Massachusetts Institute of Technology

Sandia National Laboratories

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Trapping Characteristics and Parametric Shifts in Lateral GaN HEMTs with SiO_2/AlGaN Gate Stacks

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Purpose

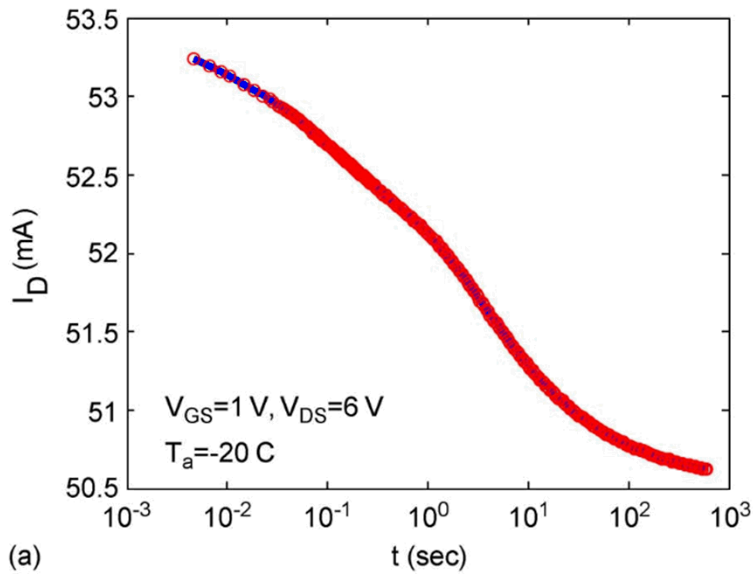
- **AlGaN/GaN HEMTs are desirable for RF/power device applications**
- **Temperature and stress dependent parametric shifts remain a critical reliability issue for HEMT power devices**
- **Explore the properties of slow-detrapping processes in HEMTs and MOS-HEMTs using modified current-transient analysis method**

Outline

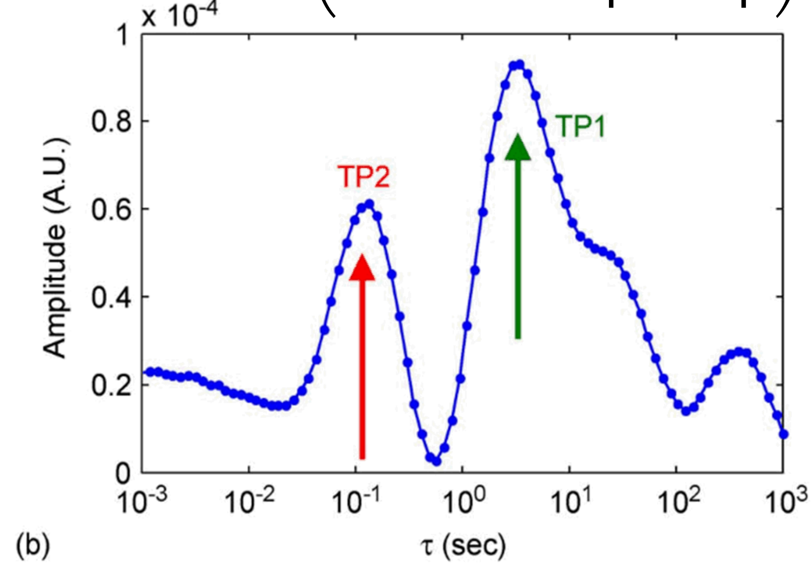
- Introduction
- Device Schematics
- Analytical Techniques
- Validation of Analytical Techniques
- Off-State Stress Schottky-Gated HEMTs
  - Off-State Stress-Time Dependent Parametric Shifts
  - Temperature Dependent Off-State Parametric Shifts
- Off-State Stress MOS-HEMTs
  - Off-State Stress-Time Dependent Parametric Shifts
  - Temperature Dependent Off-State Parametric Shifts
- Discussion
  - Mechanisms of off-state stress parametric shifts
  - Device recovery response
- Conclusions

Introduction

$$\Delta I_d = \sum \alpha_i \left(1 - e^{-t/\tau_i}\right)$$



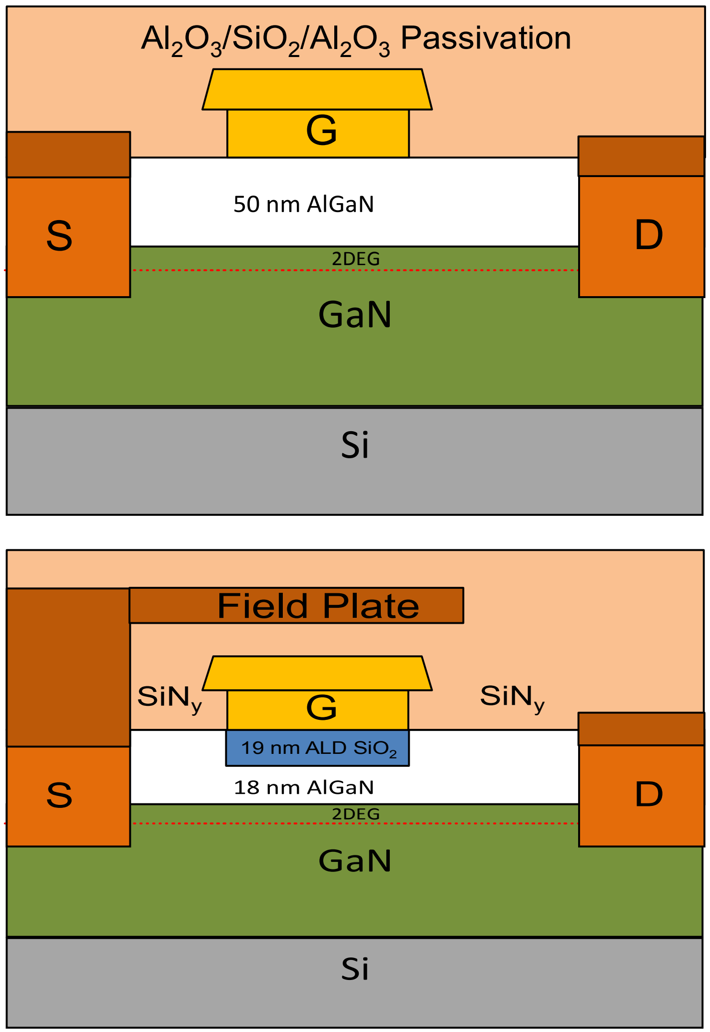
$$y_{fit} = \min\left(|y - A\alpha|^2 + \left|\frac{d}{dt} A\alpha\right|^2 \right)$$



- **Stress-induced parametric shifts remain critical reliability concern for HEMTs**
- **Original current-transient method provided framework for evaluation of slow-detrapping transients**
- **Large changes in I_d and V_{th} observed following both *on*- and *off*-state stress**
- **Reconstruction of emission spectrum provides insight into location and trap energy for detrapping processes**

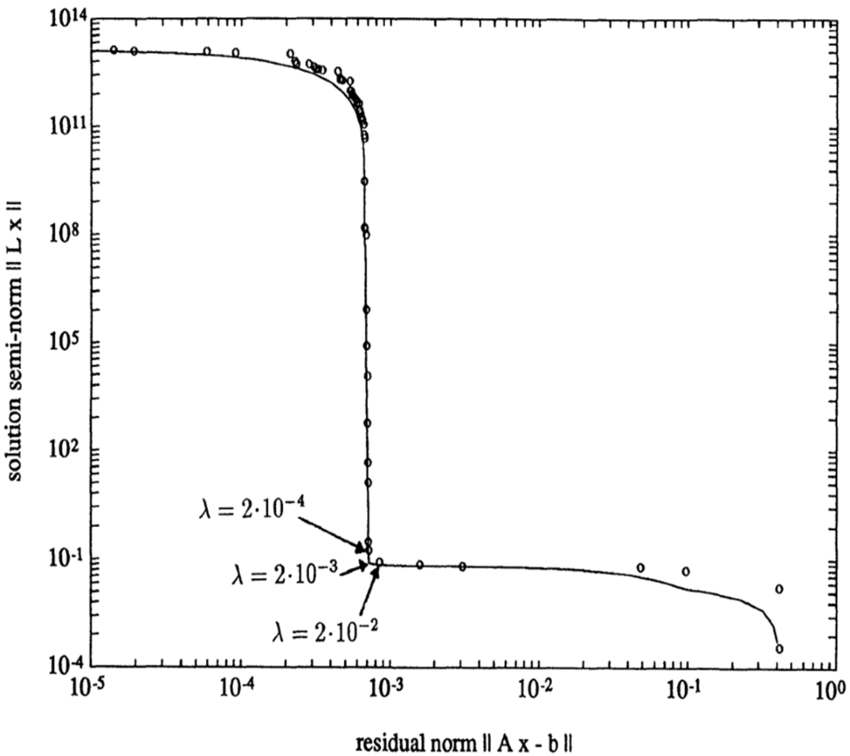
J. Joh and J. A. del Alamo, *IEEE Trans. Electron Devices*, vol. 58, no. 1, pp. 132–140, Jan. 2011.
S. DasGupta, *et al. IEEE Trans. on Electron Devices,* vol. 59, no. 8, pp. 2115–2122, Aug. 2012.

Device Schematics



- **Two devices types investigated**
  - **"Schottky"-gated HEMT**
  - **MOS-HEMT**
- **Study the off-state stress / on-state recovery response**

Regularization Analytical Techniques

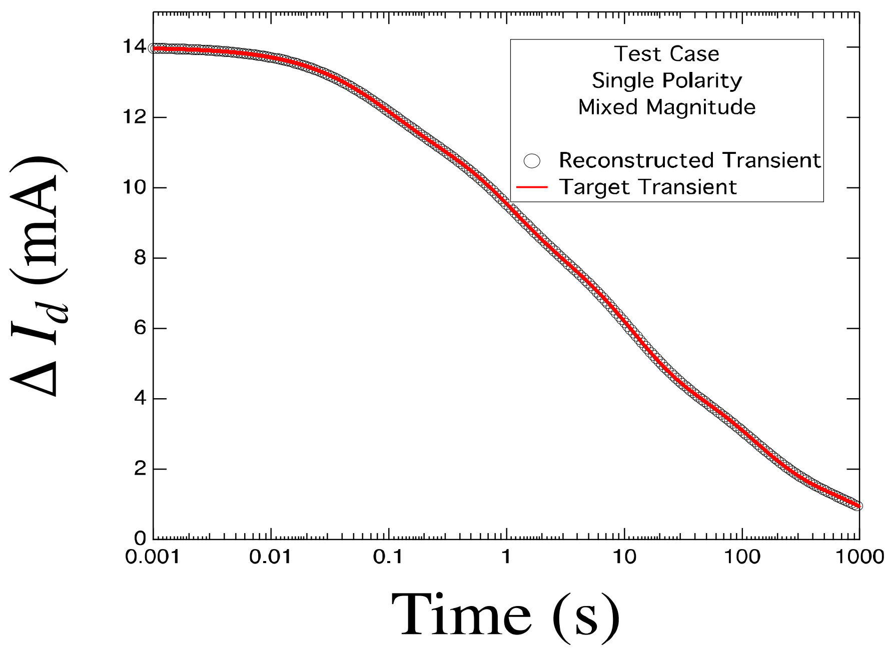


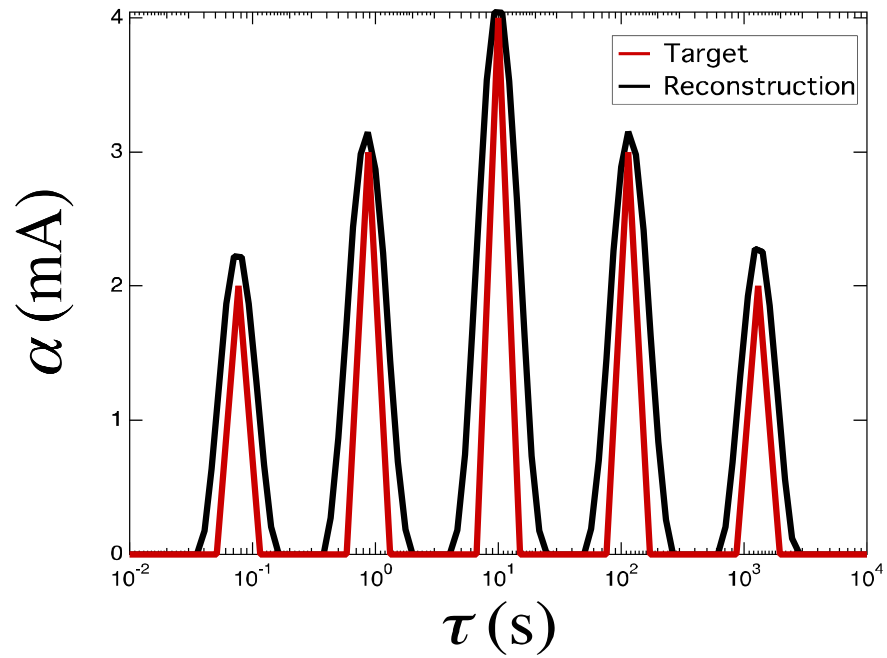
$$y_{fit} = \min\left(|y - A\alpha|^2 + \lambda \left| \frac{d^2}{dt^2} A\alpha \right|^2 \right)$$

- **Tikhonov regularization techniques**
- **Regularizor enforces parsimony, prior knowledge, curvature on solution**
- **Optimal choice of λ located on "L"-corner of LSQ term and regularizor**
- **Used in fields of nuclear physics, chemistry, NMR, L-DLTS, biology, and astronomy**

P. Hansen, "Analysis of Discrete Ill-Posed Problems by Means of the L-Curve," *SIAM Rev.*, vol. 34, no. 4, pp. 561–580, Dec. 1992.

Validation of Analytical Techniques

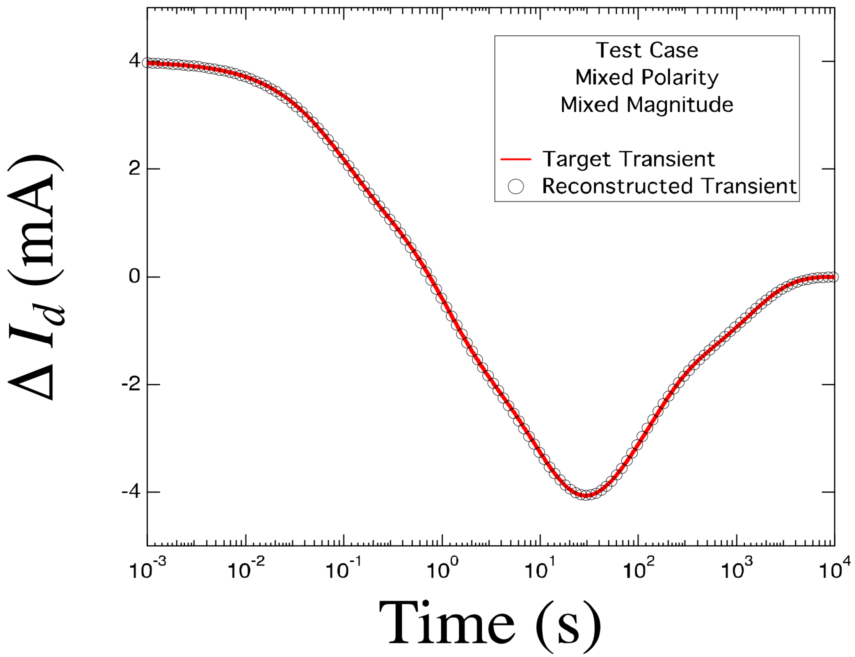


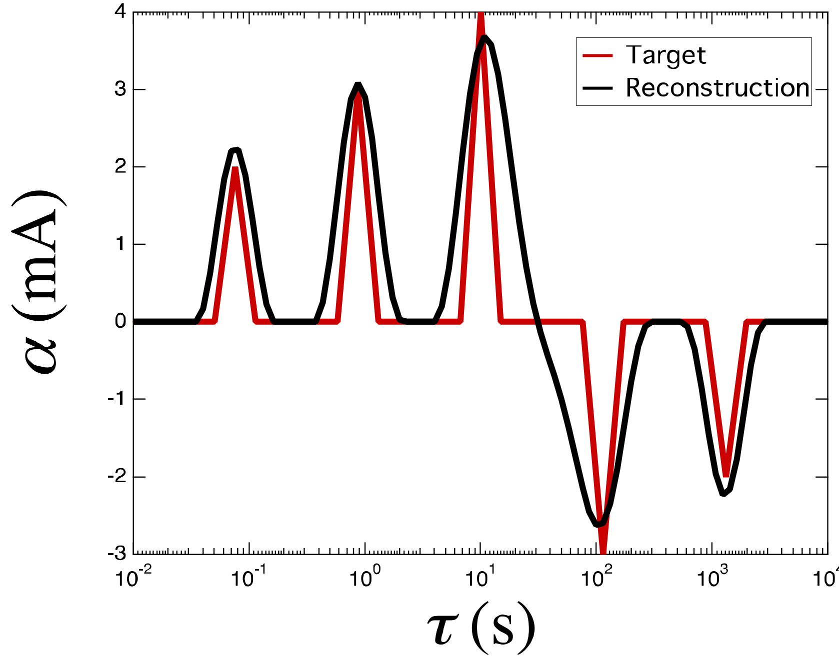


- **Artificial time-domain signal representing multiple electron trapping processes**
- **Modified current-transient method reconstructs the device response**

- **Time-constant spectrum shows method reconstructs multiple exponential processes with accurate temporal resolution and magnitude**

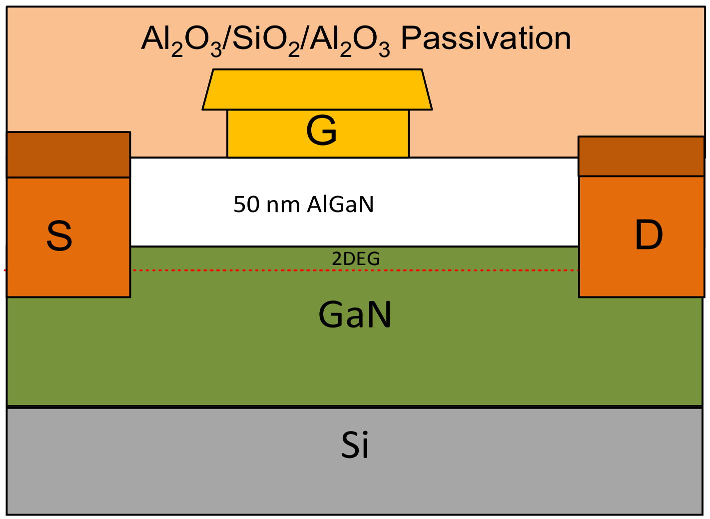
Validation of Analytical Techniques





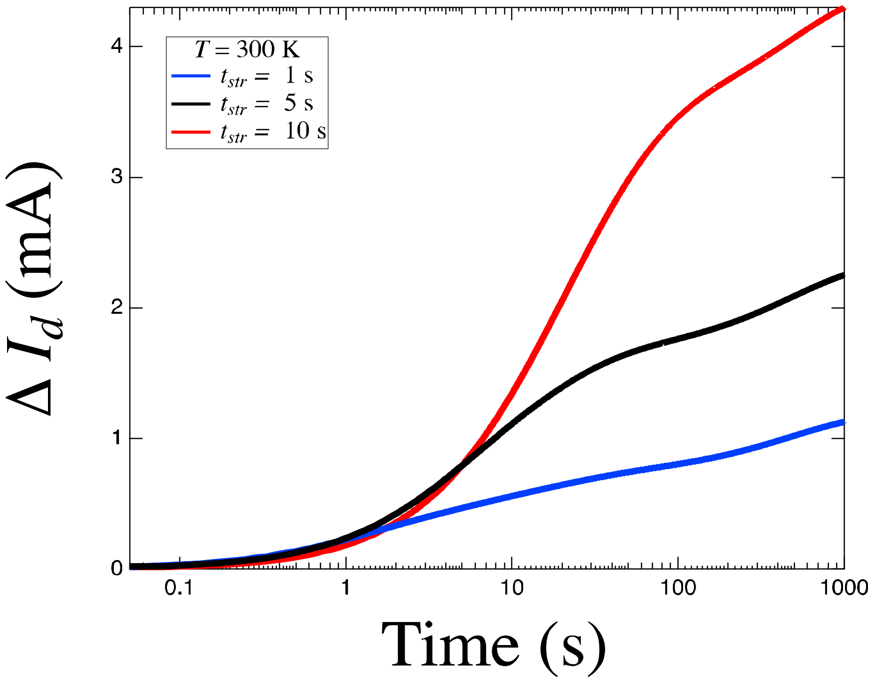
- **Artificial transient representative of simultaneous trapping and emission of electrons**
- **Corresponding time-constant spectrum shows both trapping and emission processes are recoverable with accuracy**

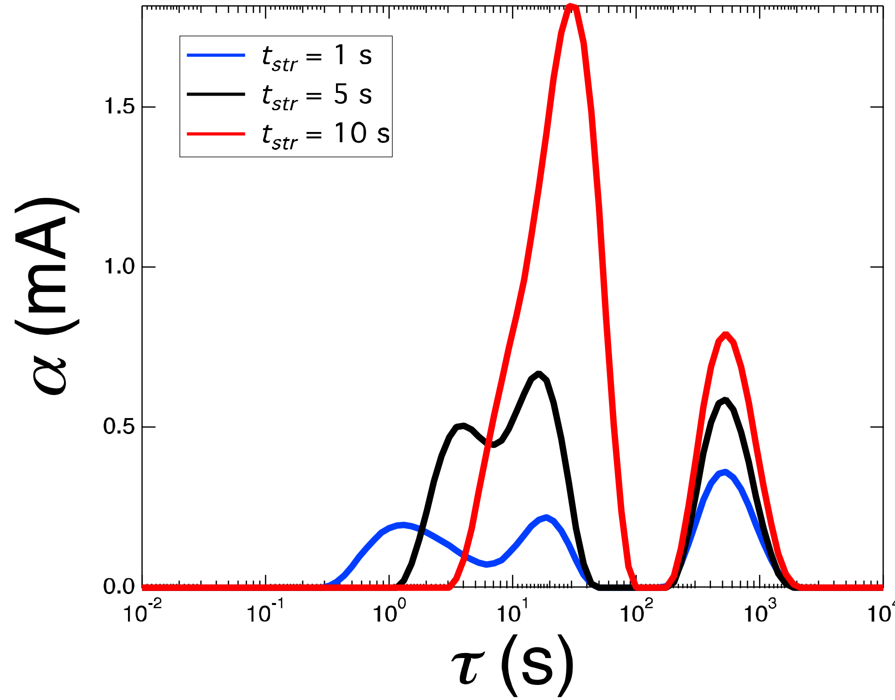
Off-State Stress
Schottky-Gated HEMTs



- **Stress-time and temperature dependent off-state parametric shifts in I_d**
- **Off-state stress conditions**
  V_{gs} = -5 V
  V_{ds} = 100 V
- **Recovery-state**
  V_{gs} = 1 V
  V_{ds} = 0.1 V

Off-State Stress-Time Dependent Parametric Shifts

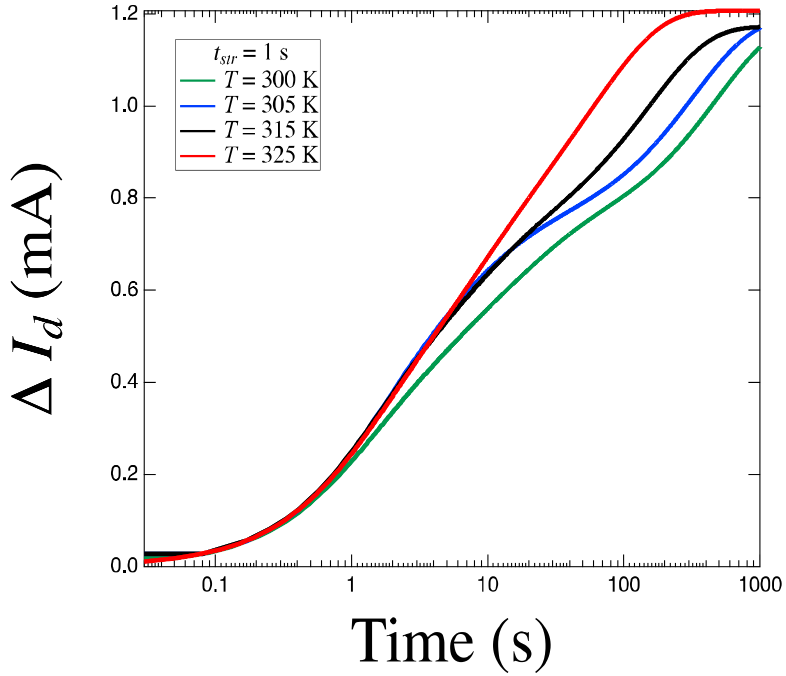


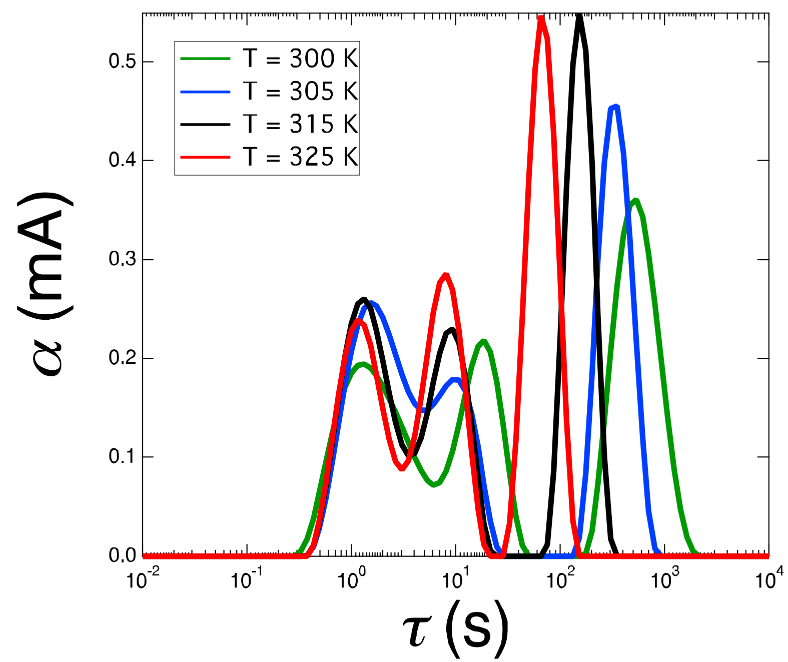


- **Large ΔI_d (> 1 mA @ T = 300 K) observed following off-state stress**
- **ΔI_d increases for longer stress time**

- **Spectrum reveals two processes**
- **Broad stress-time dependent process**
- **Slower stress-time independent process**

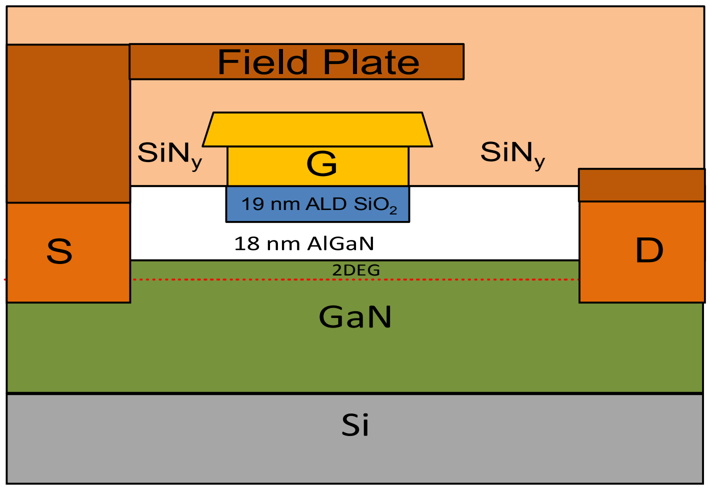
Temperature Dependent Off-State Parametric Shifts





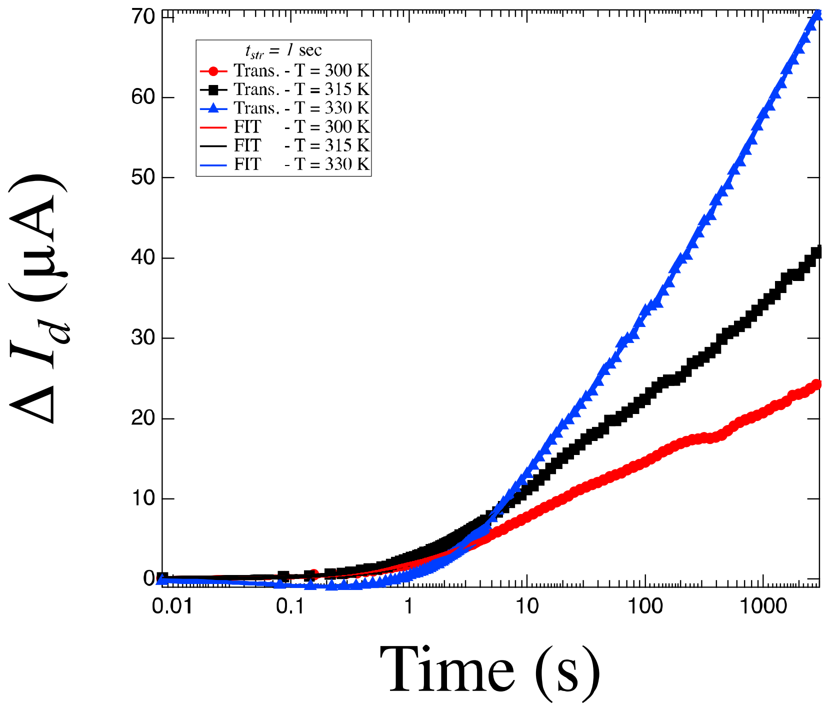
- **Large ΔI_d (> 1 mA @ T = 300 K) observed following off-state stress**
- **ΔI_d increases for increasing temperature**
- **Recovery of I_d increases at longer times for higher temperature**
- **Spectrum reveals two processes**
- **Broad stress-time dependent process shows no temperature dependence between 300 K and 325 K**
- **Slower process exhibits temp. dependence with E_a = 0.57 eV**

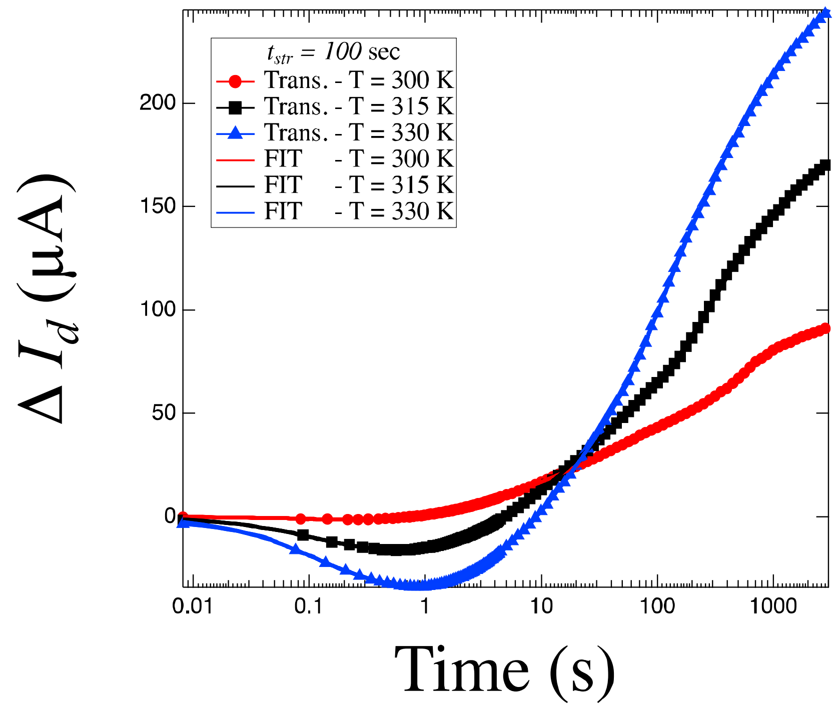
Off-State Stress
MOS-HEMT Devices



- **Stress-time and temperature dependent off-state parametric shifts in I_d**
- **Off-state stress conditions**
  V_{gs} = -5 V
  V_{ds} = 100 V
- **Recovery-state**
  V_{gs} = 1 V
  V_{ds} = 0.1 V

Off-State Stress-Time Dependent Parametric Shifts

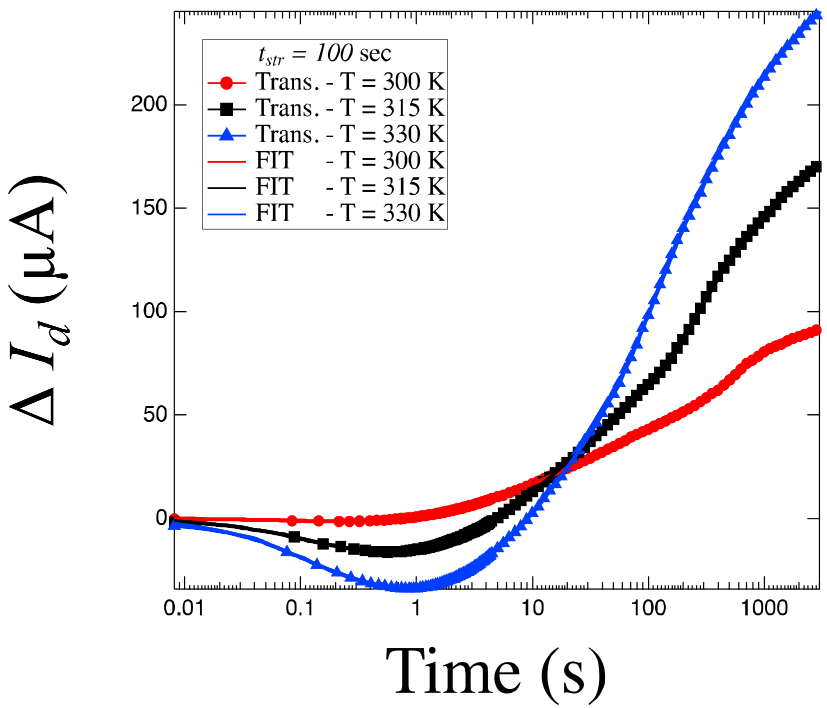


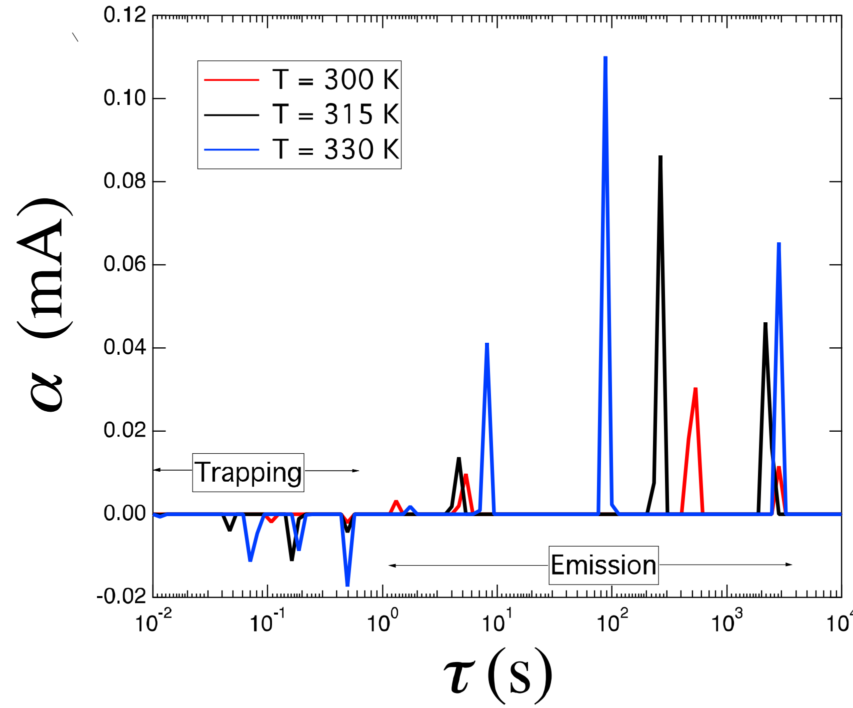


- **ΔI_d following off-state stress observed to be much smaller in MOS-HEMT devices**
- **Increasing temp. leads to larger ΔI_d**
- **Recovery transient at T = 330 K shows initial decrease followed by positive recovery**

- **For longer t_{str} we observe larger ΔI_d**
- **Short recovery times (< 10 s) exhibit decreasing I_d for increasing temperature**

Temperature Dependent Off-State Parametric Shifts

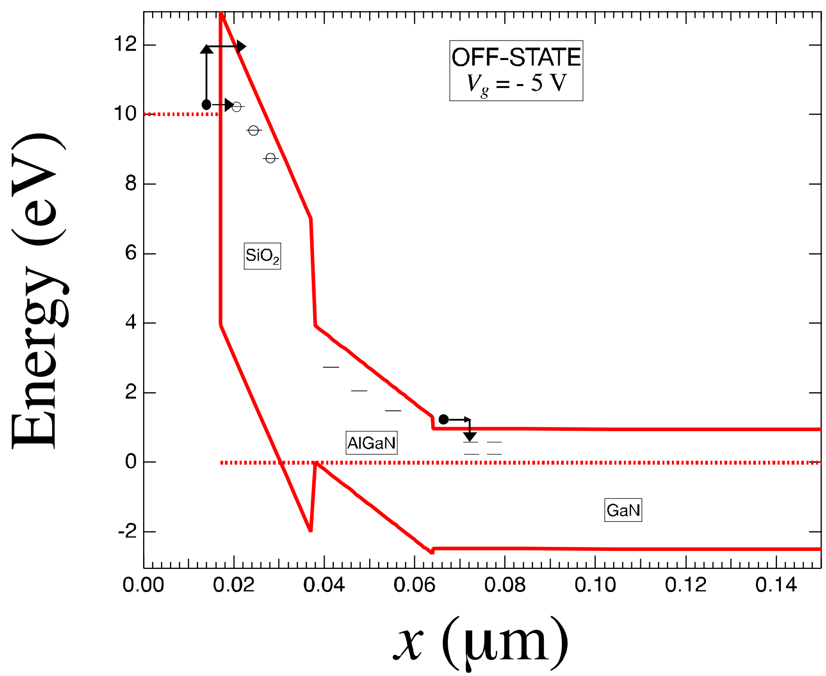




- Electron trapping leads to decreasing I_d
- Detrapping leads to increasing I_d
- Results suggest electron trapping at short recovery times (< 10 s) and emission for longer times

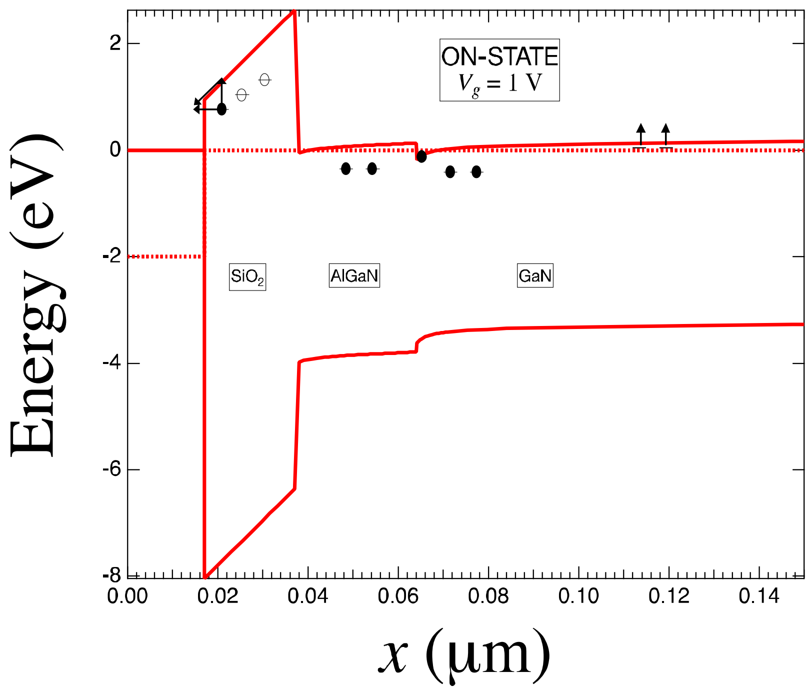
- Time constant spectrum reveals the presence of concurrent trapping and emission processes
- Temperature dependent peak present with E_a = 0.58 eV

Discussion – Off-State Stress



- **Channel is depleted of carriers**
- **Electrons are injected into the SiO_2 from the gate**
- **Electron trapping in GaN buffer would result comparable parametric shifts**
- **Results in a positive ΔV_{th} and reduction in I_d**

Discussion – Recovery Response



- **Previously empty states at AlGaN/GaN interface and in AlGaN barrier are quickly filled**
- **Leads to initial current-collapse-like response**
- **Emission processes slowly begin to recover V_{th} and I_d**

Conclusions

- Regularization techniques show improved resolution and robust reconstruction of complex recovery transient behavior of AlGaN/GaN HEMTs
- Time constant spectra show a temperature dependent peak consistent with 0.57 eV defect frequently observed in GaN
- Stress-time dependent peak is broad, shows little temperature sensitivity between 300 K and 330 K, and becomes progressively slower with increasing stress time
- MOS-HEMT devices show decreased ΔI_d compared to “Schottky”-gated devices and evidence of simultaneous trapping and detrapping processes during recovery