drain current, A/mm

Pulsed "return" currents

Pulsed transfer curves

Gate pulse amplitude, V

Depth (um)

Lateral Distance (um)

Gain

Pout, dbm; Gain, dB

Pin, dbm

> $10^{18}$ cm$^{-3}$

> $10^{16}$ cm$^{-3}$

> $10^{14}$ cm$^{-3}$

< $10^{14}$ cm$^{-3}$

HFET

DHFET

AlGaN-InGaN-GaN DHFET:
Carrier confinement and current collapse reduction

Sensor Electronic Technology, Inc.

University of South Carolina
Electrical Engineering
Mechanism of current collapse in GaN FETs

- Current collapse is not related to AlGaN layer alone
- Current collapse is caused by trapping at gate edges
- Current collapse can be eliminated by using DHFET structures
- Current collapse time delay correlates with 1/f noise spectrum
- **SOLVE THE CURRENT COLLAPSE ISSUE BY CHANNEL AND GATE EDGE ENGINEERING**
2D Simulation of AlN/GaN/InN-based HFETs

• Reveal device physics
• Verify new device designs
• Prove and optimize “two field plate concept”
• for higher breakdown voltage
• Investigate RESURF concept
• Study and understand trapping and non-ideal effects
Two Dimensional Simulation


ISE 2D GaN device simulator
Band Diagrams

Electron temperature contour map

$V_D = 10V \text{ and } V_S = V_G = 0V$

Importance of gate edge engineering confirmed

Electron density contour maps
(a) hydrodynamic (b) drift-diffusion

Distribution of trapped electrons

\[ V_D = 10V \] and \[ V_S = V_G = 0 \ V \]

Field Plate

No Field Plate, One Field Plate
Two Field Plates

![Graphs showing electric field and drain current versus drain bias and distance from source.]

Drain Current (mA/mm)
Drain Bias (V)
Electric Field (MV/cm)
Distance from Source (µm)
RESURF Effect

Breakdown voltage, $V_{br}$ (V) vs. Drain to gate separation, $L_{dg}$ ($\mu$m)

- Ideal
- Grounded substrate
- Floating substrate
- Field plates and p-n junction
- Field plates only
Breakdown in GaN HEMTs

• Predicted and observed the increase in the breakdown voltage with the drain-to-gate separation increase

• RESURF HEMT is proposed

• RESURF HEMT with two field plates should exceed 1 kV breakdown
Conclusions

• New device physics of nitride based FETs requires new designs and new modeling approaches
  • UCCM model for I-V and C-V
  • Gate leakage model: traps and tunneling
  • Current collapse modeling via dynamic
  • 2D simulation for revealing device physics

• Future Work
  • Gate recess modeling and optimization for current-collapse free devices
  • Modeling heating effects in Insulated Gate Transistors