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What vs. Why: Characterization for Insight

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Why ask Why ?

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- **Why is lemon juice made with artificial flavor ..and dishwashing liquid made with real lemons?**

- **If nothing ever sticks to TEFLON how do they make TEFLON stick to the pan?**
- **Why does the sun lighten our hair, but darken our skin?**

- **Why doesn't glue stick to the inside of the bottle?**

To make things work (better) or avoid failure, it is often necessary to perform additional experiments to understand WHY things happen, not just WHAT does (or does not) happen

Characterization for Insight

- ***Test as You Fly, Fly as You Test, and Demonstrate Margin (1998) – NASA*** **http://llis.nasa.gov/lesson/1196**
  - The process of end-to-end system verification (either through testing, simulation, or analysis) may be compromised when it is not consistent with the mission profile (**plus margin and the appropriate off-design parameters**).
  - Enforce the system-level test principle of "test as you fly, and fly as you test." Carefully **assess any planned violations** of this principle; if they are necessary, take alternate measures such as independent validation.
  - When using simulations for system-level verification, **models must have been validated (e.g., supported by test)**; and **sufficient parametric variations** in the simulations must be performed to ensure that adequate margins exist.

How do you know what parameters you are sensitive to, and what margins are sufficient, particularly in a new technology (and might there be unplanned violations) ?

Radiation Effects

- **Radiation response may be dependent on several coupled variables, esp:**
  - Bias (including standby vs. DC vs. AC)
  - Frequency of operation, switching vs. static
  - Temperature
- **Worst case may not always be the nominal (“as you fly”) operating condition**
- **Single point testing does not provide insight to delineate sensitivity to individual coupled variables**
  - Good experimental design practice includes systematic variation of individual variables
  - Test time and device number may impose practical limitations
  - Device-to device variability is an important consideration

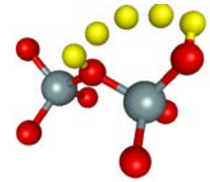
Emerging Technologies

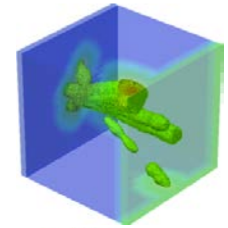
- **New structures (ET-FDSOI, FinFETS)**
  - Geometric considerations for energy deposition
- **New materials**
  - Gate stacks (CMOS)
  - III-V quantum well devices (CMOS)
  - SiC, GaN (RF and power)
- **Moving Targets**
  - Emerging technologies are not mature
  - Not all foundry process are identical

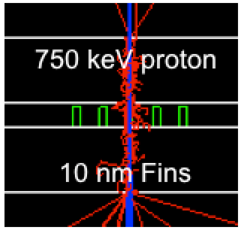
Sensitivity analyses can provide useful insight in this environment

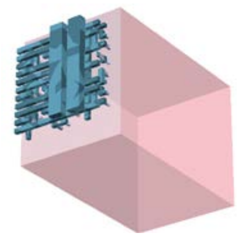
Approach: Getting to Why

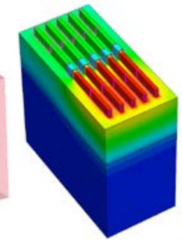
- **Study basic failure mechanisms in advanced and emerging technologies**
  - Combine hierarchical, multiscale modeling approaches with targeted experiments
  - Base models on physics-of-failure, from the atomic level to device characteristics
  - Identify defects and failure mechanisms, including acceleration techniques
  - Approach is not technology or application specific; can apply to new technologies as they are developed

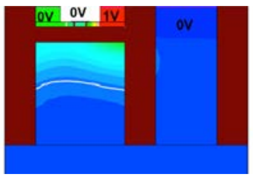


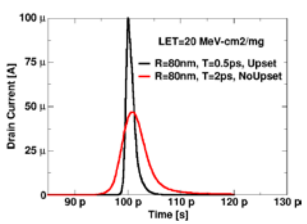


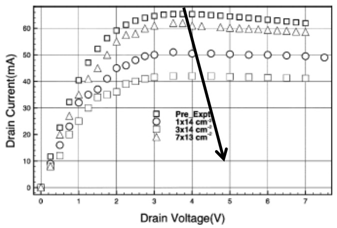




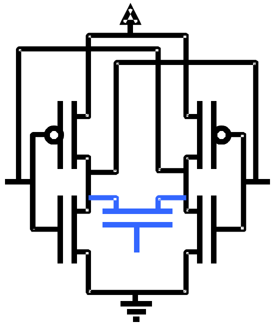


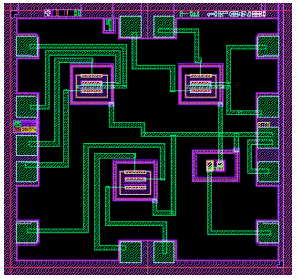






- **Facilitate technology deployment into high-reliability space and defense applications**
  - Work with emerging and state-of-the-art technologies acquired through collaborations with industry, government, and university laboratories
  - Develop physically-based, predictive radiation and reliability models & monitoring techniques





Example: Study of GaN HEMTs

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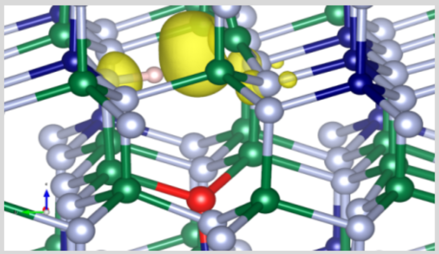
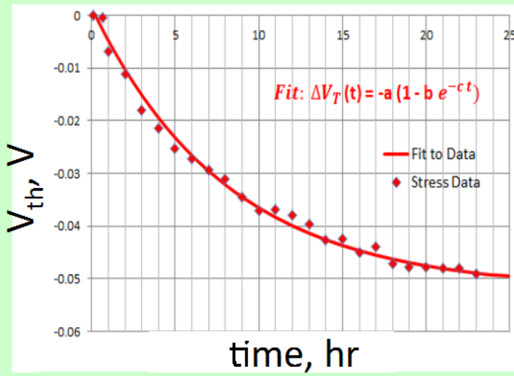
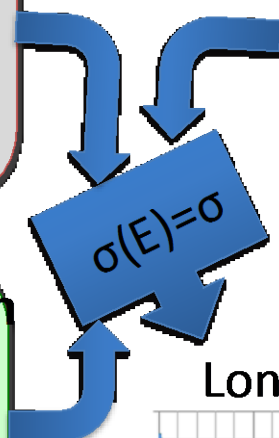
DFT

- Defect identification
- Defect activation energy



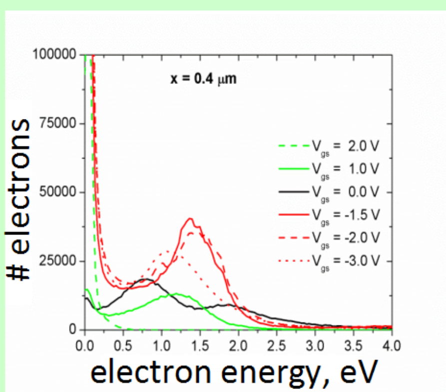
Accelerated Degradation Test



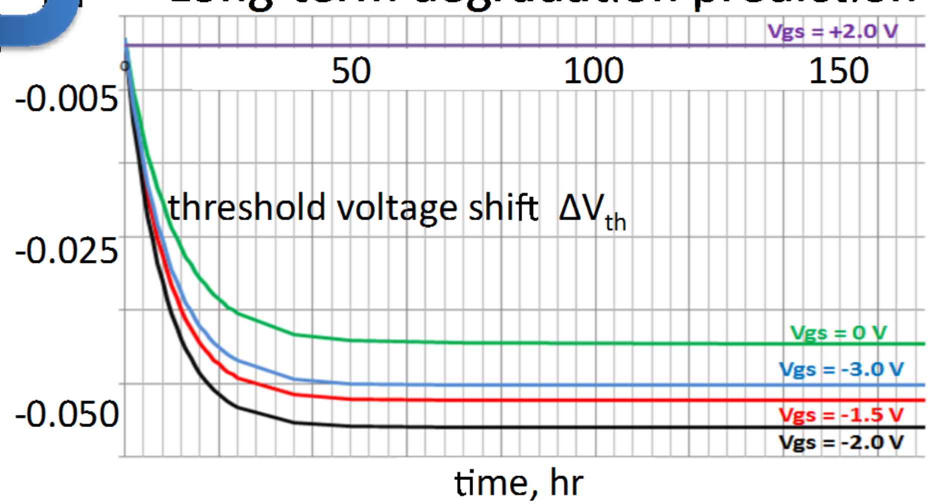


Monte Carlo Simulation

- Electron distribution in space, energy



Long-term degradation prediction



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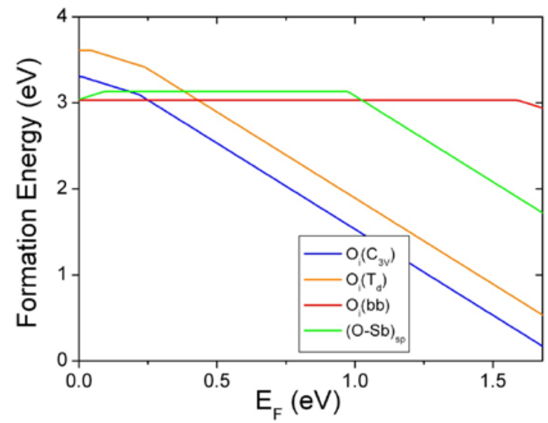
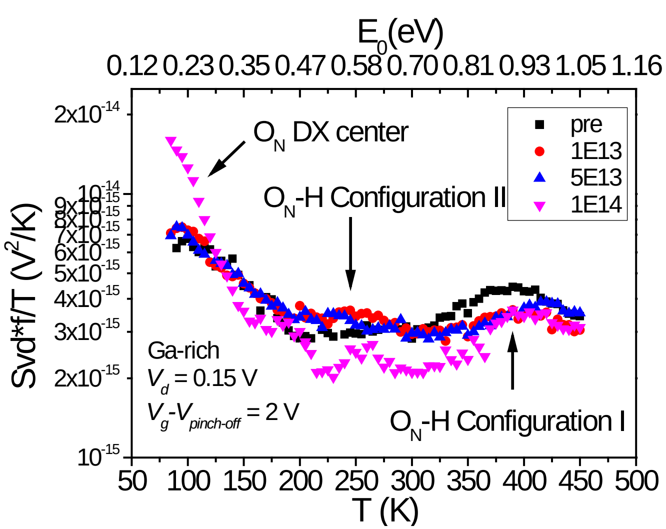
Defect Identification Techniques

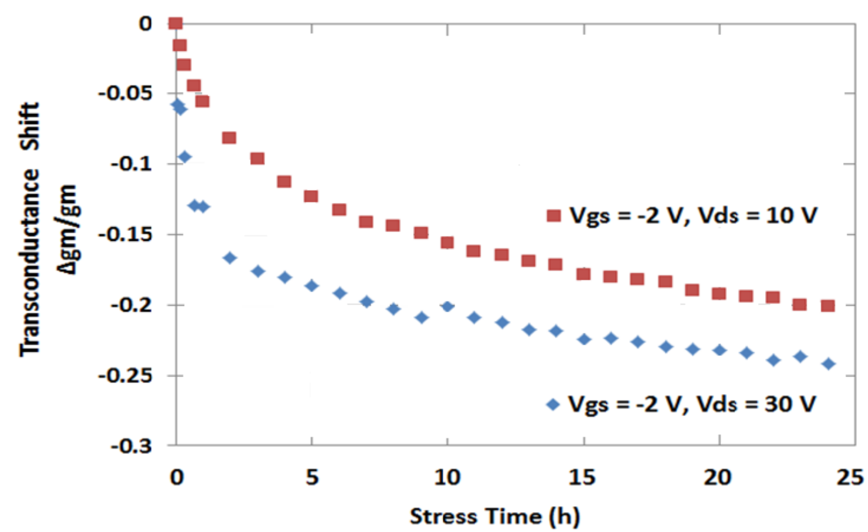
Formation Energy



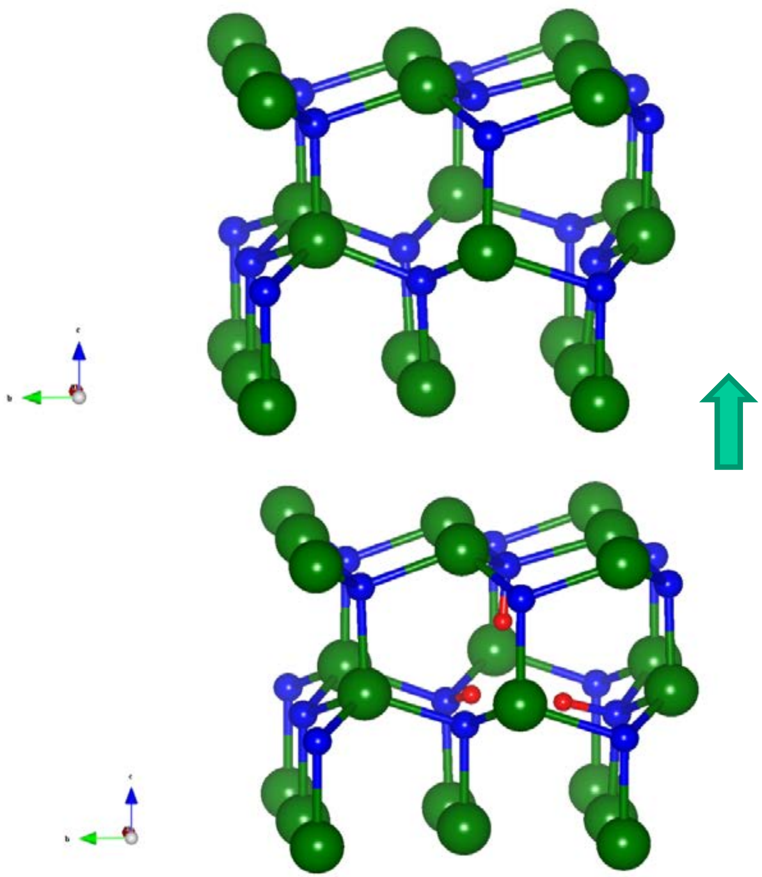
1/*f* Noise Measurements

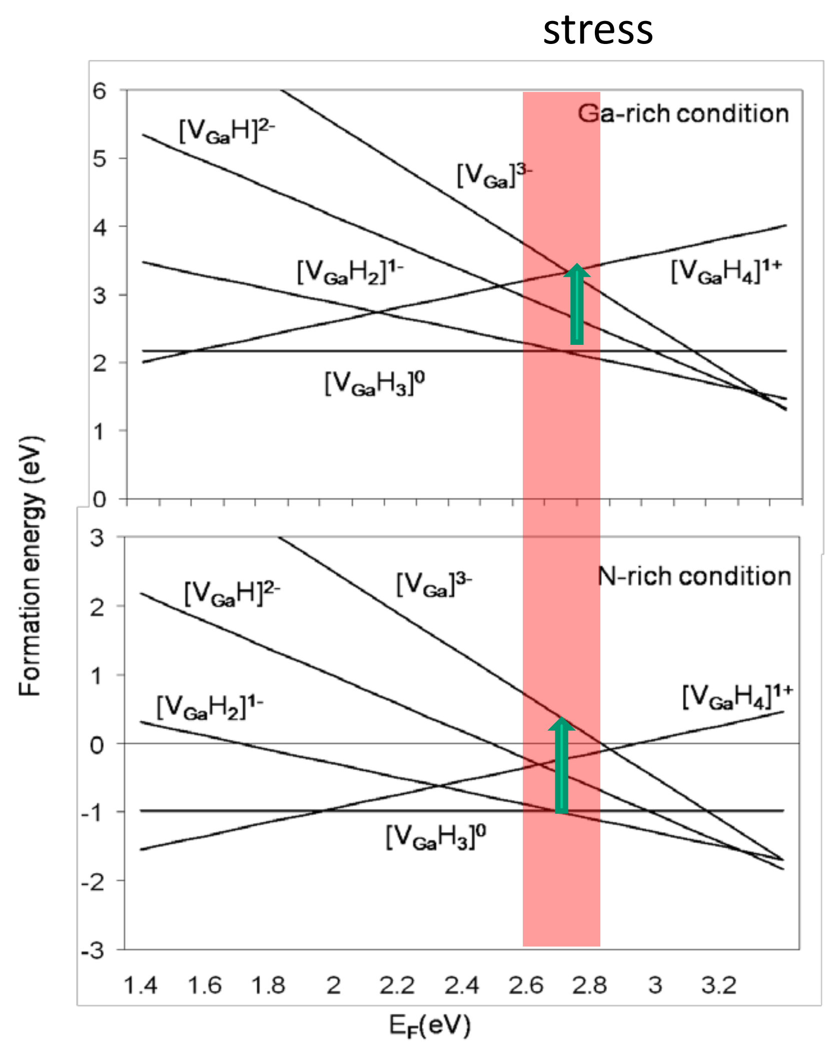


Electrical Stress



Dehydrogenation of Ga vacancy





Ga-rich, N-rich Devices: Increase in negative charge ⇒ Positive V_T shift

Growth Conditions and Degradation

- **First Set of Devices:**

  Ga-rich and N-rich: PA-MBE

  ⇒ Dehydrogenation of Ga-vacancy

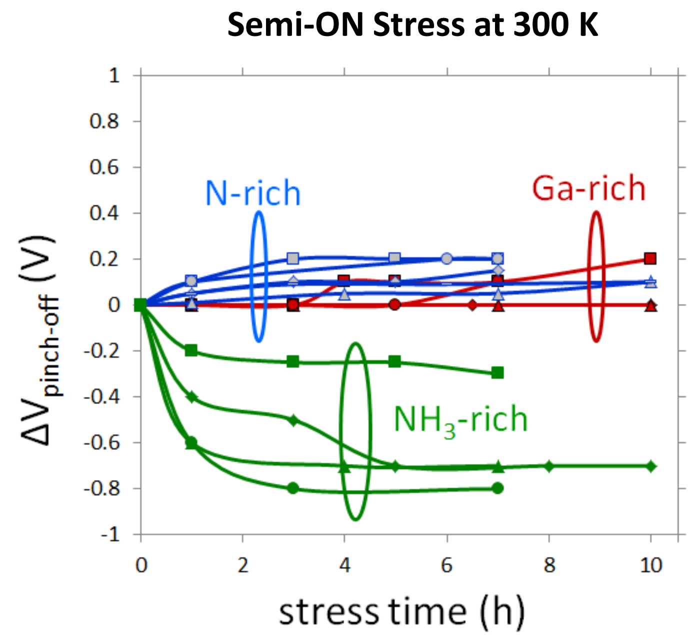
  NH_3-rich: MO-CVD

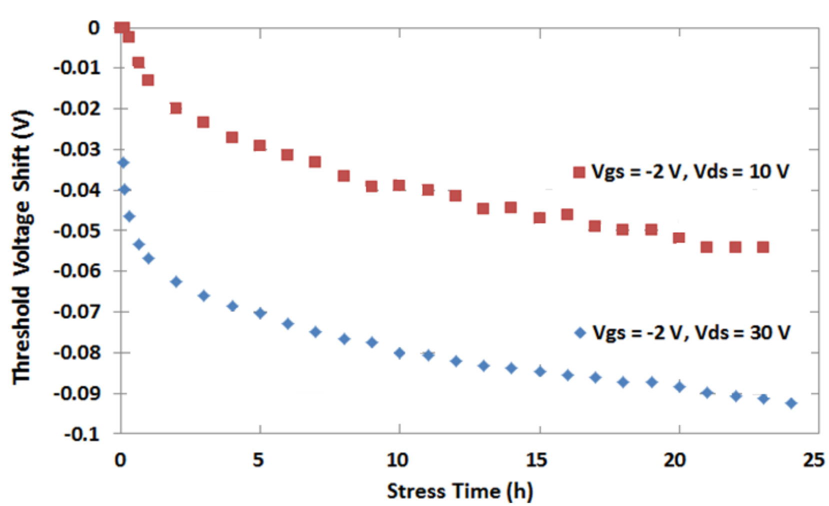
  ⇒ Dehydrogenation of N anti-site

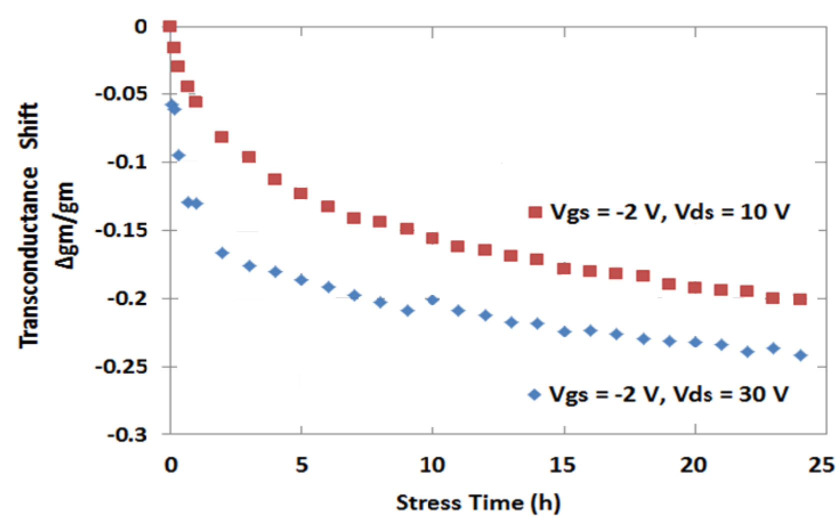
- **Second Set of Devices:**

  Ga-rich: PA-MBE

  ⇒ Dehydrogenation of substitutional oxygen







Defect Cross-Section

- Hydrogenated precursors uniformly distributed
- Defect generation process irreversible under stress
- σ constant for $E > E_{act}$

Number of activated defects

measured

$$v(E) = \sqrt{2\,E/m^*}$$

$$\frac{\partial}{\partial t}N_d(t) = \sum_{E>E_{act}} \left[N_d^{\,0} - N_d(t)\right] v(E)\, n(E)\, \sigma$$

FIT

$$\Delta V_{th}(t) = -\frac{\Delta Q_d\, d_{AlGaN}}{\varepsilon}$$

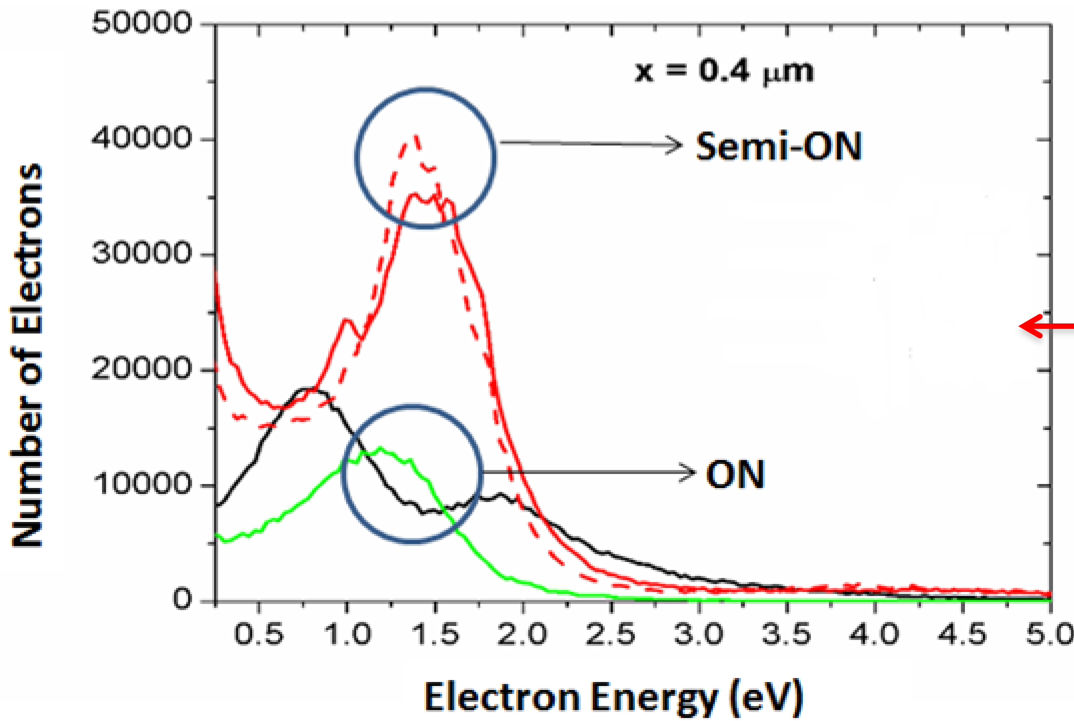
from Monte-Carlo simulations

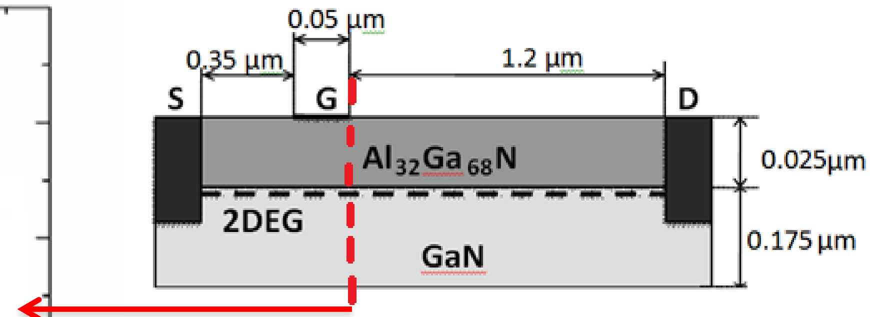
from DFT calculations

from stress experiments

Carrier Energy Distribution

- V_{DS} = +10.0 V
- T = 300 K





Modes	ON	Semi-ON	OFF
Density	High	Moderate	Low
Energy	Low	High	High

- Increase in high energy carriers ⇒ More degradation

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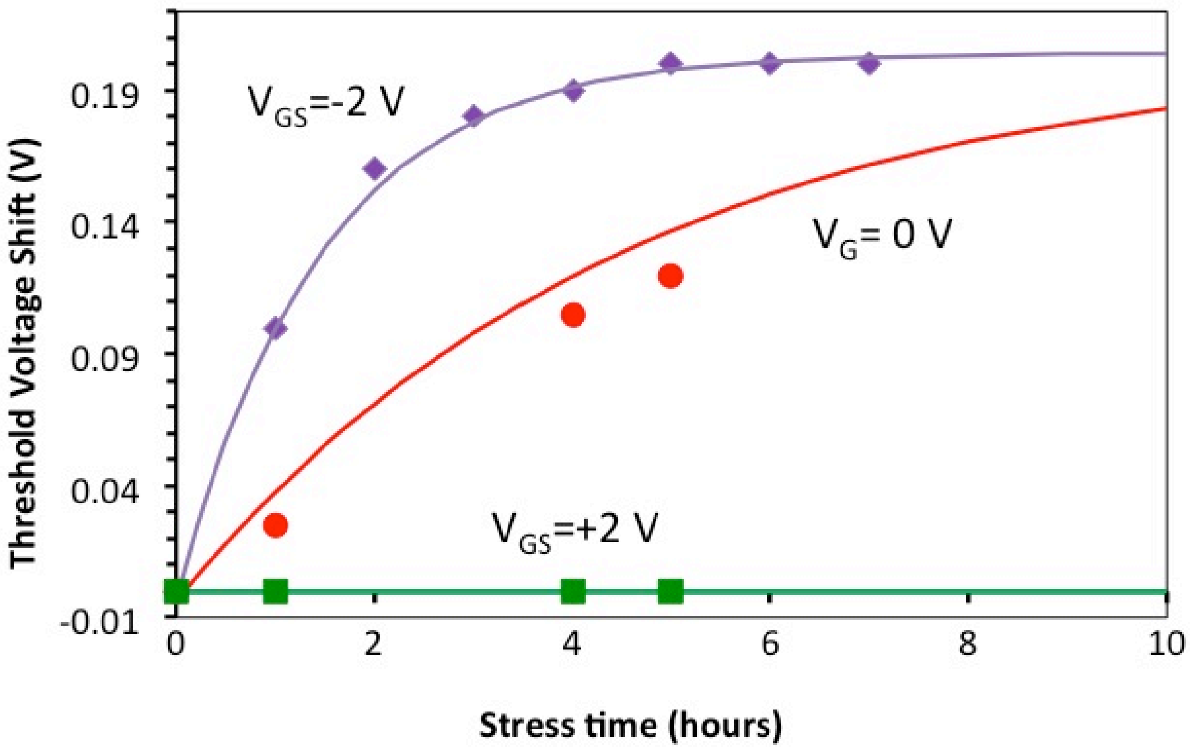
V_T Degradation Prediction



- **Devices grown under Ga-rich conditions, stressed with different gate-source voltages**
- **Lines show simulation results; dots show data**
- **Model based on V_{GS} = -2 V (semi-ON) data; V_{GS} = 0 V and +2 V curves are predicted**

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Single-Event Effects (Soft Errors)

- **Ionizing particles (heavy ions, protons, alpha particles, muons, secondary products from neutrons) deposit energy, create "extra charge"**
  - Transient currents result from collection at junctions
  - Known problem for charge-based devices: can change memory states when in storage state
- **Considerations for emerging memories may differ**
  - Storage element may be intrinsically resistant to SEE
  - Transients in surrounding circuitry (still CMOS!) may induce false write conditions
  - Window of vulnerability may be different: may only be vulnerable when programming bias conditions present

Co-sponsorship: HiRev and DTRA Basic Research

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Advanced CMOS

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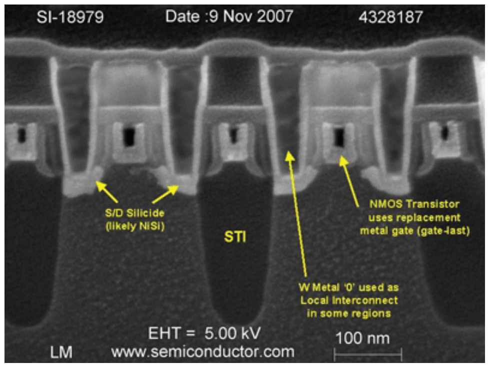
Substrate

Device Topology

Bulk/epi

Planar

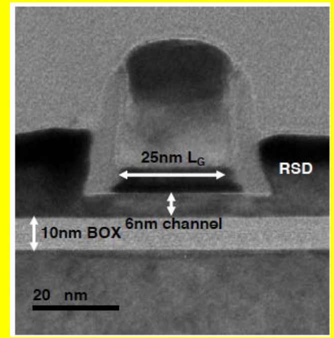


45/32/28/20 nm

IBM (PD)
ST (FD)

Intel
TSMC

SOI



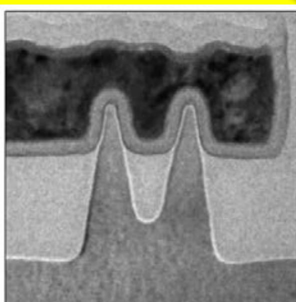
Qing Liu et al., VLSI Symposium 2011

45/32 nm (PD)
28/14 nm (FD)

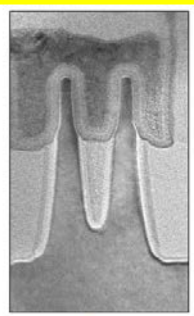
IBM

FinFET

22/16/14 nm

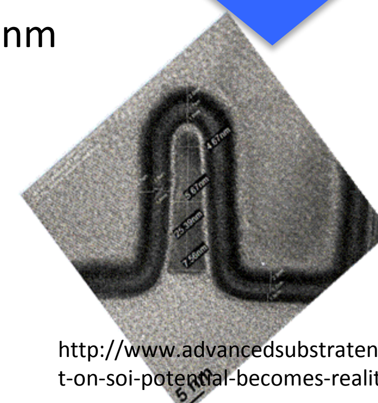


22 nm 1st Generation Tri-gate Transistor



14 nm 2nd Generation Tri-gate Transistor

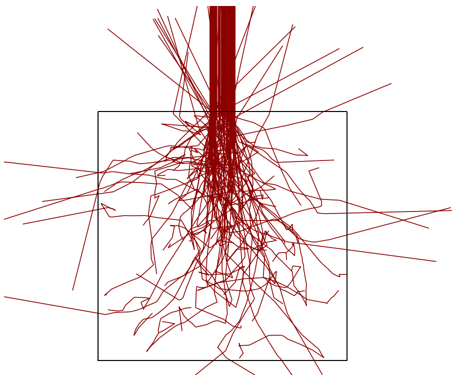
14 nm



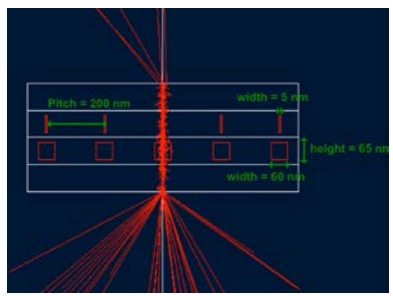
http://www.advancedsubstratenews.com/2013/11/finfet-on-soi-potential-becomes-reality/

Single-Event Modeling

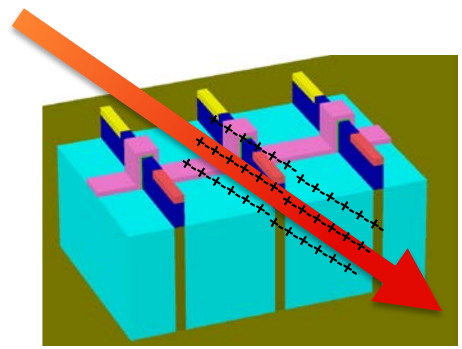
- What happens in a small fin (esp. SOI)?
- How does a single event impact a multi-fin FET?
- What happens between the fins?
- How do we model that in TCAD and circuit designs



Simulation of 250 eV electrons incident on a 5 nm Si cube

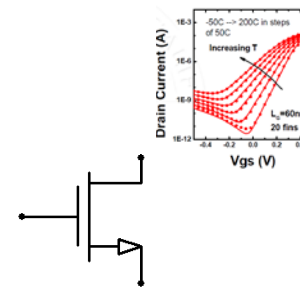


Simulation of 47 MeV Au ion on multi Fin geometry



TCAD Device Structure

(CFDRC)



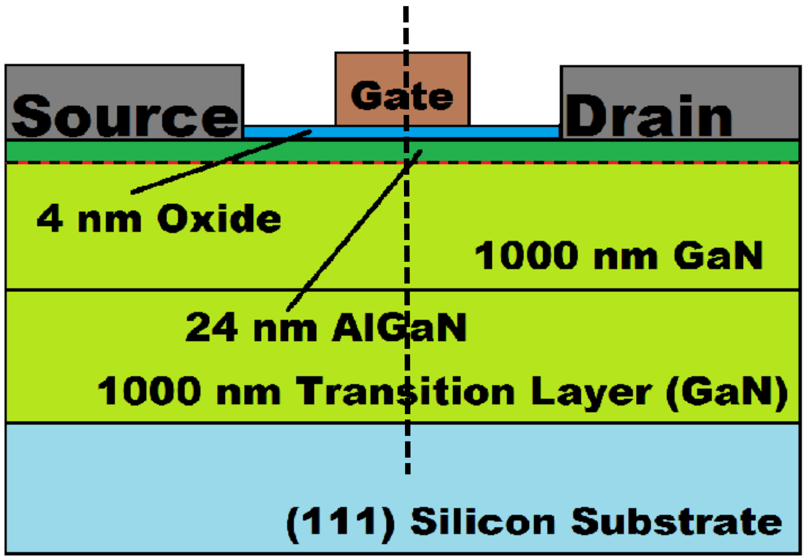
Rad response Design Models

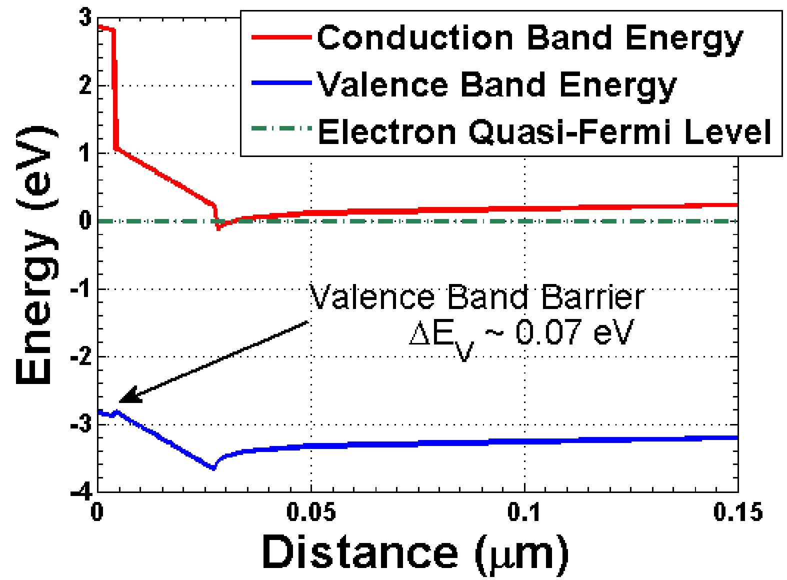
Simulation and Test go hand-in-hand

- Must have data for calibration and validation

- Modeling provides insight, fills in blanks, enables design exploration

AlGaN/GaN MOS-HEMTs

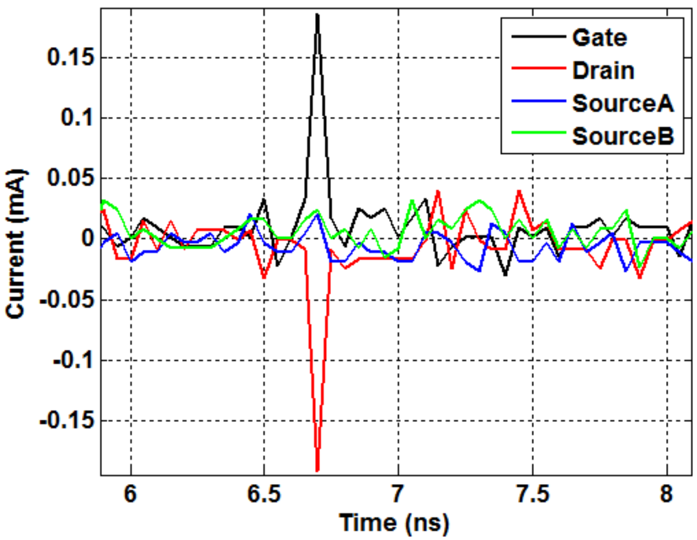


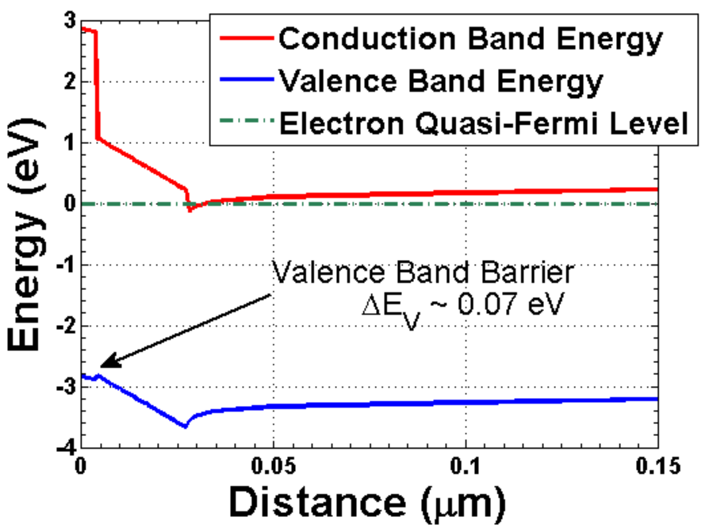


AlGaN/GaN MOS-HEMTs

Gate oxide species and band alignment play a key role in the charge collection mechanisms of MOS-HEMT devices

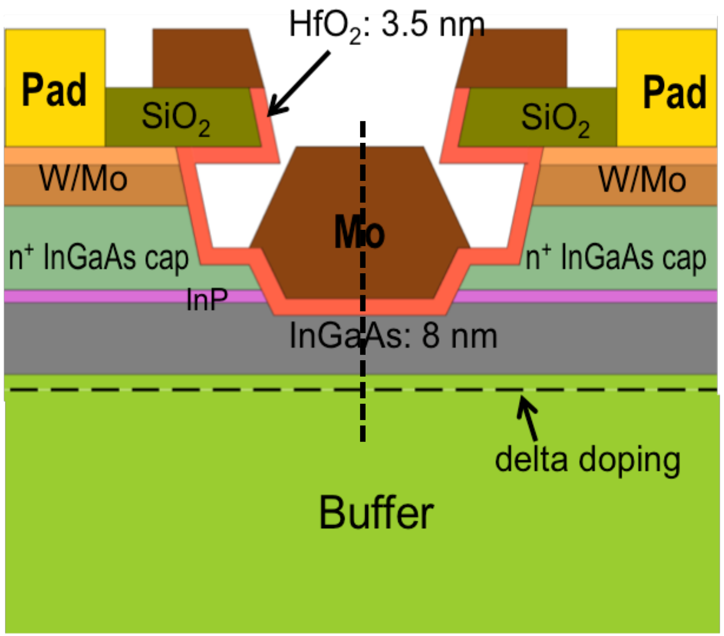
- Gate transient current observed during heavy ion irradiation despite MOS gate structure
- Small valence band barrier introduced by band alignment of HfO_2 gate oxide and AlGaN allows ion-generated holes to be collected by gate terminal
- Conventional band alignment between oxide and silicon prevents transient gate current

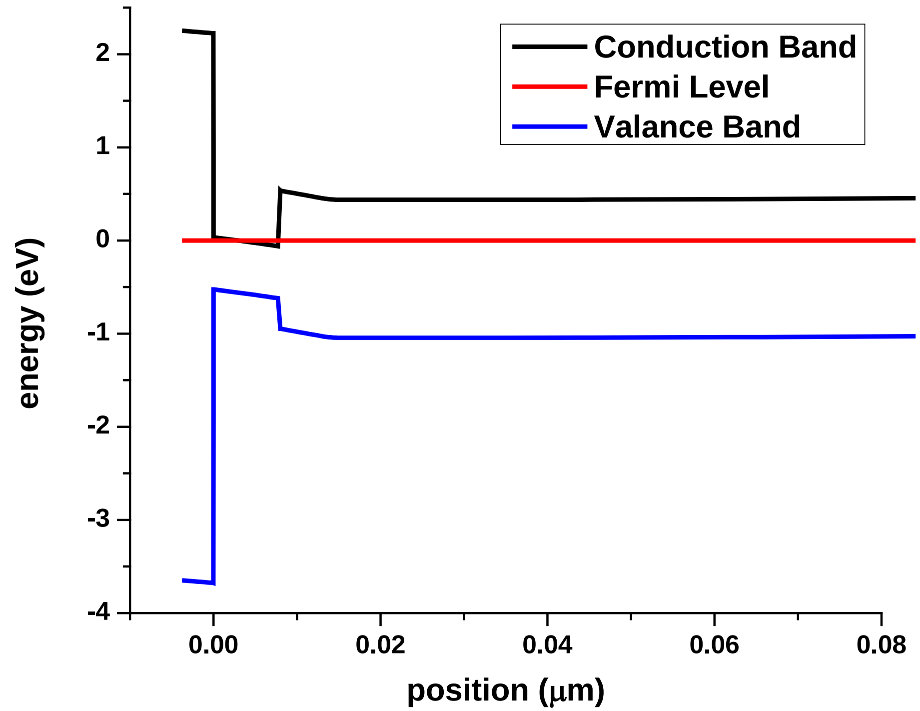




InGaAs MOSFET

- **Quantum well channel**

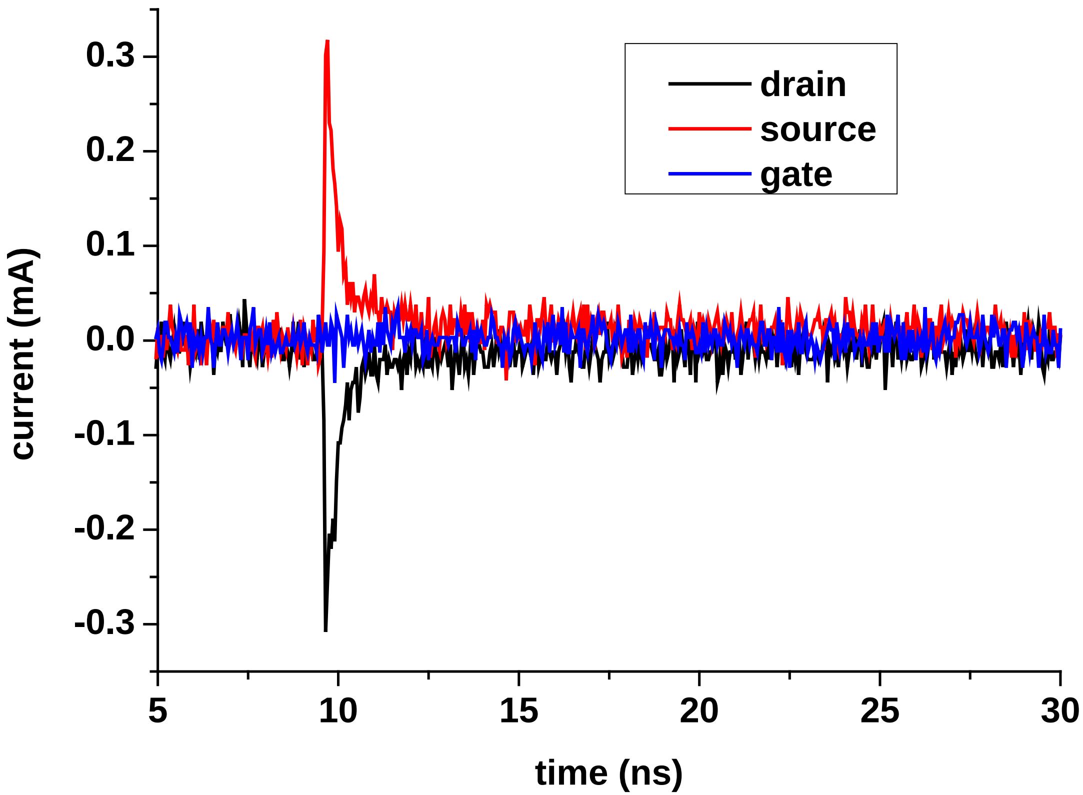


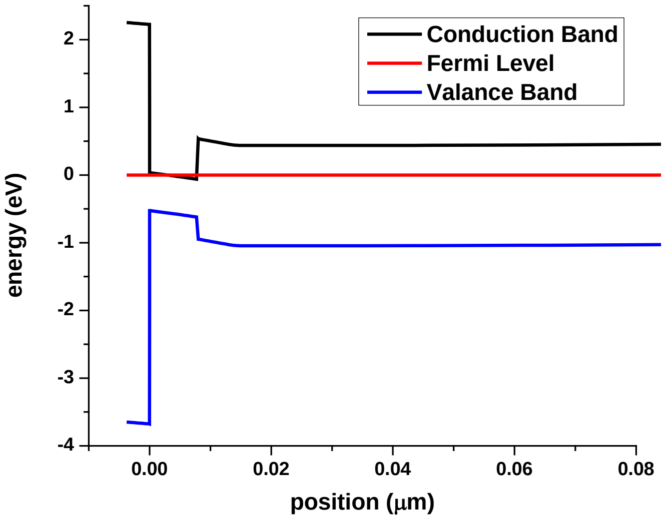


- **Both electrons and holes are collected in the channel**

InGaAs MOSFET

- No gate transients due to large barrier



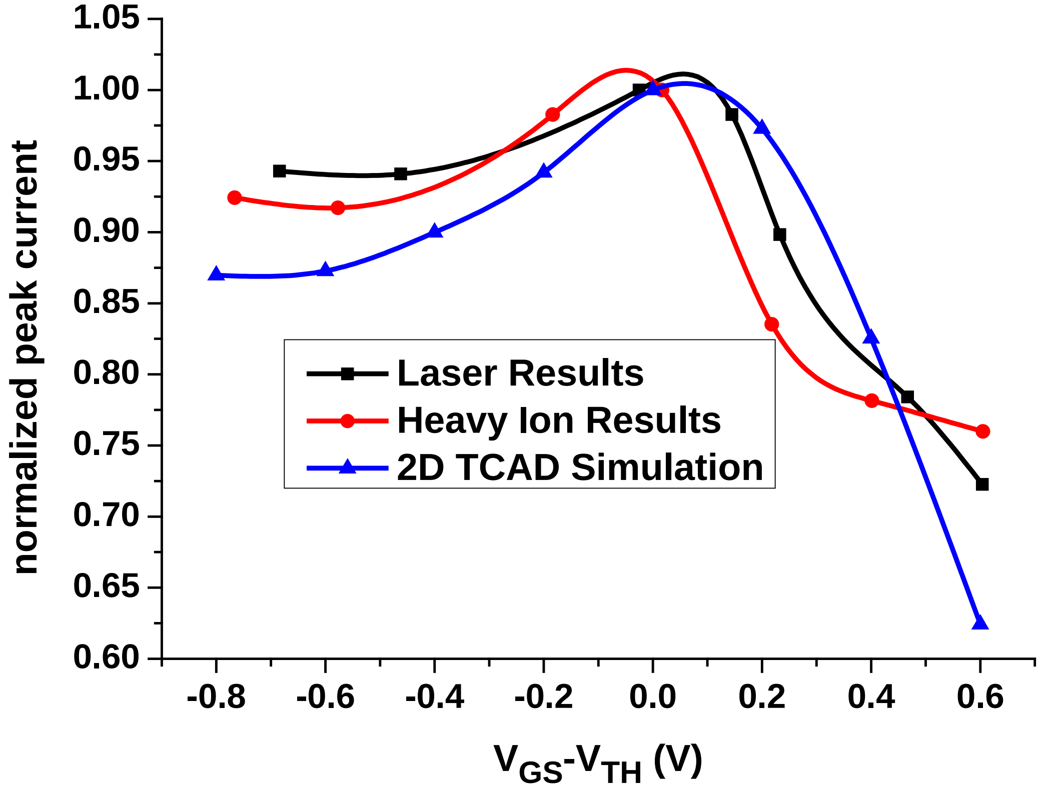


- Fast collection: ~100 ps, direct collection
- Slow collection: ~3 ns, source to drain pathway

- **Source and drain transient have the same magnitude (transients come from the channel current)**

Bias Dependence

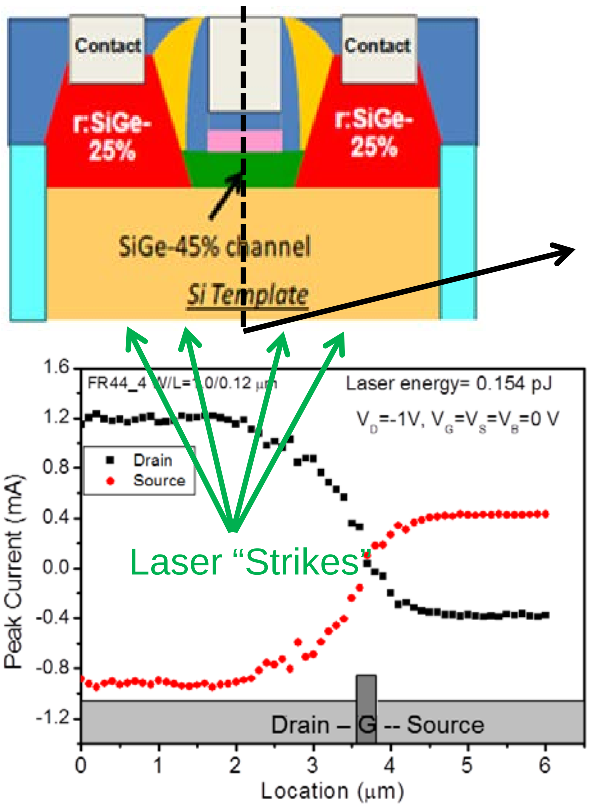
- **Peak drain current is maximum near the threshold voltage**

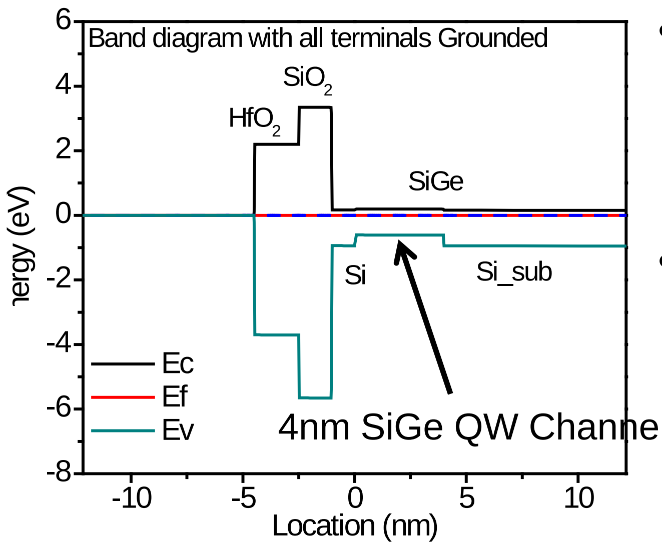


- **It decreases quickly in inversion and slowly in accumulation and depletion**

SiGe QW pFETs

- **Ultra-thin conduction channel in quantum-well structures requires consideration of potential effects of SETs of both polarities in device characterization**





- Laser irradiation allows charge collection to be mapped spatially
- Transient polarity reverses as laser “crosses” channel

- Simulations show polarity flipping effect not present in thicker-channel devices

Conclusions

- **Assuring reliability of emerging technologies is challenging**
  - Lack of life-test data
  - Uncertainty about physical mechanisms
- **Physics-based reliability approach**
  - Lower cost, more efficient than conventional approaches
- **Accomplishments**
  - Electrical reliability of GaN HEMTs
  - Single-event transients in alternate-channel MOSFETs

"'Because I said so' or 'Just wait until you have kids of your own' section?"