GaN HEMT Reliability at the Device Level: A HiREV (High Reliability Electronics Virtual Center) Assessment

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Outline

- Background
- Why use GaN HEMTs?
- Survey of “Pathologies” (open lit. basis)
- How are “pathologies” accelerated (open lit.)
- Gaps and Solutions
- Paths Forward
- Conclusions

- **For this discussion:**
  - ➢ **Open literature only!**
  - ➢ **Radiation effects out of scope.**
  - ➢ **Package level reliability out of scope**
  - ➢ **<u>NOT</u> a final product with industry buy-in**

Background

- DoD has been part of the ongoing national GaN development and maturation effort (~$800M) – materials, device, circuit to subsystems

- Lifetime and lifetime assessment are key to successful transition

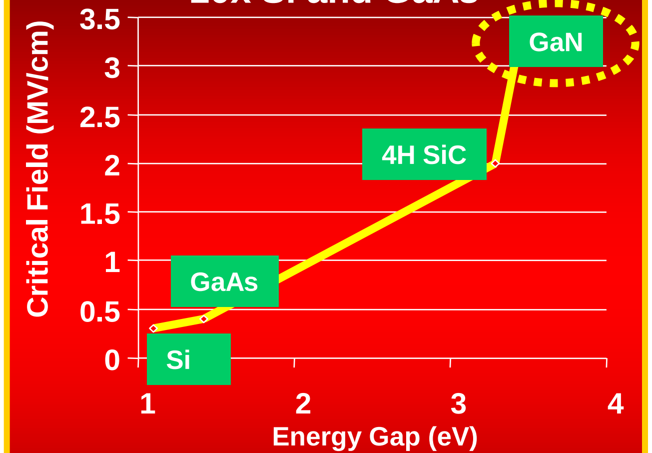
- DoD has been and is now analyzing data from national efforts and performing supplementary tests

- GaN HEMTs are the focus of a large percentage of HiREV's reliability science activity

Why GaN HEMTs?

The Next Generation of MMICs

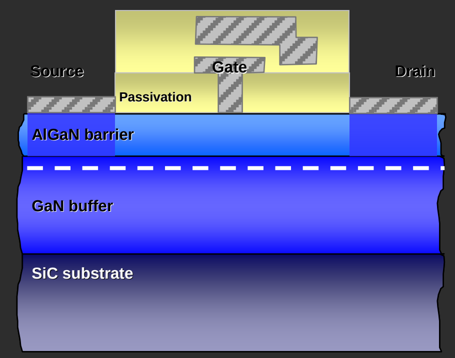
Critical Electric Field of GaN is 10x Si and GaAs



High voltage operation for analog and RF components

$P_{max} \propto E_g^4$

Benefit of GaN HEMTs

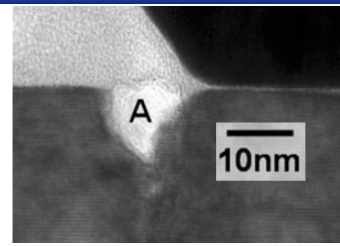


Gallium Nitride HEMT on Silicon Carbide

Dramatically higher…

- Output power
- Efficiency
- Bandwidth

Survey of “Pathologies”



S. Y. Park et al., Microelectronics Reliability 49 (2009) 478–483.

Ohmic Metal/ Semiconductor reactions

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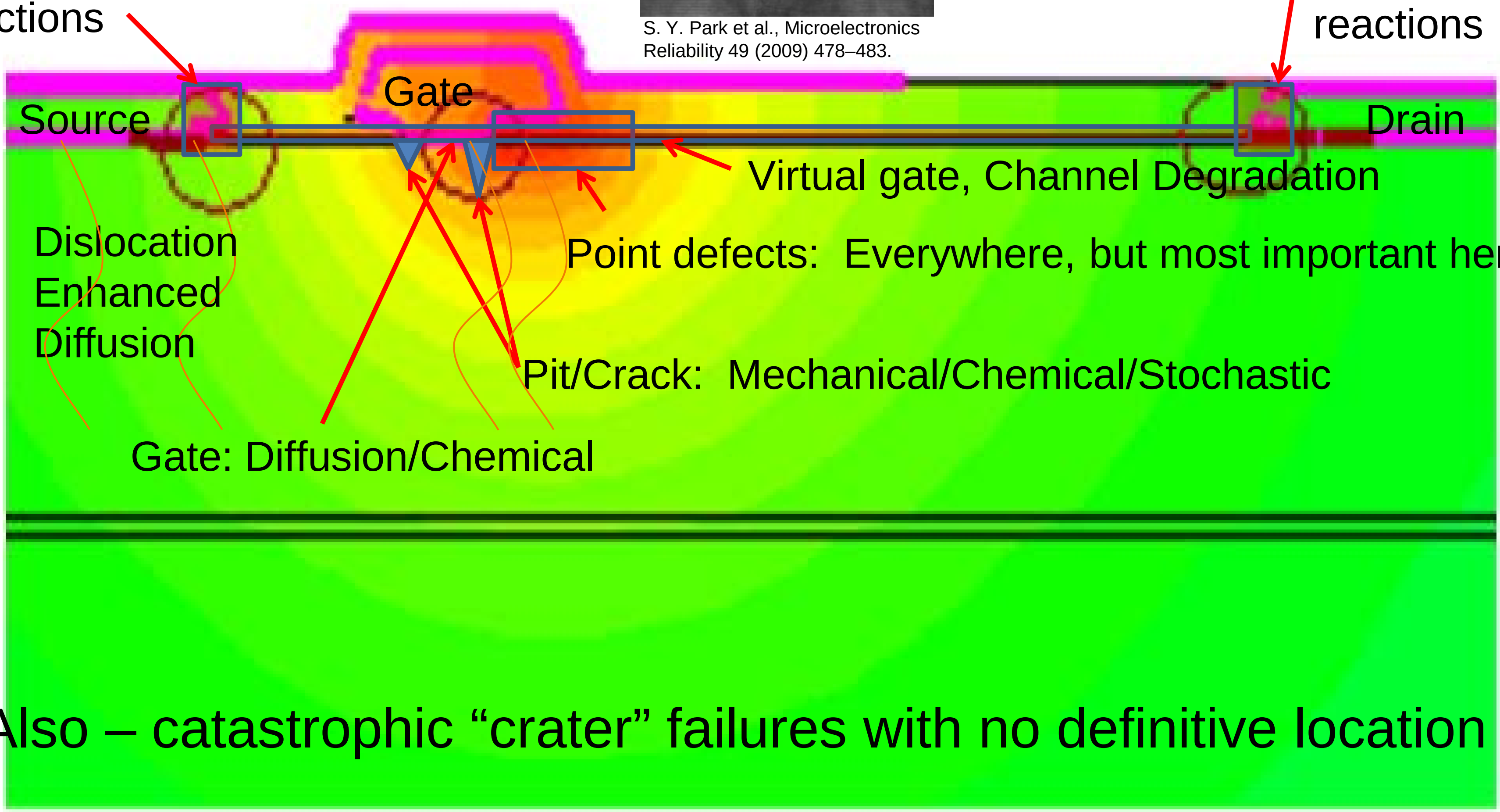
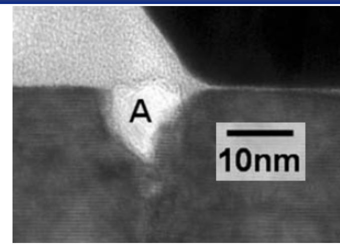


Survey of Accelerants



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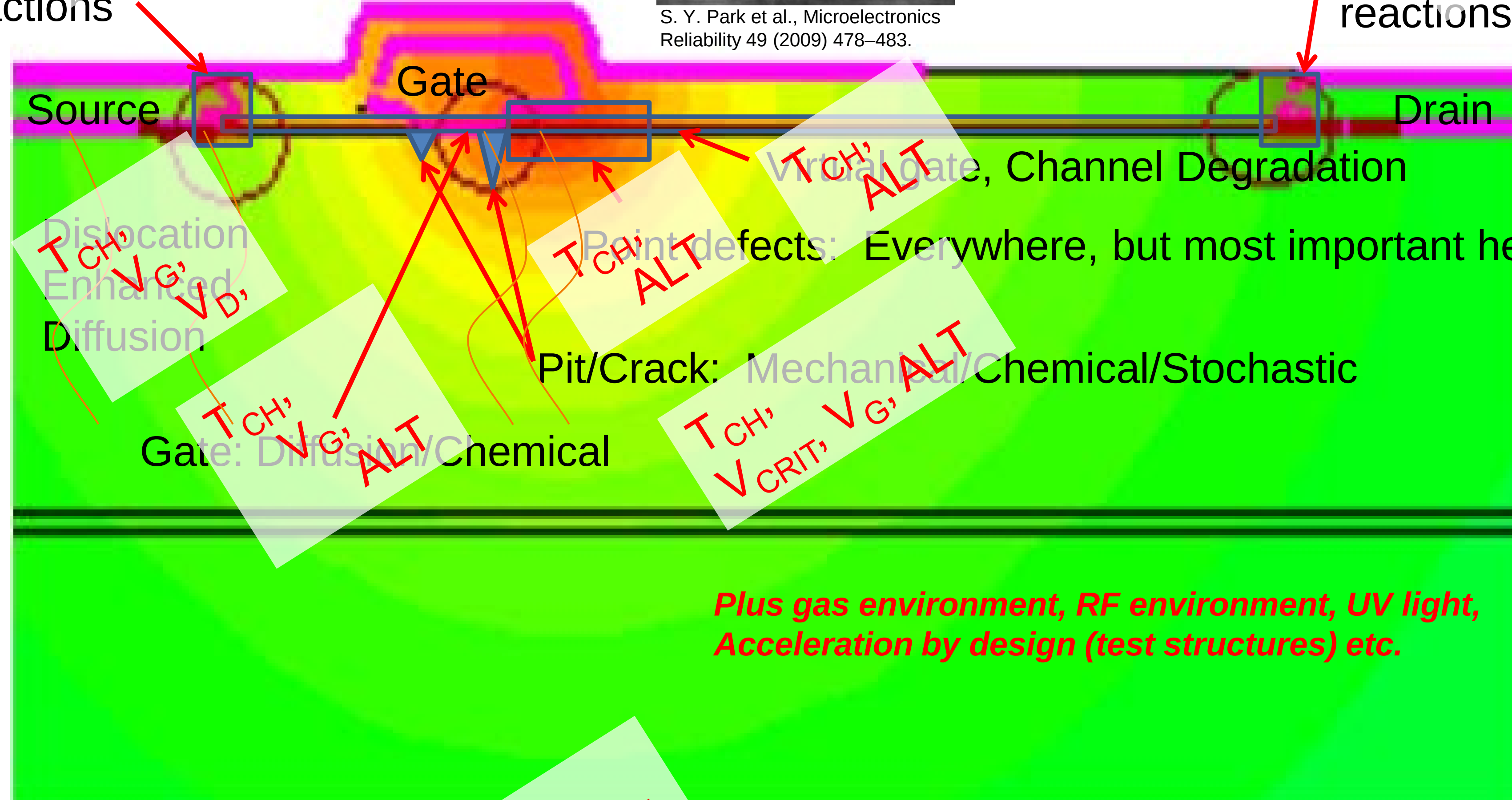


Also – catastrophic "crater" failures with no definitive location

Survey of Open Literature

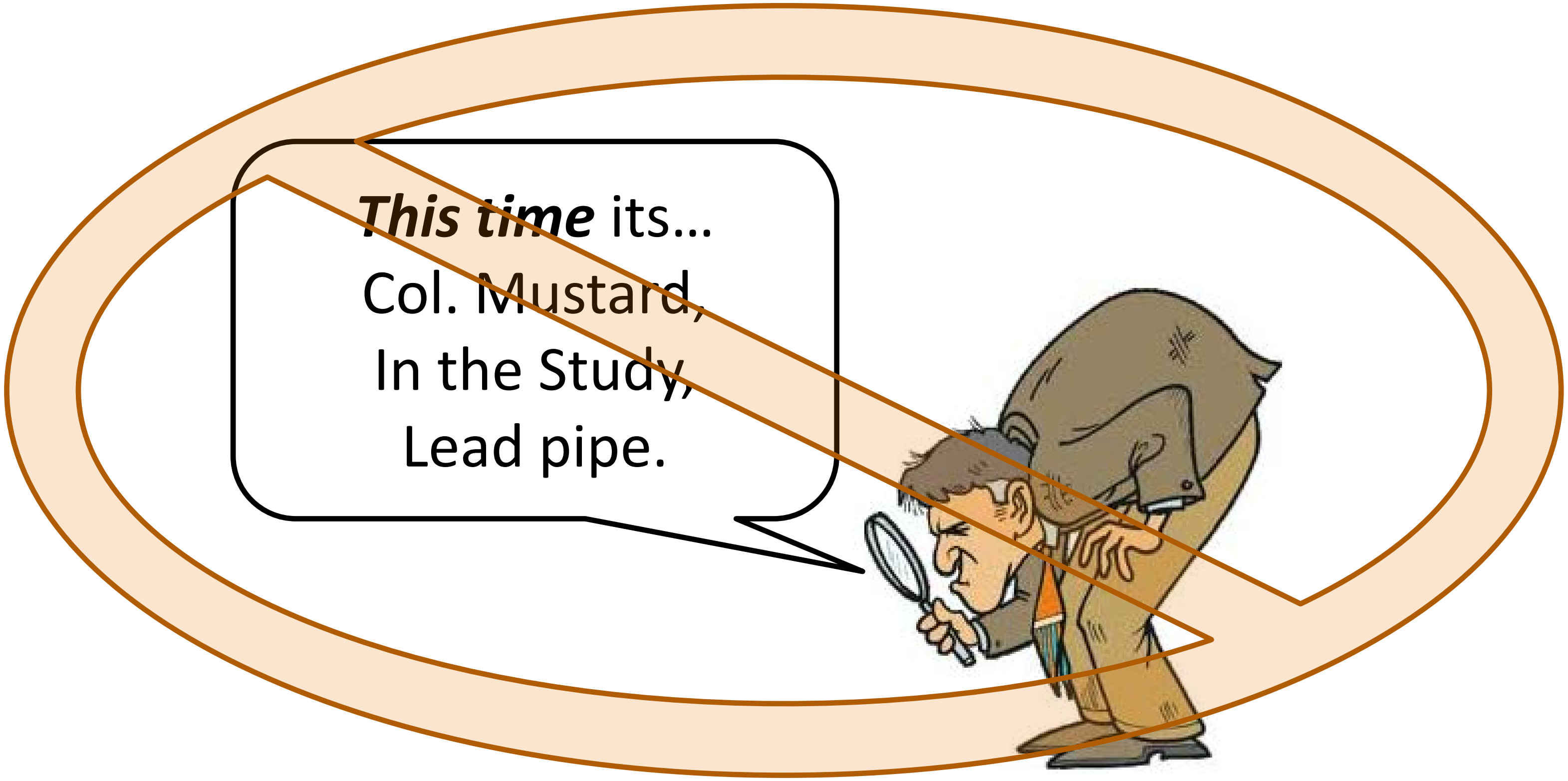
Physics of Failure	Stressor	Failure Metric	Conclusions Drawn
•Diffusion •Defect Percolation •TDDB at Gate •Surface barrier oxidation •Ohmic/Gate intermixing •Critical elastic E •Cracking/pitting •Traps* •Alloying, melting •Dislocations •SBH change •Interface Relax. •TDDB •Unknown	•DC Electrical (I_D, V_D, V_G, V_{crit}, "semi-on") •DC pulsed •RF •RF pulsed •T_{BP} or T_{CH} •Pulsed T •UV light •Ambient gas •Ambient RF •Use of proxy parts •Starting conditions/ Processing marginality	•DC Electrical/parametric •RF electrical •Model Guided •Transients •DLTS or I-DLTS •Other (PE/Thermal IR/noise/Raman/ SEM or AFM image judgment)	•T_{CH}: Negative Ea •Low Ea (0.12-0.39) •Mid Ea •Mult. Ea's one part •$V_{crit} = V_D - V_G$ •V_G •Hot electrons •Recoverable/not •Gradual/quick •Ambient Dominated •DC-RF similar/not •Unknown

** Multi-dimensional space in Physics of Fill, Type, Location, Physics of Fail*

What we would like

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

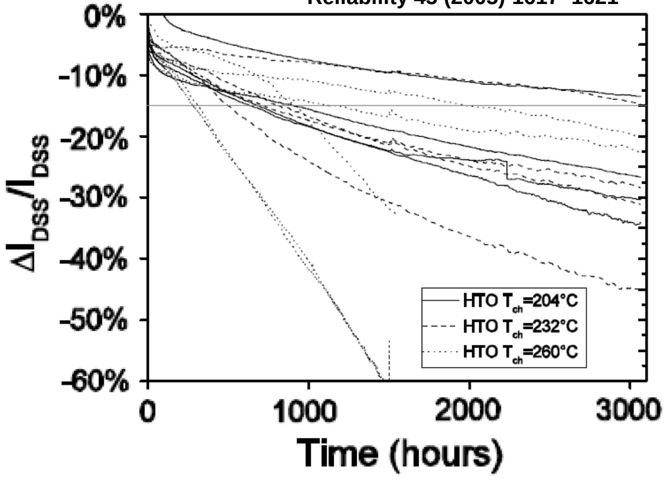
→ Well defined "path" to follow for reliable conclusions



Why are we not there?

- Large variation in degradation rate of nominally “identical” parts.
  - Cuts across industry.
  - A “fog” that clouds reliability testing results.
  - → **Rapidly getting better!**
- Much larger variation for parts across fabs
  - Rapid tech advancement, “old” parts
  - Secrecy/Proprietary limits sharing
    - **Limited distributions of new parts**
    - **Process details, origin of parts often unknown**
  - → **HiREV University Foundry run.**
- Large variation in test protocols
  - R_{th}: IR thermal, micro-Raman, modeling
  - Uneven treatment of burn-in
  - Each data source explores a *subset* of stressor par space.
  - Adequacy of existing test channels?
  - →**HiREV role as independent tester facilitating uniform testing**
  - →**HiREV working fundamental science and tool assessment**

A. Sozza et al., Microelectronics Reliability 45 (2005) 1617–1621



Why are we not there?

- Complex materials system.
  - Coupled mechanical/thermal/electrical physics.
  - Very large peak E fields, temperatures, thermal gradients.
  - Complex interplays cited in literature (i. e. drifting charged point traps).
  - Lag between experiment and modeling.

  → **Bigger effects drive need for more accuracy (i. e. R_{TH} + E_a)!**

  → **Fully coupled models (and awareness of complexity) is critical!**

  → **HiREV has both in-house and funded efforts in these areas.**

- Traps, traps, traps
  - Nearly impossible to directly measure, yet a genuine issue.
  - Easy to cite, hard to quantify: density, location(s), species, conditions.
  - Wide bandgap: means traps have microseconds to many days lifetime.
  - Confusion: Creation, depassivation, and/or just filling?

  → **This will require closure. Verification/Validation Critical.**

On Open Exploration vs. Guideline Driven

Good things happen when Universities 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 Universities ignore guidelines!

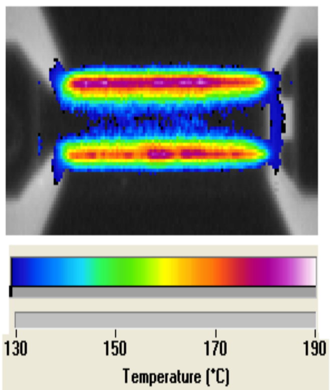
- Hard to find papers on some topics (ESD, > 1 vendor).
- Time duration for parts on test not usually long enough
- Under-focus on consistency and enough data to **fully** replicate work

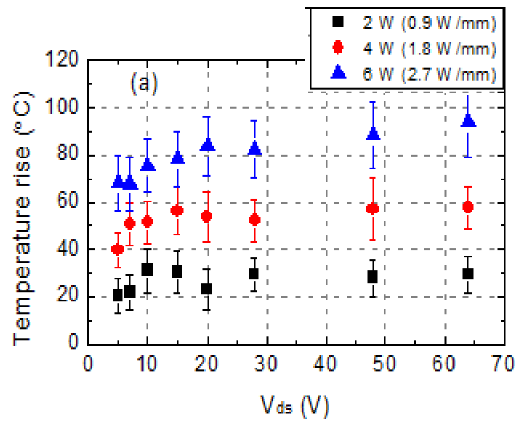
    Need better documentation, critical data being discarded!
    Need to standardize tests when possible
    Statistics important, outliers too.

→ **Need to address these gaps to get work from there to here!**

→ **Journals practices are moving in our direction**

Example: HiREV Thermal Characterization





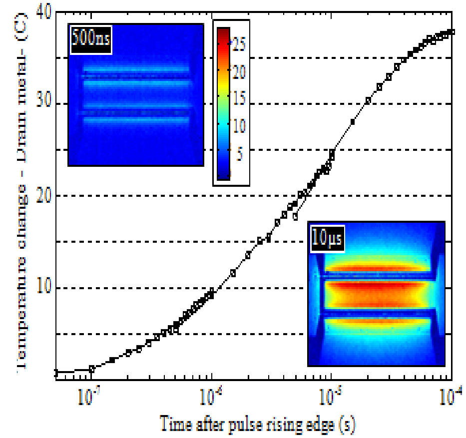
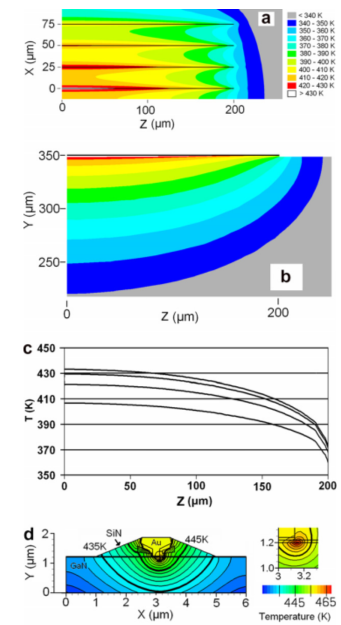


Figure 3. Drain metal rising thermal transient from time=50 nanoseconds to 100 microseconds.



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

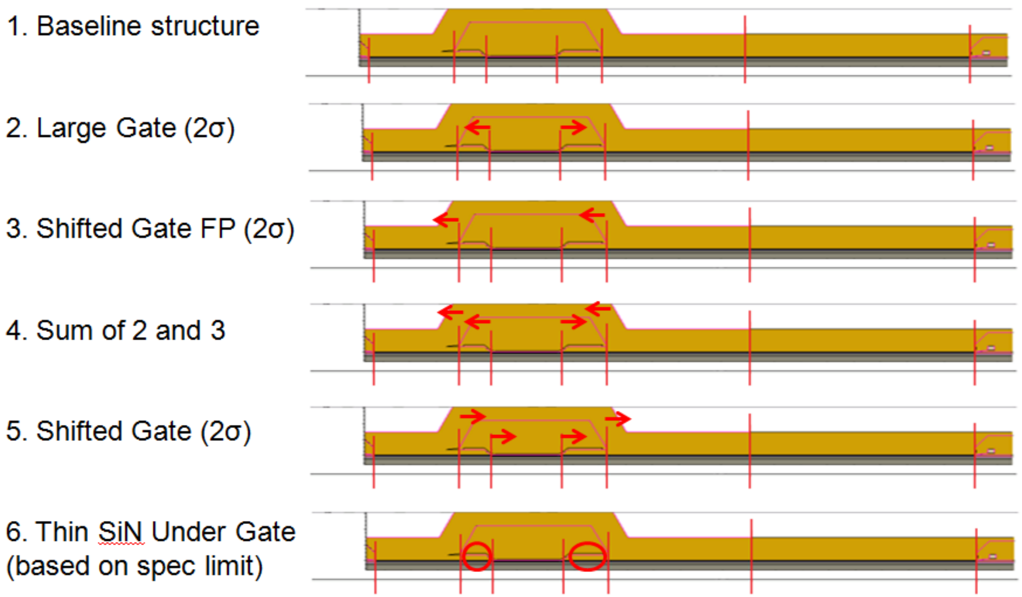
Thermoreflectance

- 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 → lots of validation!

Example: HiREV GaN HEMT Modeling

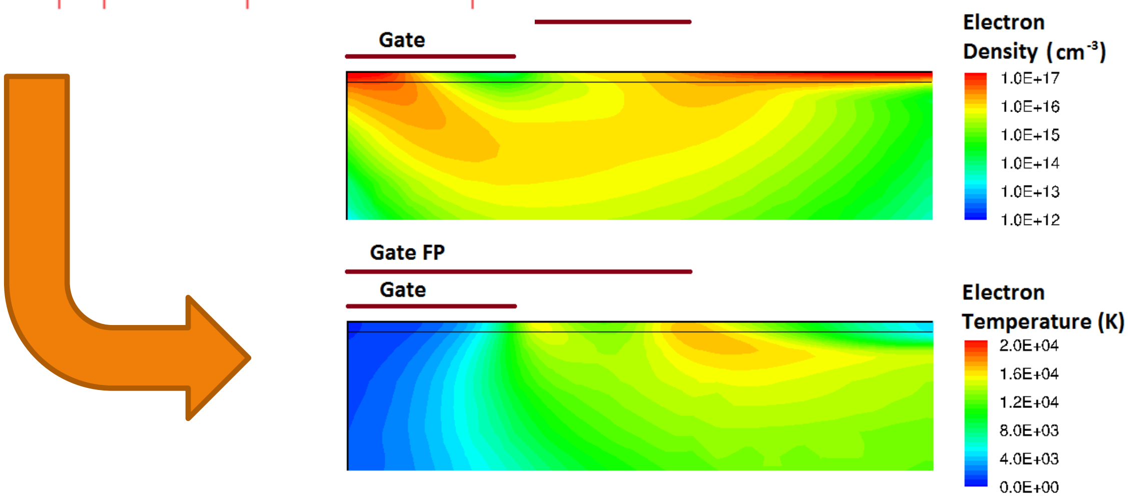


Electro-Thermal Physics

- Full device to package
- A Critical Link:

Measurable data (electrical, etc.) → 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)
  - Quality/completeness of reporting
  - Key gaps in science

- HiREV working to fill some key gaps in science
  - Example: Understanding Thermals
  - Example: Electro-Thermal Modeling

- Many thanks to the HiREV team for thoughts/feedback/guidance!

Supplemental past this point

Approach

Synthesis of published/publishable (non-proprietary) knowledge streams
- Past several years' MURI reviews
- Literature surveys
- HiREV team discussions
- Personal experience: 6 yrs. Phys. based modeling, FA of GaN HEMTs

"What we know" applied to some key questions

1. Test protocols: Variation seen in open literature & expected impact
"Your mileage may vary!"
2. Deltas: AlGaN/GaN vs. AlGaAs/GaAs
3. R_{th}: Key & under-appreciated issues
- IR thermal, micro-Raman, modeling
- Bias dependence (DC operating regime), DC vs. RF
4. Survey of device stressors in open literature (by design or accidental)
- T_{BP}, T_{CH}, I_D, time, V_D, V_G, $V_{CRIT}=V_D-V_G$, RF power

Survey of Open Literature

About 80 open literature sources, 2007 or newer

- By Physics of Failure:

Diffusion, Defect percolation, TDDB at gate, Surface barrier oxidation, melting, Ohmic metal intermixing, voiding, Critical Elastic Energy, Cracking, pitting, *trap creation/depassivation and/or filling + gate/SiN/barrier/channel and/or deep epi + static charge/mobility degradation/transient charge/hopping conduction*, SBH change, interface relaxation, Gate metal intermixing, dislocation density – static charges, traps, highway for impurities.

- By Stressor (accelerant):

DC Electrical (I_D, V_D, V_G, $V_{CRIT}=V_D-V_G$, “semi-on”), DC pulsed, RF, RF pulsed, UV light, use of proxy parts (many…), T_{BP}, T_{CH}, gas ambient, RF ambient, impurity starting conditions, T cycling, and combinations of these!

Survey of Open Literature

Continued…

• By Failure Metric:

DC Electrical parametric ($I_{DSS,}$ $I_{DMAX,}$ V_{knee}, many…), RF power drop, RF PAE drop, Model guided conclusions, Electroluminescence, Thermal IR, Current Transient, DLTS, I-DLTS, Noise Spectral Density, micro-Raman, SEM, TEM, plan view AFM/SEM image judgment.

• By Conclusion(s) Drawn:

Negative E_a, low (0.12, 0.26, 0.39 eV) E_a, mid E_a, high E_a (2.5 eV) more than one E_a seen on the same part (fn of T), T_{CH} critical for E_a but is a fn(X, Y, Z, Time), non-thermal (V_{CRIT}, V_G, hot electrons) stresses and "ambients" important or dominant, 10^6 variation in lifetime in nominally identical parts in one case, load plane shrinks as T increases, parts sometimes "recover", some fail gradually and some quickly, DC and RF stress not the same, or maybe they are?