High-voltage GaN-HEMT devices, simulation and modelling

Stephen Sque, NXP Semiconductors
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Outline

- GaN and related materials
- The AlGaN/GaN heterostructure
- GaN wafers
- GaN devices
- Issues facing high-voltage GaN-HEMT development
- High-voltage breakdown
- GaN-HEMT device simulation
- Compact modelling of GaN HEMTs
- Summary and conclusion
Outline

- **GaN and related materials**
- The AlGaN/GaN heterostructure
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Gallium nitride

- Gallium nitride (GaN) is a binary III-V compound material, with:
  - Wurtzite (hexagonal) crystal structure
  - Wide band gap of 3.4 eV (direct)
  - High thermal conductivity

![Diagram of Gallium Nitride Crystal Structure]
Properties of GaN

- Selected properties at 300 K:

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>4H-SiC</th>
<th>Diamond</th>
<th>GaAs</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap (eV)</td>
<td>1.1</td>
<td>3.2</td>
<td>5.5</td>
<td>1.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>11.9</td>
<td>10</td>
<td>5.5</td>
<td>12.5</td>
<td>9–10</td>
</tr>
<tr>
<td>Breakdown field (MV/cm)</td>
<td>0.3</td>
<td>3</td>
<td>5</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>Thermal conductivity (W/K/cm)</td>
<td>1.48</td>
<td>3.30</td>
<td>20.00+</td>
<td>0.54</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Aluminium nitride

- Aluminium nitride (AlN) is a binary III-V compound material, with:
  - Wurtzite (hexagonal) crystal structure
  - Wide band gap of 6.2 eV (direct)
  - High thermal conductivity
AlGaN

- Take GaN and replace a fraction \( x \) (the *mole fraction*) of the Ga atoms with Al atoms \( \Rightarrow \text{Al}_x\text{Ga}_{1-x}\text{N} \)

- Most material properties are then intermediate between those of GaN and AlN

<table>
<thead>
<tr>
<th>Quantity</th>
<th>GaN</th>
<th>Al(<em>{0.2})Ga(</em>{0.8})N</th>
<th>AlN</th>
<th>Units</th>
<th>Interpolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap</td>
<td>3.43</td>
<td>3.77</td>
<td>6.20</td>
<td>eV</td>
<td>Bowed, factor (-1.33)</td>
</tr>
<tr>
<td>Breakdown field</td>
<td>3.3</td>
<td>4.32</td>
<td>8.4</td>
<td>MV/cm</td>
<td>Linear (?)</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>9.5</td>
<td>9.3</td>
<td>8.5</td>
<td></td>
<td>Linear</td>
</tr>
</tbody>
</table>

GaN crystal growth

- Convention: [0001] direction is along \( c \) axis from Ga to N

- A-face: atom of type A is on top of bilayer

- Single-bond (low energy) surface

[O. Ambacher et al., J. Appl. Phys. 85 (6), 3222 (1999)]
Ga–N bonds are *polar*

The Wurtzite crystal structure is *non-centrosymmetric* (*i.e.*, it lacks inversion symmetry)

Result: **spontaneous polarisation** of the material

**Note:** $P_{SP}$ of AlN is stronger than that of GaN

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[O. Ambacher *et al.*, J. Appl. Phys. 85 (6), 3222 (1999)]

Piezoelectric effect

- Applying stress to the material distorts the crystal structure, causing further polarisation: **piezoelectric polarisation** $P_{PE}$
  
  - If the horizontal lattice parameter $a$ is varied from its natural value $a_0$ there will be non-zero piezoelectric polarisation along the vertical ($c$) axis:

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

  Constant for a given $x$ (Al fraction)

[O. Ambacher et al., J. Appl. Phys. 85 (6), 3222 (1999)]
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The AlGaN/GaN heterostructure

- AlN has a smaller lattice constant $a_0$ than GaN
- …and more spontaneous polarisation $P_{SP}$
- Grow $\text{Al}_x\text{Ga}_{1-x}\text{N}$ on top of (relaxed) GaN:

$$\text{Al}_x\text{Ga}_{1-x}\text{N} \downarrow P_{SP} \rightarrow \text{Ga}_x\text{N} \downarrow P_{SP}$$

Net positive polarisation-induced sheet charge
The AlGaN/GaN heterostructure

- Electronic band gap of AlN is larger than that of GaN
  - The band gap of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ is somewhere in-between

- Electrons confined to a thin region near the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ interface

- This is the **two-dimensional electron gas** (2DEG)
  - Areal density $\sim 10^{13}$ electrons/cm$^{-2}$

- No doping $\Rightarrow$ no impurity scattering $\Rightarrow$ very high mobility
Formation of the 2DEG

- Where do the electrons for the 2DEG “come from”?
- Model: donor-like surface states “provide” electrons

Electrons can come from Ohmic contacts. Surface donors play a role in the electrostatics.

Theory

Measurements

[J. P. Ibbetson et al., Appl. Phys. Lett. 77 (2), 250 (2000)]
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GaN wafers

- Choice of substrate is very important

- **Sapphire** (Al$_2$O$_3$)
  - 😊 Semi-insulating, can withstand high growth temperatures, relatively cheap
  - 😞 Very low thermal conductivity, large lattice mismatch, large CTE mismatch

- **Silicon carbide** (SiC)
  - 😊 High thermal conductivity, low lattice mismatch, relatively low CTE mismatch
  - 😞 High cost, crystallographic defects

- **Silicon** (Si)
  - 😊 Low cost, excellent availability of large diameters, acceptable thermal conductivity, processing in standard silicon fabs (high productivity)
  - 😞 Large lattice mismatch, very large CTE mismatch
GaN-on-Si wafers

- Base: silicon substrate with (111) face
- Example recipe:
  1. Thin seed layer of AlN
  2. Thick buffer layer: superlattice of alternating GaN and AlGaN layers
  3. High-quality GaN layer
  4. AlGaN barrier
  5. GaN cap layer

- Reduce dislocation density
- Stress control / wafer bow

[S. Lenci et al., Elec. Dev. Lett. 34 (8), 1035 (2013)]
Dislocations

- High initial dislocation density reduced towards surface (2DEG) by optimisation of buffer design

Dislocations $\sim 10^9 \text{ cm}^{-2}$

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GaN devices
High–electron-mobility transistor (HEMT)

- Ohmic contacts to 2DEG (Ti/Al)
- Source and drain metallisation (Al)
- Gate metal (Ni) on top of GaN cap
  - Schottky contact
- SiN passivation
- Metal field plate(s)

NXP process: [J. J. T. M. Donkers et al., CS-MANTECH 2013, 259]
GaN devices – HEMT operation

Zero bias

Off-state

On-state

Off-state, high voltage
GaN devices
Schottky barrier diode (SBD)

- “HEMT without a source”

- “Gate” → **anode**
  - Longer to handle high current

- “Drain” → **cathode**
GaN devices – diode operation

- Forward operation (anode+, cathode−)
  - Electrons flow from 2DEG across AlGaN into anode

- Reverse operation
  - Electron leakage from anode edges
GaN devices – cap layer

- A few extra nanometres of GaN grown on top of AlGaN

- Possible advantages:
  - Decreased reverse leakage through Schottky contact
  - Reduced peak electric field
  - AlGaN protected against processing
  - Nitrogen degassing prevented
  - Increased device gain
  - Increased power added efficiency
  - Improved DC reliability

[E. T. Yu et al., Appl. Phys. Lett. 73 (13), 1880 (1998)]
[P. Waltereit et al., J. Appl. Phys. 106, 023535 (2009)]
[S. Arulkumaran et al., Jpn. J. Appl. Phys. 44, 2953 (2005)]
GaN devices – HEMT characteristics

- $V_T$: threshold voltage, typically $-2$ to $-4 \text{ V}$
- $V_F$: diode forward turn-on voltage, typically $+1$ to $+2 \text{ V}$

- $I_{on}$: on-current, typically taken at $V_{GS} = 0 \text{ V}$ for $V_{DS} = 0.1 \text{ V}$
- $\Rightarrow$ On-resistance $R_{on} = \frac{V_{DS}}{I_{on}}$
GaN devices – performance

- Wide band gap \( \Rightarrow \) high critical field \( \Rightarrow \) **high voltage**
- High carrier concentration and velocity \( \Rightarrow \) **high current**

### High power

### High frequency

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_g (eV) )</td>
<td>1.1</td>
<td>1.42</td>
<td>3.26</td>
<td>3.39</td>
<td>5.45</td>
</tr>
<tr>
<td>( n_i (cm^{-3}) )</td>
<td>( 1.5 \times 10^{10} )</td>
<td>( 1.5 \times 10^6 )</td>
<td>( 8.2 \times 10^{-9} )</td>
<td>( 1.9 \times 10^{-10} )</td>
<td>( 1.6 \times 10^{-27} )</td>
</tr>
<tr>
<td>( \varepsilon_r )</td>
<td>11.8</td>
<td>13.1</td>
<td>10</td>
<td>9.0</td>
<td>5.5</td>
</tr>
<tr>
<td>( \mu_n )</td>
<td>( 1350 )</td>
<td>( 8500 )</td>
<td>( 700 )</td>
<td>( 1200 ) (Bulk)</td>
<td>( 1900 )</td>
</tr>
<tr>
<td>( \nu_{sat} (10^7 cm/s) )</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>( E_{br} (MV/cm) )</td>
<td>0.3</td>
<td>0.4</td>
<td>3.0</td>
<td>3.3</td>
<td>5.6</td>
</tr>
<tr>
<td>( \Theta )</td>
<td>( 1.5 )</td>
<td>0.43</td>
<td>3.3-4.5</td>
<td>1.3</td>
<td>20</td>
</tr>
<tr>
<td>( JM = \frac{E_{br} \nu_{sat}}{2\pi} )</td>
<td>1</td>
<td>2.7</td>
<td>20</td>
<td>27.5</td>
<td>50</td>
</tr>
</tbody>
</table>

[Stephen Sque, ESSDERC tutorial 16th September 2013]


[A. Johnson, RCA Review **26**, 163 (1965)]
GaN devices – performance

- Baliga figure of merit
  - Based on minimising the conduction losses in power FETs
  - Assumes power losses are solely due to the on-state power dissipation
  - Applies to lower frequencies where conduction losses dominate

\[ BFOM = \varepsilon_r \mu E_c^3 \]

[B. J. Baliga, Elec. Dev. Lett. 10 (10), 455 (1989)]

<table>
<thead>
<tr>
<th>Material</th>
<th>( E_g ) (eV)</th>
<th>( \varepsilon_r )</th>
<th>( \mu_r ) (cm(^2)/Vs)</th>
<th>( E_c ) (MV/cm)</th>
<th>( v_{sat} ) (10(^7) cm/s)</th>
<th>( n_i ) (cm(^{-3}))</th>
<th>BFOM*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>11.8</td>
<td>1350</td>
<td>0.3</td>
<td>1.0</td>
<td>1.5x10(^10)</td>
<td>1</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>13.1</td>
<td>8500</td>
<td>0.4</td>
<td>2.0</td>
<td>1.8x10(^6)</td>
<td>17</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.26</td>
<td>10</td>
<td>720</td>
<td>2.0</td>
<td>2.0</td>
<td>8.2x10(^-9)</td>
<td>134</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>2.86</td>
<td>9.7</td>
<td>370</td>
<td>2.4</td>
<td>2.0</td>
<td>2.4x10(^{-5})</td>
<td>115</td>
</tr>
<tr>
<td>2H-GaN</td>
<td>3.44</td>
<td>9.5</td>
<td>900</td>
<td>3.0</td>
<td>2.5</td>
<td>1.0x10(^{-10})</td>
<td>537</td>
</tr>
</tbody>
</table>

\( E_g \): bandgap; \( \varepsilon_r \): dielectric constant; \( \mu_r \): electron mobility; \( E_c \): critical electric field; \( v_{sat} \): saturation velocity; \( n_i \): intrinsic carrier density.

*BM = \varepsilon \mu E_c^3 \), BFOM was normalized by the BM of Si.

[N. Ikeda et al., Proc. IEEE 98 (7), 1151 (2010)]
GaN devices – benchmarking

- Minimise **specific on-resistance** ($R_{on} \times A$)
- Maximise **breakdown voltage**

![Graph showing specific on-resistance vs breakdown voltage](image)

[M. Su et al., Semicond. Sci. Technol. 28, 074012 (2013)]
GaN devices – benchmarking

- Some more **specific-on-resistance vs. breakdown-voltage** plots

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[N. Ikeda et al., Proc. ISPSD 2011, 284]

See also [Q. Jiang et al., EDL 34 (3), 357 (2013)] and [Z. Tang et al., EDL 34 (3), 366 (2013)]
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Issues

Schottky gate
- Reverse leakage
- Normally-on device
- Forward turn-on

High electric field
- Edge leakage
- Charge injection
- Limits breakdown

Final passivation
- Parasitic breakdown

First passivation
- On-resistance
- Dynamic behaviour

High electric field
- Charge injection
- Limits breakdown

AlGaN barrier
- Gate leakage
- Diode turn-on
- Charge trapping, threshold shift
- Inverse piezoelectric effect

GaN and buffer layers
- Punch-through breakdown
- Vertical leakage/breakdown
- Dynamic behaviour

Punch-through breakdown
- Vertical leakage/breakdown
- Dynamic behaviour
Issues – gate leakage

- Various mechanisms potentially involved in gate leakage


See also [L. Xia et al., Appl. Phys. Lett. 102 (11), 113510 (2013)]
Issues – current collapse

- On-state current temporarily reduced following off-state stress

- Also known as **dynamic** $R_{on}$
  - On-state resistance depends on recent history of device biasing
Issues – current collapse

- Device design and substrate composition can have a strong influence on the magnitude of current collapse (dynamic-$R_{\text{on}}$ increase)

![Graph showing the relationship between Vds (V) and Id (mA) for different off-state stresses and gate configurations.]

- Off-state stress:
  - 0 V
  - 30 V
  - 50 V
  - 65 V

- Also [S. DasGupta et al., Appl. Phys. Lett. 101 (24), 243506 (2012)]

[O. Hilt et al., Proc. ISPSD 2012, 345 (2012)]

Stephen Sque - ESSDERC tutorial 16th September 2013
Issues – virtual-gate effect

- **Off-state stress:**
  - Electrons from gate injected into trap states next to gate

- **On-state after stress:**
  - Trapped electrons act like a negatively biased gate
  - 2DEG partially depleted underneath ⇒ increased $R_{on}$

- **Later (~seconds):**
  - Electrons de-trap, 2DEG current restored

---

[Inferred from the image]

- [R. Vetury et al., Trans. Elec. Dev. 48 (3), 560 (2001)]
- [T. Mizutani et al., TED 50, 2015 (2003)]
Issues – buffer trapping

- **Off-state stress:**
  - Electrons trapped in bulk (deep donors/acceptors?)

- **On-state after stress:**
  - Trapped electrons partially deplete the 2DEG above ⇒ increased $R_{on}$

- **Later (~minutes):**
  - Electrons de-trap, 2DEG current restored

---


Issues – inverse piezoelectric effect

- **Piezoelectric effect:**
  mechanical stress $\Rightarrow$ polarisation \( (i.e., \text{internal electric field}) \)

- **Inverse (or converse) piezoelectric effect:**
  applied voltage $\Rightarrow$ electric field
  $\Rightarrow$ mechanical stress

  [J. Joh *et al.*, Microelec. Reliab. 50 (6), 767 (2010)]

- High field at drain-side edge of gate
  $\Rightarrow$ local stress $\Rightarrow$ defect formation
  $\Rightarrow$ device degradation (reliability)
  - Mitigate with field-plate design $\Rightarrow$
  - Not the full story…

  See [Meneghesso / Meneghini / Zanoni]

  [Y. Ando *et al.*, TED 59 (12), 3350 (2012)]

Also [N. A. Mahadik *et al.*, Appl. Phys. Lett. 93 (26), 262106 (2008)]
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Breakdown – measurement

- Typical breakdown measurement:
  - Start with all terminal biases zero
  - Reduce $V_G$ to a few volts below threshold
  - Increase $V_D$ and record terminal currents

- Current criterion often used for defining breakdown voltage $V_{br}$ (e.g., $V_{DS}$ for $I_D = 1$ mA/mm)

- Other definitions for $V_{br}$ used!

  $V_{br}$

- Drain injection technique: $V_S = 0$, set $I_D$, sweep $V_{GS}$ and find max. $V_{DS}$

Breakdown – mechanisms

- **Extrinsic**: air arcing, conductive surface layer
- **Intrinsic**: impact ionisation, punch-through, vertical breakdown
Breakdown – mechanisms

- Compare terminal currents to assess the relative contributions of different physical mechanisms to breakdown

- Example using current criterion for breakdown:

  - Dominated by gate-leakage impact-ionisation
  - Dominated by drain-to-source punch-through
  - Dominated by vertical current

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Breakdown – punch-through

- At high drain biases in the off-state, electrons can travel through the bulk GaN underneath the (turned-off) gate ⇒ drain-to-source current

- Prevent using: longer gate, acceptor doping in the bulk, back barrier, ...


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Breakdown – impact ionisation

- **Impact ionisation**: high-energy electrons (or holes) can knock other electrons out of valence-band states into conduction-band states, creating electron-hole pairs and hence raising the current.

- **Avalanche breakdown**: *every* electron (or hole) creates another electron-hole pair, and the current grows uncontrollably.
Breakdown – impact ionisation

- Positive temperature coefficient: $V_{br}$ increases with increasing $T$ \( \Rightarrow \) suggests impact ionisation (increased phonon scattering)
  
  [N. Dyakonova et al., Electron. Lett. 34 (17), 1699 (1998)]
  [T. Nakao et al., Phys. Stat. Sol. (c) 0 (7), 2335 (2003)]
  [M. Wang and K. J. Chen, TED 57 (7), 1492 (2010)]
  [X. Z. Dang et al., Electron. Lett. 35 (7), 602 (1999)]

- Impact-ionisation parameters for GaN have been evaluated theoretically
  
  [J. Kolník et al., J. Appl. Phys. 81 (2), 726 (1997)]
  [F. Bertazzi et al., J. Appl. Phys. 106, 063718 (2009)]

- …and determined experimentally
  
  [K. Kunihiro et al., EDL 20 (12), 608 (1999)]
  [N. Dyakonova et al., Appl. Phys. Lett. 72 (10), 2562 (1998)]

Not the full story? See also [Meneghesso / Meneghini / Zanoni]
Breakdown – gate-to-drain length scaling

- Breakdown voltage $V_{br}$ scales with gate-to-drain length $L_{GD}$ until vertical breakdown becomes dominant.

![Graph showing Drain current (A) vs. Drain voltage (V) with Lgd=2, 4, 6, and 8 μm.]

$\Delta V_{br} / \Delta L_{GD} < 3$ MV/cm? – leakage, electric field peaks, etc.

See also [N. Ikeda et al., Proc. IEEE 98 (7), 1151 (2010)]

Breakdown – vertical current

- Vertical leakage mechanisms / activation energies depend on wafer type
  [A. Pérez-Tomás et al., J. Appl. Phys. 113, 174501 (2013)]

- Traps identified in carbon-doped GaN-on-Si buffer layers

Breakdown – buffer optimisation

- Increasing the thickness of the buffer can increase breakdown voltage due to improved material quality and reduced vertical leakage
  [S. L. Selvaraj et al., Elec. Dev. Lett. 33 (10), 1375 (2012)] (see earlier slide)

- The inclusion of a carbon-doped “back barrier” can postpone punch-through to higher $V_{DS}$ (at the expense of increased on-resistance)
  [E. Bahat-Treidel et al., Trans. Elec. Dev. 57 (11), 3050 (2010)]
  [S. A. Chevtchenko et al., Appl. Phys. Lett. 100, 223502 (2012)]

See also [N. Ikeda et al., Proc. IEEE 98 (7), 1151 (2010)]
Breakdown – passivation optimisation

- SiN surface passivation can increase the breakdown voltage by modifying the surface charges/traps (and hence the electric field)

Electroluminescence

[Y. Ohno et al., Appl. Phys. Lett. 84 (12), 2184 (2004)]
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Simulation – structure

S/D electrodes
- Work function
- Contact resistance

Surface passivation
- Fixed charge?

Interface donors
- Energy level(s)
- Concentration
- Dynamics

Ohmic contacts
- n-type doping
- Shape / profile

Schottky gate
- Work function
- Tunnelling models

Surface passivation
- Fixed charge?

AlGaN barrier
- Polarisation charges
- Traps / fixed charge

Bulk GaN
- Doping concentration, energy level, depth profile, and dynamics

Interface(s)
- Polarisation charge?
- Energy band offsets

Substrate
- Doping (conductivity)
- Energy band offsets

Buffer layer(s)
- Superlattice?
- Doping

Material parameters
- Band gaps, electron affinities, permittivities, carrier mobilities, impact-ionisation parameters…

AlGaN

GaN

SiN
Simulation – set-up

- Density gradient vs. classical simulation
- Lattice temperature equation – necessary for high-power simulation
- Drift-diffusion vs. hydrodynamic model
- Tunnelling at contacts and interfaces – Schottky gate
- Different levels of polarisation models – fixed charges vs. built-in polarisation
- Thermionic heterointerface condition
- Mobility models – doping dependence, saturation, surface (2DEG) vs. bulk
- Anisotropy? – mobility / impact ionisation
- Fermi-Dirac vs. Boltzmann statistics, incomplete ionisation of impurities
- Generation – band-to band, impact ionisation
- Recombination – direct (band-to-band), Shockley-Read-Hall
- Numerical precision – low carrier concentrations, steep gradients
Simulation – internal observations

- Electron and hole distribution in off-state at high drain bias
  - Can be correlated to (for example) electroluminescence measurements

[Y. Kong et al., Proc. ICMMT 2012, 1]
Simulation – internal observations

-7 V

Impact ionisation

SiN

2DEG

Impact ionisation

G

Gate leakage

Electron

punch-through

Hole current

Hole current

Electron

punch-through

To substrate

[own work]

S (0 V)

D

+1235 V

GaN

SiN

GaN
Simulation – field plates

- There is a large peak in the surface electric field at the drain side of the gate (foot)
- Using a gate field plate (head) can reduce this field peak, but adds a new one
- Using another field plate can reduce these peaks but adds a third one
- Field-plate design must be optimised
  - Can affect breakdown, capacitances, current collapse, degradation, etc.

\[
E_x \, dx = -V_{DS}
\]

References:
- [N.-Q. Zhang et al., Elec. Dev. Lett. 21 (9), 421 (2000)]
- [J. Li et al., Elec. Lett. 37 (3), 196 (2001)]
- [A. Wakejima et al., Appl. Phys. Lett. 90, 213504 (2007)]
- [W. Saito et al., Trans. Elec. Dev. 54 (8), 1825 (2007)]
- [H. Hanawa et al., IRPS 2013, CD.1.1]
Simulation – field plates

- Simulations can be used to optimise the device geometry to obtain the maximum $V_{br}$ with minimum degradation in frequency response and $R_{on}$  


- Unity current gain (cut-off) frequency: $f_T = \frac{g_m}{2\pi C_G}$  

  Minimise increase in gate capacitance

---

FP height (SiN thickness)  
FP length  
Surface field at $V_{br}$  

$V_D = 630$ V
Simulation – field plates

- Making the gate-connected field plate too long can reduce $V_{br}$
  - Depending on definition of $V_{br}$!

[H. Onodera and K. Horio, Proc. EMICC (EuMIC) 2012, 401]
Simulation – comparison to measurements

- Kelvin probe force microscopy used to map internal potential distribution (w/wo FP)

[A. Wakejima et al., Appl. Phys. Lett. 90, 213504 (2007)]

See also [S. Kamiya et al., Appl. Phys. Lett. 90, 213511 (2007)]
Simulation – drain field peak?

- Electric field peak at drain at very high voltage – enough to cause breakdown?
  - Dependent on specific details of Ohmic-contact implementation?

![Graph showing electric field vs distance with voltage and material properties][1]

[H. Onodera and K. Horio, Proc. EMICC (EuMIC) 2012, 401]

[W. Saito et al., TED 50 (12), 2528 (2003)]
also [W. Saito et al., Proc. IEDM 2003, 687]
Simulation – impact ionisation

- Improved modelling of impact ionisation can have a significant effect on simulated breakdown voltages
  - Treat impact-ionisation parameters as tuning parameters

![Graph showing impact ionization coefficient vs. inverse electric field](image1)

![Graph showing drain current vs. drain voltage](image2)

[K. Kodama et al., J. Appl. Phys. 114, 044509 (2013)]
Simulation – buffer optimisation

- Thinning the lowly doped “spacing layer” between surface and carbon-doped layer can increase breakdown voltage via a decrease in the surface electric field peak.

\[ V_D = 300 \text{ V} \]


See also [M. J. Uren et al., Trans. Elec. Dev. \textbf{59} (12), 3327 (2012)]
Simulation – multiphysics

- Thermo-electro-elastic simulations:
  - fully coupled thermal, mechanical, and electrical equations

- Used to investigate (for example):
  - The role of thermal and piezoelectric stresses on defect formation
  - …and the impact on electrical characteristics

[TEM [U. Chowdhury et al., EDL 29 (10), 1098 (2008)]

[M. G. Ancona et al., J. Appl. Phys. 111, 074504 (2012)]
[M. G. Ancona, Proc. IEDM 2012, 315]
Outline

- GaN and related materials
- The AlGaN/GaN heterostructure
- GaN wafers
- GaN devices
- Issues facing high-voltage GaN-HEMT development
- High-voltage breakdown
- GaN-HEMT device simulation
- Compact modelling of GaN HEMTs
- Summary and conclusion
Modelling – compact models

- Models for GaN devices are needed to enable application development via circuit simulation and optimisation

- Different types of compact model:
  - **Table-based**: measured device data stored in large look-up tables
    - Very fast, but extrapolation outside of measured range is treacherous, and accurate scaling to other device dimensions is not possible
  - **Empirical**: uses whichever mathematical functions have the right shape
    - Good fits possible, but parameters are not physically meaningful, scaling is not physical, and extrapolation is still dubious
  - **Physics-based**: equations derived from modelling physical phenomena
    - Parameters physically meaningful, scaling is physical, extrapolation reliable
    - **Threshold-voltage–based**: physical expressions smoothed together
    - **Surface-potential–based**: uses a single expression for all regimes, inherent symmetry, established as the preferred approach in MOS modelling
      [Gildenblat et al., J. Solid-State Circ. 39 (9), 1394 (2004)]

See also [L. Dunleavy et al., Microwave Magazine 11 (6), 82 (2010)]
Modelling – empirical model

- **Chalmers (a.k.a. Angelov) model**
  - An empirical model for HEMT and MESFET devices, introduced in 1992
  - Extended in 1996 to include temperature, dispersion, and soft breakdown
    [I. Angelov *et al.*, TMTT **44** (10), 1664 (1996)]
  - **Widely used for (RF) GaN-HEMTs**
  - Modified in 2010 to make parameters more physical
Modelling – empirical model

- Modified form of the Angelov model for GaN-on-Si power switches

\[ I_{ds} = I_{p_{kt}} \left[ 1 + \tanh \left( \psi(V_{gs}) \right) \right] \cdot \tanh(\alpha_T V_{ds} + k_T V_{ds}^3) [1 + \lambda V_{ds}] \]

\[ \psi = \sinh \left[ P_1t(V_{gs} - V_{p_{kt}}) + P_2t(V_{gs} - V_{p_{kt}})^2 + P_3t(V_{gs} - V_{p_{kt}})^3 \right] \]

\[ \alpha_T = \alpha_R + \alpha_S [1 + \tanh(\psi)] \]

\[ I_{p_{kt}} = I_{p_{k0}} + (I_{p_k} - I_{p_{k0}}) \tanh(\alpha_R V_{ds}) \]

\[ V_{p_{kt}} = V_{p_{k0}} + (V_{p_k} - V_{p_{k0}}) \tanh(\alpha_R V_{ds}) \]

\[ P_{it} = P_{i0} + (P_i - P_{i0}) \tanh(\alpha_R V_{ds}) \]

Introduce temperature dependence for the model parameters

[S. Stoffels et al., Proc. THERMINIC 2011, 1 (2011)]

See also [S. Stoffels THERMINIC 2012]
Modelling – empirical model

- Analytical model including current collapse


Stephen Sque - ESSDERC tutorial 16th September 2013
Modelling – physics-based model

- Model for 2DEG charge density:
  \[ n_s = \frac{C_g V_g}{q} \frac{V_g + V_{th} [1 - \ln(\beta V_{gon})]}{V_g \left(1 + \frac{V_{th}}{V_{g0}}\right) + \frac{2\gamma_0}{3} \left(C_g V_{go}^2 \frac{V_{g0}}{q}\right)^{2/3}} \]
  [S. Khandelwal et al., Trans. Elec. Dev. 58 (10), 3622 (2011)]

- Expression extended for validity in sub-threshold regime…
  \[ n_{s,\text{unified}} = \frac{2V_{th}(C_g/q) \ln\{1 + \exp(V_{go}/2V_{th})\}}{1/H(V_{go,p}) + (C_g/qD) \exp(-V_{go}/2V_{th})} \]

  …and used as basis for drain-current model…

\[
\begin{align*}
L_d,\text{above} &= \frac{\mu_0 C_g W_g}{L_g G_{mob} G_{field}} \left\{ \sum_{i=1}^{6} c_i (\psi_{gd}^i - \psi_{gs}^i) + c_0 \ln \left( \frac{\psi_{gd}}{\psi_{gs}} \right) \right\} \\
L_d,\text{sub} &= \frac{2\mu_0 W_g qD V_{th}^2}{L_g G_{mob} G_{field} \exp(V_{go}/V_{th})} \exp \left( V_{go}/V_{th} \right) \left( 1 - \exp \left( -V_d S / V_{th} \right) \right)
\end{align*}
\]

…to which carrier velocity saturation, channel-length modulation, short-channel effects, and self-heating are added

[S. Khandelwal and T. A. Fjeldly, Solid-State Electronics 76, 60 (2012)]
See also [Yigletu et al., Proc. WiSNet / SiRF / RWS / PAWR 2013]

See also [U. Radhakrishna et al., Proc. IEDM 2012, 319/13.6.1 (2012)]
and [X. Cheng et al., TED 56, 2881 (2009)]
Modelling – physics-based model

- “Zone-based” compact model based on observations from device simulations
  - Different equations derived for different regions of the device, then smoothly joined
  - Alternative to equivalent-circuit models

Simulations

Output


and [D. Hou et al., TED 60 (2), 639 (2013)]
Modelling – surface-potential–based model

- The “first surface-potential–based compact model for RF GaN HEMTs”

\[
(V_{GS}^* - \psi_s)^2 = k_0^2 \left\{ \phi_T \left[ \exp \left( \frac{\psi_s - V}{\phi_T} \right) - 1 \right] - \psi_s + V \right\}
\]

\[
I_D = \frac{W}{G_L} \left\{ \frac{qN_D t_{GaN} V_{DS} - \bar{Q}_{tot} \Delta \psi}{e_0} + C_{ins} k_0 \frac{3}{2} \left[ F(\psi_s) - F(\psi_{SL} - V_{DS}) \right] \right\}
\]

Model

Sub-circuit implementation


TCAD / physics

Output

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Modelling – surface-potential–based model

- A Surface-Potential-Based Compact Model for AlGaN/GaN MODFETs

\[
\varphi_s = E_F + V_c
\]

\[
n_s = c_{ox}(V_{go} - V_{off} - \varphi_s)
\]

\[
I_{ds} = \beta \mu_{LF} \frac{(V_{gs} - V_{off} + V_q - \varphi_{sm})\varphi}{r_L + \delta_0 \varphi \mu_a / V_{CL}}
\]

- Analytical Modeling of Surface-Potential and Intrinsic Charges in AlGaN/GaN HEMT Devices

\[
n_s = D V_{th} \left[ \ln \left( 1 + e^{\frac{E_f - E_0}{V_{th}}} \right) + \ln \left( 1 + e^{\frac{E_f - E_1}{V_{th}}} \right) \right]
\]

\[
E_{0,1} = \gamma_{0,1} n_s^{2/3}
\]

\[
n_s = \frac{e}{q_d}(V_{go} - E_f - V_x)
\]

\[
I_{ds} = \frac{\mu_{eff} C_g}{\sqrt{1 + \theta_{sat}^2 \psi_{ds}^2}} \frac{W}{L} (V_{go} - \psi_m + V_{th}) (\psi_{ds}) (1 + \lambda V_{ds})
\]

See also [R. Jana and D. Jena, Proc. DRC 2012, 147 (2012)]
and [Martin / Hahe / Lucci (2012–2013)]
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Summary and conclusion

- The **material properties** of GaN and AlGaN, together with the remarkable properties of the AlGaN/GaN **heterostructure**, enable the creation of **high-power, high-frequency** devices.

- **Issues** affecting AlGaN/GaN-based device development include: leakage currents, current collapse (dynamic behaviour), reliability, and sub-optimal breakdown.

- **Device simulation** can be used to explore and address these issues, for example through buffer-composition and field-plate optimisation.

- **Compact models** for GaN HEMTs are maturing into surface-potential–(physics-) based models with high accuracy, efficiency, and scalability (the Compact Model Council is currently choosing a standard GaN-HEMT compact model).
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