GaN HEMT Reliability: An Assessment of the Open Literature

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Eric Heller
Physicist
AFRL/RXAN
Air Force Research Laboratory
Outline

• Motivation
• Survey of “Pathologies”
• How are “Pathologies” accelerated
• Gaps and Some Paths Forward
• Conclusions

For this discussion:
  ➢ Open literature only!
  ➢ Radiation effects and package level reliability out of scope.
  ➢ NOT a final product with industry buy-in
Motivation

• From Don’s talk: *Lifetime assessment* is key to successful transition (especially for DoD)
• Academic community has said, done, and published much on *degradation and failure findings & physics*. There are *new* and *enhanced* stressors/drivers in GaN vs. legacy materials: Some of this is relevant!

**A simplified view of cultural drivers**

**Academic:**
- Find the **novel**
- Publish the **outcome**
- Move on

**Industry:**
- Eliminate/mitigate **relevant** flaws quickly
- Not publish but **retaining full** qual “**recipe**”
- Sell product with right balance of **performance** to **promised** lifetime

*This is a useful natural tension!*
Survey of “Pathologies”

Source Gate Drain

Ohmic Metal/ Semiconductor reactions

Virtual gate, Channel Degradation
Dislocation + point defect interaction
Point defects: Everywhere, but most important here
Pit/Crack: Mechanical/Chemical/Stochastic

Gate: Diffusion/Chemical

Dislocation Enhanced Diffusion

Also – catastrophic “crater” failures with no definitive location in channel

Survey of Accelerants

Ohmic Metal/Semiconductor reactions

Virtual gate, Channel Degradation
Dislocation + point defect interaction
Point defects: Everywhere, but most important here
Pit/Crack: Mechanical/Chemical/Stochastic

Gate: Diffusion/Chemical

Plus gas environment, RF environment, UV light, Acceleration by design (test structures) etc.

Also – catastrophic “crater” failures with no definitive location in channel
**Survey of Open Literature**

<table>
<thead>
<tr>
<th>Physics of Failure</th>
<th>Stressor</th>
<th>Failure Metric</th>
<th>Life Limiter</th>
</tr>
</thead>
</table>
| • Diffusion        | • DC Electrical ($I_D$, $V_D$, $V_G$, $V_{crit}$, “semi-on”) | • DC electrical or parametric | • $T_{CH}$  
  Negative Ea  
  Low Ea (0.12-0.39)  
  **Mid Ea**  
  Multiple Ea’s, one part | |
| • Defect Percolation | • DC pulsed | | |
| • TDDDB at Gate    | • RF | | |
| • Surface barrier oxidation | • RF pulsed | | |
| • Ohmic intermixing | • $T_{BP}$ or $T_{CH}$ | | |
| • Gate intermixing | • Pulsed Temperature | | |
| • **Critical elastic E** | • UV light | | |
| • Crack/Pitting    | • Ambient gas | | |
| • Traps*           | • Ambient RF | | |
| • Alloying, melting | • Use of proxy parts | | |
| • Dislocations     | • Starting conditions/Processing marginality | | |
| • SBH change       | | | |
| • Interface Relax. | | | |
| • Multi-Fail models | | | |
| • Unknown          | | | |

*Multi-dimensional space in Physics of Fill, E Depth, Type, Location, Physics of Fail*
What we would like

• Well defined Physics of Failure, Stressor(s), Fail Metric(s)
  (like Si CMOS)

→ Well defined “path” to follow for reliable conclusions

*This time* its...
Col. Mustard,
In the Study,
Lead pipe.
Why are we not there?

BIN 1. MATERIALS/PROCESS IMMATURETY

• Large variation in degradation rate of nominally “identical” parts.
  - A “fog” that cuts across industry.
  → Rapidly getting better!

• Much larger variation across processes!
  - Secrecy/Proprietary limits sharing
    Limited distributions of new parts
    Process details, origin of parts often unknown
  - “Cutting edge” conclusions drawn from old or marginal parts!
  → HiREV University Foundry run.

If we had the luxury of starting from scratch...
  - Use modern parts
  - Minimize sharing restrictions for academic research
  - Verify findings with multiple vendors
Why are we not there?

BIN 2. TEST AND FAILURE ANALYSIS IMMATURITY

• Large variation in test protocols
  - $R_{th}$: IR thermal, micro-Raman, modeling
  - Random tested population or cherry-picked?
  - Each data source explores a subset of stressor parameter space.
  → HiREV role as independent tester facilitating uniform testing
  → HiREV working full statistical understanding of problem

• Failure Analysis is mostly “find once and report”, not protocol development
  - Very few “findings” use a closed loop approach (pre-post stress)
  - Little said on how the “found” defect is known to be the “real” defect!
  → HiREV working to cross-correlate FA findings and close the loop

If we had the luxury of starting from scratch...
  - Compare/set test protocols early
  - Compare/set Failure Analysis protocols early
  - Fully document for full reproducibility!
Why are we not there?

BIN 3. THE UNDERLYING PHYSICS HAS CHANGED

• Very large peak E fields, temperatures, thermal gradients.
  - Can make “nonstandard” drivers relevant.
    - Complex interplays cited in literature (i.e. drifting charged point traps).
  - Can require coupled mechanical/thermal/electrical physics.
    - Awareness of this complexity is now critical!
  - Adequacy of existing test channels and test methodology?
    ➔ HiREV working fundamental science and tool assessment
    ➔ HiREV working full understanding of the “stressor space”

• Traps, traps, traps
  - Nearly impossible to directly measure, yet a genuine issue.
  - Easy to cite, hard to quantify: density, location(s), species, conditions.
  - High dislocation density, probably here to stay
  - Wide bandgap: means traps have microseconds to many days lifetime.
    ➔ This will require closure. Verification/Validation Critical.
    ➔ HiREV working to directly quantify traps under the gate (expt. & model)
Example: HiREV Thermal Characterization

IR Thermography
- Quick look at heating uniformity
- Good for part-part variation
- Not good for absolute temperatures
- ~3-5 μm spatial resolution

μRaman
- Accurate point thermometry
- 1 μm spatial resolution
- Mapping possible
- Measures GaN or SiC temperature only; optical access limitations

Thermoreflectance
- Transient measurement with 50ns resolution
- Submicron spatial resolution
- Full device imaging
- Surface localized

Electro-Thermal Modeling
- Thermal Transients
- Best spatial resolution
- Full device to package
- Buried not an issue
- Only as good as input data \(\rightarrow\) lots of validation!
Example: HiREV Fail Analysis (FA) Characterization

Incoming Parts

STRESS

Draw

Legend: NOW IN WORKS

Incoming Parts

Multi-bias IR + Multi-bias PE + EBIC + SEM

STRESS + Parametric & Parametric Analysis

Multi-bias IR + Multi-bias PE + EBIC + SEM

TEM → Wet Etch

μ-Raman + μ-PL + AFM + Specialty (Kelvin probe, etc.)

Optional plan view FA (where to cut?)

Outgoing Parts

STRESS

Optimal Pre-Stress Characterization

Optimal Post-Stress Characterization

Down Select
Example: HiREV GaN HEMT Modeling

**Electro-Thermal Physics**
- Full device to package

- A Critical Link: Measurable data (electrical, etc.) $\rightarrow$ Root Causes (E, T, $T_e$, traps, etc.)

- Sensitivity analyses: Understand key unknowns (bulk, interlayers, processing)

- Validation is Critical!
Conclusions

• Many GaN HEMT reliability concerns are expressed in the open literature.
  - But, with “Fog” in Data, Test Methodology, Conclusions.
  - Uncertain how much is worrisome.
  - Not appropriate either to ignore or to follow every lead!

• Gaps can largely be binned
  - Sample limited or institutional (old, proprietary parts)
  - Unfixed test/FA protocols and quality/completeness of reporting
  - Key gaps in science

• HiREV working to fill key gaps
  - Where we believe there is a “void” to fill
  - Always looking for partners to assist!

• Many thanks to the HiREV team for thoughts/feedback/guidance!
Stress Test Cost / Realism

DC Quick ($V_G$ or $V_D$)

↓

DC Long

↓

RF Long Large Signal

↓

DC Pulsed, RF Pulsed, Thermal Shock, DC/RF Cryo,

Others: Radiation, UV light, Environmental (gas, RF power, ESD, …), physically relevant stress sequences, etc.
On Open Exploration vs. Guideline Driven

Good things happen when Academics ignore guidelines!
- Lots of good stuff in the open lit. not captured by specs like JEP 118.
  - Non thermal accelerants
  - Hot electrons, Critical biases, Traps and defect percolation
  - Full and time dependent role of dislocations (not going away)
  - Piezoelectricity (and Inverse PZ) will need to be addressed
  - Clouds reliability testing results
→ Need consistent application of these novel tests to relevant and modern parts for multiple vendors!

Bad things happen when Academics ignore guidelines!
- Hard to find papers on some topics (ESD, > 1 vendor).
- Time duration for parts on test not usually long enough
- Under-focus on consistency and enough data to fully replicate work
  Need better documentation, critical data being discarded!
  Need to standardize tests when possible
  Statistics important, outliers too.
→ Need to address these gaps to get work from there to here!
→ Journals practices are moving in our direction