Electrochemical Oxidation, Threading Dislocations and the Reliability of GaN HEMTs

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Outline

• Why HEMTs?  Why GaN?  Why GaN-on-Si?
• Physical degradation: pit formation
• Effects of
  - dislocations
  - SiN density passivation
• Modeling and reliability projections
GaN HEMT Structure

Source

SiN passivation

GaN cap

nucleation or buffer layer (AlN or AlN/GaN superlattice)

Substrate (Al₂O₃, SiC or Si)

gate

GaN

AlₓGa₁₋ₓN

2D electron gas

drain

e.g. Au/Ni/Ti

Au Ni

Passivation

Gold/Nickel/Titanium

E.g. Au/Ni/Ti
2D Electron Gas

$\text{Al}_x\text{Ga}_{1-x}\text{N}$ spontaneous polarization and piezoelectric polarization due to misfit strain

extrinsic GaN $\Rightarrow$ no impurity scattering in quantum well
$\Rightarrow$ high electron mobility $\Rightarrow$ high switching frequency
# Materials Properties and Performance

<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>Band Gap $E_g$ (eV)</td>
<td>1.1</td>
<td>1.42</td>
<td>3.26</td>
<td><strong>3.39</strong></td>
<td>5.45</td>
</tr>
<tr>
<td>Breakdown Field $E_{br}$ (MV/cm)</td>
<td>0.30</td>
<td>0.4</td>
<td>3.0</td>
<td><strong>3.3</strong></td>
<td>5.6</td>
</tr>
<tr>
<td>Electron Mobility $\mu$ cm$^2$/Vs</td>
<td>1350</td>
<td>8500</td>
<td>700</td>
<td>1200 (Bulk)</td>
<td>1900</td>
</tr>
<tr>
<td>Saturation velocity $v_{sat}$ ($10^7$ 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>Johnson Figure of Merit</td>
<td>1.0</td>
<td>2.7</td>
<td>20.0</td>
<td>27.5</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Johnson Figure of Merit for Power Transistor Performance

$$= E_{br} v_{sat} / 2\pi$$

(power-frequency limits)

Performance Based on Materials Properties

solid symbols - Todays costs: dashed lines-expected trends

## Substrate and Threading Dislocation Density

<table>
<thead>
<tr>
<th></th>
<th>lattice misfit %*</th>
<th>delta thermal expansion coefficient ((x \times 10^{-6})^*)</th>
<th>approximate** threading dislocation density (cm^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN on sapphire</td>
<td>-13.8</td>
<td>1.9</td>
<td>(\sim 10^5 - 10^7 )**</td>
</tr>
<tr>
<td>GaN on SiC</td>
<td>-3.4</td>
<td>-1.4</td>
<td>(\sim 10^7 )**</td>
</tr>
<tr>
<td>GaN on Si</td>
<td>20.1</td>
<td>-2.0</td>
<td>(\sim 10^8) to (10^9 )**</td>
</tr>
</tbody>
</table>

GaN on Si has about 100x higher dislocation density than GaN on SiC

Two Components of $I_{D,\text{sat}}$ Degradation

- Permanent physical damage
- Current collapse due to filling of trap states

Physical Degradation: Pits and Cracks

Cross-Sectional TEM Images

Correlation with Electrical Degradation

Uttiya Chowdhury, ... Jungwoo Joh, and Jesus A. del Alamo et al, EDL 29, 108 (2008)
Physical Degradation: De-processing

- Stress devices. In this case in the off-state for various $V_{DG}$
- **Chemically remove SiN passivation and gate/contact metals**
- Inspect Using SEM and AFM.
- Increasing $V_{DG}$ causes an increase in the number and depths of the pits.

Correlation of Electrical and Physical Degradation

Electrical degradation

Physical degradation

Mechanism of Pit Formation:

**Accelerated by Electric Field**

\[ V_{SD} = 30V \text{ and } V_{GD} = -12V \]

Pits form at gate edge with highest electric field

**Ga/Al Oxide Reaction Product**

before deprocessing

\[ V_{SD} = 30V \text{ and } V_{GS} = +12V \]

Ga/Al oxide particles on surface

Mechanism of Pit Formation:

Accelerated by the presence of water

Strong temperature dependence

Model: Field- and Water-Assisted Electrochemical Oxidation

\[ 2\text{Al}_x\text{Ga}_{1-x} \text{N} + 3\text{H}_2\text{O} = x\text{Al}_2\text{O}_3 + (1 - x)\text{Ga}_2\text{O}_3 + \text{N}_2 \uparrow + 3\text{H}_2 \uparrow. \]

Reduction half reaction:
\[ 2\text{H}_2\text{O} + 2e^- = \text{H}_2 + 2\text{OH}^- \]

Decomposition and oxidation:
\[ 2\text{Al}_x\text{Ga}_{1-x} \text{N} + 6h^+ = 2x\text{Al}^{3+} + 2(1 - x)\text{Ga}^{3+} + \text{N}_2 \uparrow \]
and
\[ 2x\text{Al}^{3+} + 2(1 - x)\text{Ga}^{3+} + 6\text{OH}^- = x\text{Al}_2\text{O}_3 + (1 - x)\text{Ga}_2\text{O}_3 + 3\text{H}_2\text{O} \]

GaN-on-Si HEMTs

W.A. Sasangka, G.J. Syaranamual, C.L. Gan, and C.V. Thompson, Proc. IRPS 2015
Pits and Dislocations

- All pits have dislocations associated with them

W.A. Sasangka, G.J. Syaranamual, C.L. Gan, and C.V. Thompson, Proc. IRPS 2015
Pits and Dislocations

TEM Cut Along Gate Edge, Early Pit Formation

White Lines: Gate edges
Yellow Lines: FIB slice for Cross-Sectional TEM
Pits and Dislocations

cross-section along gate edge

Dislocation density:
• Screw + mixed \( \approx 2 \times 10^9 / \text{cm}^2 \)
• Edge \( \approx 4 \times 10^9 / \text{cm}^2 \)

# of pits with dislocations
• Screw = 8 out of 15
• Edge = 4 out of 15
• Mixed = 3 out of 15

W.A. Sasangka, G.J. Syaranamual, C.L. Gan, and C.V. Thompson, Proc. IRPS 2015
Dislocation Motion During Stressing

untested, dislocation etch  
tested, de-processed  
tested, de-processed, dislocation etch

uniform dislocation distribution  
dislocation density higher at gate edge

Dislocations move to gate edge

W.A. Sasangka, G.J. Syaranamual, R. I. Made, C.L. Gan, and C.V. Thompson, AIP Advances 6, 095102 (2016).
Dislocation Motion During Stressing

W.A. Sasangka, G.J. Syaranamual, R. I. Made, C.L. Gan, and C.V. Thompson, AIP Advances 6, 095102 (2016).

higher $|V_G|$ ⇒ higher TD density at the gate-edges
Dislocation Motion During Stressing

High overall residual stress. Piezoelectric stress causes peak stress and stress gradient at gate edge.

W.A. Sasangka, G.J. Syaranamual, R. I. Made, C.L. Gan, and C.V. Thompson, AIP Advances 6, 095102 (2016).
Degradation of SiN Passivation

- Drain-side SiN degraded (lower film density than source side); XTEM and confirmed by EELS
- Increases diffusivity of oxidant (i.e. oxygen) from the ambient toward the GaN

Constant reverse bias at 225°C

$V_G = -10$ and $-20$ V, $V_D = 20$ V for 500 hrs.

Degradation of SiN

Degraded regions: “Nano-globes”

EELS scan along AA’

Globes contain oxygen, suggesting silicon oxide formation

Failure Time Distribution for Low and High Density SiN

- Low density: 2.25 g/cm³
  High Density: 2.48 g/cm³

- High Density SiN:
  - $t_{50}$: increases by $> 2X$
  - $t_{1}$: increases by $> 3X$

Electrical Degradation

- Two stages: fast and slow modes
- Fast mode similar for high and low density SiN
- Slow mode faster for low density SiN

Physical Degradation: Model

- Electrochemical oxidation
- Pits nucleate and grow at screw dislocations
- Fast and slow modes
- Fast mode similar for high and low density SiN
- Slow mode faster for low density SiN

In the initial fast mode, oxidant at interface **diffuses to gate** to supply oxidation reaction.

In slow mode, oxidant **diffuses through SiN to interface to gate edge**

Summary and Conclusions

• GaN HEMTs, for a wide range of high-frequency and high-power applications.

• Failure due to trap states and physical degradation.

• Focusing on pitting at gate edges:
  - Electrochemical oxidation at threading dislocations that can move to gate edge
  - The SiN passivation layers degrade and their density affects the rate of pitting
  - Trapped oxygen at the GaN/SiN interface contributes to failure
  - This failure mechanism is complex and is not captured by a simple reliability model.