Electrochemical Oxidation, Threading Dislocations and the Reliability of GaN HEMTs

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Outline

- Electrical and physical degradation – off-state testing
- Physical degradation: pit formation
  - effects of electric field and ambient
  - electrochemical oxidation
- Effects of
  - dislocations
  - SiN density
- On-state stressing
- Effects of carbon: initial and post-stressing leakage current
- Modeling and reliability projections
Typical GaN HEMT Structure Used in These Studies

commercial and research grade devices
Two Components of $I_{D,sat}$ Degradation

- Irreversible (physical damage)
- Reversible (trap states)

Physical Degradation: Pits and Cracks

Cross-Sectional TEM Images

Z contrast

Uttiya Chowdhury, ... Jungwoo Joh, and Jesus A. del Alamo et al, EDL 29, 108 (2008)
Correlation of Electrical and Physical Degradation

Both permanent and reversible stress degradation correlate with pit size

Correlation of Electrical and Physical Degradation

- Device Structure: GaN cap layer and AlGaN/GaN grown on SiC using MOCVD (experimental devices, corporate collaborator).
- Step stress to determine $V_{\text{crit}}$ at which a sharp increase in the drain current occurs (off-state) $V_{GS} = -7$ V, $V_{DG}$ stepped from 8 to 50 V at 1V intervals. Also fixed $V_{DG}$ for different times ($V_{DS}=0$).
- Chemically remove SiN passivation and gate/contact metals.
- Inspect Using SEM and AFM.

Correlation of Electrical and Physical Degradation

- 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: Electric Field

left: $V_{SD} = 30V$ and $V_{GD} = -12V$
right: $V_{SD} = 30V$ and $V_{GS} = +12V$

Pits form only on high-field gate edge

Mechanism of Pit Formation: Effect of Temperature

- Pitting is electric field driven and thermally activated
- Confirmation that electrical degradation correlates well with physical degradation
Pits and Particles

Increasing time: growth of particles on surface at gate edge

\[ V_{ds} = 0V \quad V_{gs} = -40V \]

Pits and Particles

Auger electron spectra

Gallium aluminum oxide particles

AFM of Pits

before deprocessing

6000 s

after deprocessing

One to one correlation of pits with particles

\[ V_{ds} = 0V \quad V_{gs} = -40V \]

Mechanism of Pit Formation: Effects of Ambient

Air

Vacuum (1 × 10⁻⁷ Torr)

OFF-state bias ($V_{gs} = -7V$ and $V_{ds} = 43V$) for 3000s at RT in darkness

**Physical Degradation: Chemistry (EDX)**

X-sectional TEM, EDX Chemical analysis along yellow scan line

Left: ambient air; Right: $1 \times 10^{-7}$ Torr vacuum.

Mechanism of Pit Formation: Effects of Water

Summary so Far

• Pits are associated with Al/Ga/O particles

• Pit Formation is Accelerated by
  - Electric Field
  - Temperature
  - $\text{H}_2\text{O/}\text{O}_2$
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:
\[ 2\text{Al}_x\text{Ga}_{1-x}\text{N} + 6h^+ = 2x\text{Al}^{3+} + 2(1-x)\text{Ga}^{3+} + \text{N}_2 \uparrow \]
\[ \text{and} \]
\[ 2x\text{Al}^{3+} + 2(1-x)\text{Ga}^{3+} + 6\text{OH}^- = x\text{Al}_2\text{O}_3 + (1-x)\text{Ga}_2\text{O}_3 + 3\text{H}_2\text{O} \]
Model: Field- and Water-Assisted Electrochemical Oxidation

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

Diffusion of OH\(^-\) through SiN
\[ \text{WVTR} = \text{known water vapor transmission rate} = 0.01–0.1 \text{ g/m}^2 \text{ day} \]

\[ \text{WVTR} \sim \frac{3 V_p \rho M_{\text{H}_2\text{O}}}{2 M_{\text{Al}_{x}\text{Ga}_{1-x}\text{N}}} \sim 0.05–0.1 \text{ g/m}^2 \text{ day} \]

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

Source of holes: Number of holes scales with pit volume
- Interband tunneling
- Probably assisted by mid-gap states
- Wrong scaling with \( E_{\text{max}} \) for impact ionization
Stressed under off-state bias. at a gate voltage $V_G = -10$ V and $V_D = 10$ V, 20 V or 40V. Stressed for 20 hrs. at a fixed temperature (250°C) in air.
Pit Area and Electrical Degradation Correlate

as in other studies

W.A. Sasangka, G.J. Syaranamual, C.L. Gan, and C.V. Thompson, Proc. IRPS 2015
Pits and dislocations: Chemistry (EELS)

Figure: STEM image with EELS coloring and locations of EDX analysis.

<table>
<thead>
<tr>
<th>Point #</th>
<th>Al</th>
<th>Ga</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 %</td>
<td>49.23%</td>
<td>50.77%</td>
<td>0 %</td>
</tr>
<tr>
<td>2</td>
<td>0 %</td>
<td>54.56%</td>
<td>45.44%</td>
<td>0 %</td>
</tr>
<tr>
<td>3</td>
<td>18.87%</td>
<td>12.47%</td>
<td>0 %</td>
<td>68.66%</td>
</tr>
</tbody>
</table>

- Pit area is
  - oxygen and aluminum rich and
  - gallium and nitrogen deficient

W.A. Sasangka, G.J. Syaranamual, C.L. Gan, and C.V. Thompson, Proc. IRPS 2015
• All pits have dislocations associated with them
• It is likely that the dislocation pre-existed before stressing (TD density $\sim 10^9$/cm$^2$)
• Pits form at dislocations rather than at the location of highest electric field

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
Dislocation density:
- Screw + mixed = $2 \times 10^9 / \text{cm}^2$
- Edge = $4 \times 10^9 / \text{cm}^2$

Number of pits with dislocation:
- Screw = 8 out of 15
- Edge = 4 out of 15
- Mixed = 3 out of 15

- Preferential pit formation at screw or mixed dislocations
- All pits have TDs, but not all TDs have pits
Field Effects
Triangle-Gate Structure for Reliability Studies

- A custom designed triangle-gate structure was used to isolate the effects of high electric field on the degradation mechanism
- Additionally, this structure helps to pin-point the location for TEM sample preparation

W.A. Sasangka, G.J. Syaranamual, C.L. Gan, and C.V. Thompson, Proc. IRPS 2015
Pits do not form preferentially at the point of highest electric field, further suggesting a role for defects.

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

Dislocation etch reveals higher threading dislocation near gate edges after stressing than in unstressed device

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).
Dislocation Motion During Stressing

- Residual stress measured using synchrotron
- Piezoelectric stress calculated and added to measured residual stress
- Stress peaks at gate edges at \( \sim 1.5 \) GPa

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

mechanical stress is sufficiently high to drive dislocations to move to the gate region to relieve stress

TABLE I. Slip systems in GaN that meet the criteria for dislocation movement (i.e., Peierls stress < total resolved shear stress).

<table>
<thead>
<tr>
<th>Category</th>
<th>Slip Direction</th>
<th>Slip Plane</th>
<th>Peierls Stress (GPa)</th>
<th>Resolved Shear Stress (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prismatic</td>
<td>$\langle 11\bar{2}0 \rangle$</td>
<td>${1\bar{1}00}$</td>
<td>0.15196</td>
<td>0.81</td>
</tr>
<tr>
<td>Pyramidal</td>
<td>$\langle 11\bar{2}0 \rangle$</td>
<td>${1\bar{1}01}$</td>
<td>0.73293</td>
<td>1.41</td>
</tr>
<tr>
<td>Basal</td>
<td>$\langle 11\bar{2}0 \rangle$</td>
<td>${0001}$</td>
<td>0.84987</td>
<td>1.6</td>
</tr>
</tbody>
</table>

several slip systems can be activated

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

- SiN at the drain side is degraded (lower film density than source side); XTEM and confirmed by EELS
- Lower density SiN increases the diffusivity of oxidant (i.e. oxygen) from the ambient towards the GaN

Constant reverse bias at 225°C
\[ V_G = -10 \text{ and } -20 \text{ V}, \quad V_D=20 \text{ V} \]
for 500 hrs.

Degradation of SiN

Degraded regions: ‘Nano-globes”

EELS scan along AA’

Globes contain oxygen. Suggesting silicon oxide formation form in SiN

# Effects of Composition and Density of SiN on the Device Reliability

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Passivation A</th>
<th>Passivation B (high density)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive Index</td>
<td>2.0229</td>
<td>2.0063</td>
</tr>
<tr>
<td>Thickness</td>
<td>1205.5 A</td>
<td>1178.5 A</td>
</tr>
<tr>
<td>Composition (EELS)</td>
<td>$\text{Si}<em>36\text{N}</em>{64}$</td>
<td>$\text{Si}<em>{21}\text{N}</em>{79}$</td>
</tr>
<tr>
<td>Density (XRR)</td>
<td>$2.25\text{ g/cm}^3$</td>
<td>$2.48\text{ g/cm}^3$</td>
</tr>
<tr>
<td>Breakdown field of capacitor</td>
<td>3.3 MV/cm</td>
<td>7.2 MV/cm</td>
</tr>
</tbody>
</table>

Failure Time Distribution for Low and High Density SiN

- Failure Criterion: 15% decrease in $I_{D_{\text{saturation}}}$
- Use of 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

- Degradation caused by electrochemical oxidation
- Pits nucleate and grow at screw dislocations
- Physical degradation occurs in two stages: 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, original oxidant at interface is depleted. Oxidant diffuses along SiN/AlGaN to interface to growing pit

## Electrical Degradation: Off-state vs. On-state

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Off-state</th>
<th>On-state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{DS}$ (V)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>$V_{GS}$ (V)</td>
<td>-10</td>
<td>0</td>
</tr>
<tr>
<td>$V_{DG}$ (V)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Stressing duration (h)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Base Temperature ($^\circ$C)</td>
<td>250</td>
<td>150</td>
</tr>
<tr>
<td>Actual Temperature ($^\circ$C) (thermo-reflectance)</td>
<td>250.4</td>
<td>216.6</td>
</tr>
<tr>
<td>Number of samples</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Average $I_{D\text{-saturation}}$ degradation (%)</td>
<td>$6.8 \pm 4.0$</td>
<td>$36.2 \pm 11.2$</td>
</tr>
</tbody>
</table>

Test temperature adjusted to account for Joule heating so both devices are approximately at the same temperature.

On-state stressing results in higher degradation rate.

Physical Degradation: **Off-state vs. On-state**

Electrical degradation is associated with pit formation, but for ON-state pits are also formed at locations away from gate edge

On-State Degradation: Role of current density:

Low current density

High current density

At high current density the pitted area extends further from the gate.
On-State Degradation: Role of current density:

At high current density the pitted area extends further from the gate.
On-State Degradation: Particles and Pits

- Particles are associated with pits
- Particles contain Ga, Al and O
- Particles and pits associated with threading dislocations
Physical Degradation: Off-state vs. On-state

Off-state model, Feng et al. (IEEE, 2014)

- On-state current supplies electrons from the channel to form holes though impact ionization to reduce $H_2O$.
- Pit formation away from the gate edge is also associated with threading dislocations

Proposed on-state model

Effects of Carbon Residue on Leakage Current

Initial Leakage Current: ‘Bad’ and ‘Good’ Devices

Effects of Carbon Residue on Leakage Current

Initial Leakage Current: ‘Bad’ and ‘Good’ Devices

Method for determination of the apparent zero-bias Schottky barrier height ($\phi_{B0}$) and ideality factor ($n$) from a $J_{Gate}$-$V_{Gate}$ curve ($V_{Gate} > 0$ V).

Effects of Carbon Residue on Leakage Current

Initial Leakage Current: ‘Bad’ and ‘Good’ Devices

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Good devices</th>
<th>Bad devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{th}$ (V)</td>
<td>$-2.6 \pm 0.2$</td>
<td>$-2.5 \pm 0.3$</td>
</tr>
<tr>
<td>$\phi_{bi0}$ (eV)</td>
<td>$0.79 \pm 0.03$</td>
<td>$0.4 \text{ to } 0.62$</td>
</tr>
<tr>
<td>$n$</td>
<td>$2.03 \pm 0.4$</td>
<td>$3.9 \pm 0.6$</td>
</tr>
<tr>
<td>$J_{Gate}$ (A/m$^2$)</td>
<td>$&lt;10^2$</td>
<td>$&gt;10^4$</td>
</tr>
<tr>
<td># of devices</td>
<td>24 out of 30</td>
<td>6 out of 30</td>
</tr>
</tbody>
</table>

$\phi_{B0} (\text{bad}) \sim 0.4 \text{ to } 0.62$V

$\phi_{B0} (\text{good}) = 0.8$

Method for determination of the apparent zero-bias Schottky barrier height ($\phi_{B0}$) and ideality factor ($n$) from a $J_{Gate}$-$V_{Gate}$ curve ($V_{Gate} > 0$ V).

Effects of Carbon Residue on Leakage Current

Initial Leakage Current: ‘Bad’ and ‘Good’ Devices

- Carbon is present in Ni at hot spots
- C lowers Schottky barrier height by lowering the work function of Ni (literature)
- Postulate: C forms from resist residue associated with lift off process

Effects of Carbon Residue on Leakage Current

Post-Stressing Leakage Current

Y. Gao, W.A. Sasangka, C.V. Thompson, and C.L. Gan, Microelectronics Reliability (in press)
Effects of Carbon Residue on Leakage Current

Post-Stressing Leakage Current

Y. Gao, W.A. Sasangka, C.V. Thompson, and C.L. Gan, Microelectronics Reliability (in press)
Modeling and Reliability Projections

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

Effect of SiN density

Fast and Slow Process

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

In slow mode, original oxidant at interface is depleted. Oxidant diffuses along SiN/AlGaN to interface to growing pit

- Both mechanisms involve thermally activated processes
- The activation energy for the rate-limiting process for the two mechanisms is likely to be different will be different

Oxidation Without External Oxygen

Untested device
Oxidation Without External Oxygen

Device Tested in Vacuum

Summary and Conclusions

- Electrical and physical degradation (pits) correlate.
- The rate of pit formation and growth increases with $V_{DG}$, electric field, temperature, and in air.
- Pits have associated regions/particles of aluminum and gallium mixed with oxygen.
- Postulate: Pits form due to electrochemical oxidation of Ga
- The density of SiN passivation affects the rate of physical degradation.
- Failure proceeds first by a fast mode and then by a slow mode.
- Slow mode associated with oxidant trapped at SiN/substrate interface: slow mode associated with diffusion of oxidant through the SiN.
- On-state failure also involves pit formation at dislocations due to electrochemical oxidation, but not confined to gate edge.