SAND2015-2488C

Exceptional service in the national interest

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

M. P. King, D. Piedra, J. R. Dickerson,
S. Dasgupta, M. Sun, M. J. Marinella,
T. Palacios, and R. J. Kaplar

Massachusetts Institute of Technology

Purpose

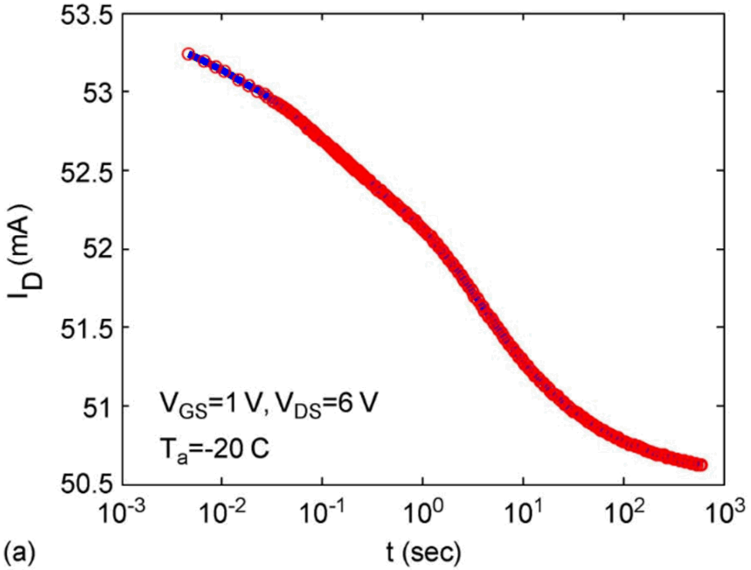
- AlGaN/GaN HEMTs are desirable for RF/power device applications
- Temperature and stress dependent parametric shifts remain a critical reliability issue for HEMT power devices
- Explore the properties of slow-detrapping processes in HEMTs and MOS-HEMTs using modified current-transient analysis method

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

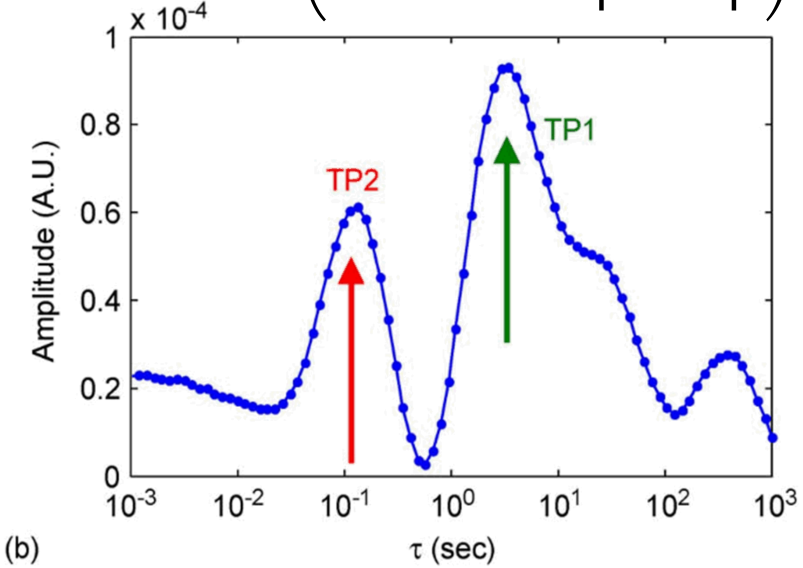
Introduction

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



(a)

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

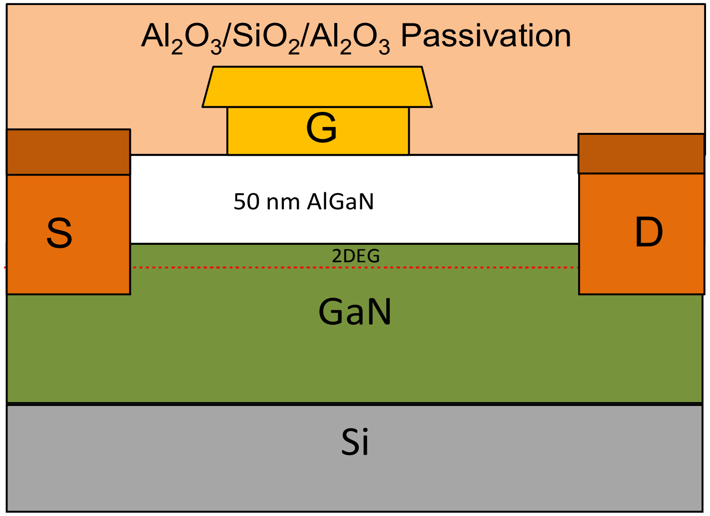


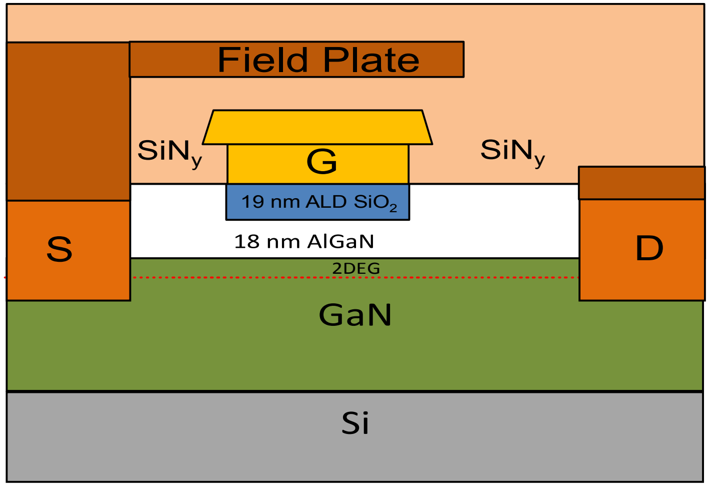
(b)

- 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.

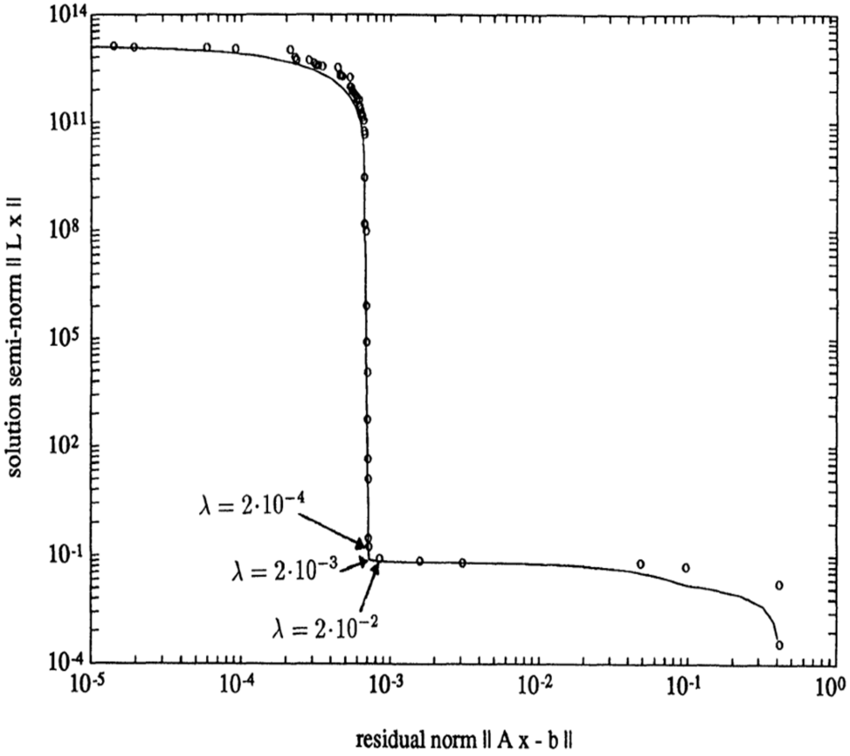
Device Schematics





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

Regularization Analytical Techniques

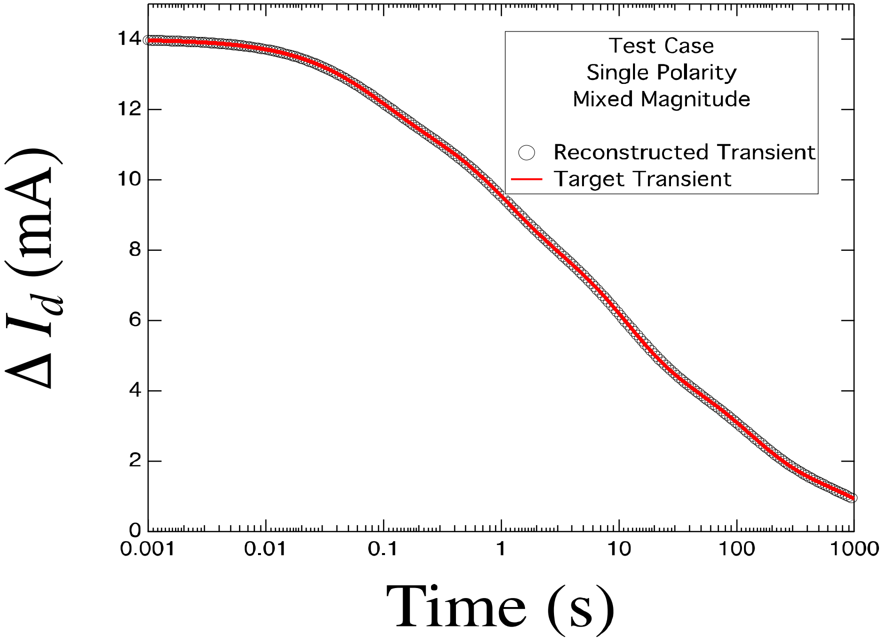


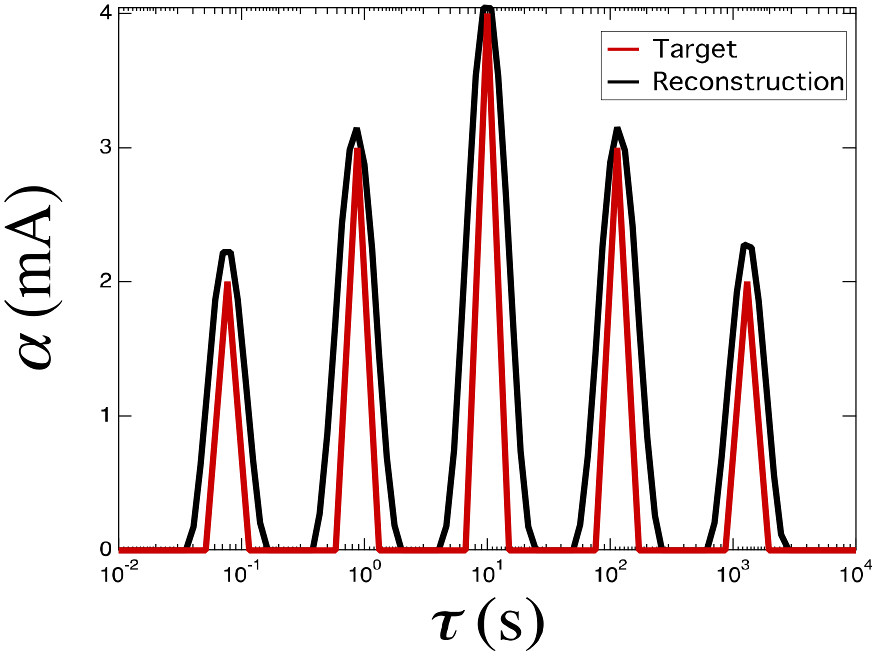
$$y_{fit} = \min\left(|y - A\alpha|^2 + \lambda \left| \frac{d^2}{dt^2} A\alpha \right|^2 \right)$$

- 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

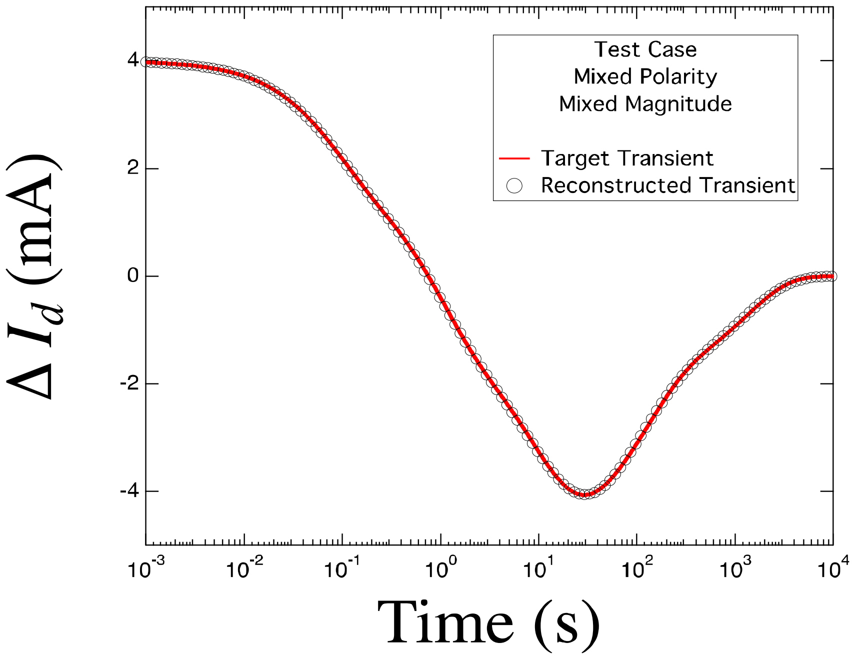


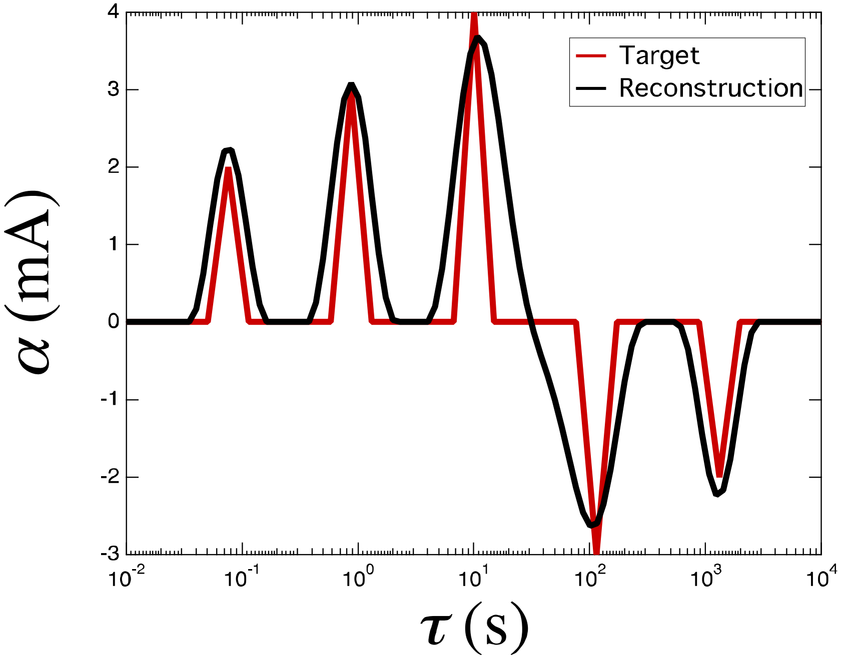


- Artificial time-domain signal representing multiple electron trapping processes
- Modified current-transient method reconstructs the device response

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

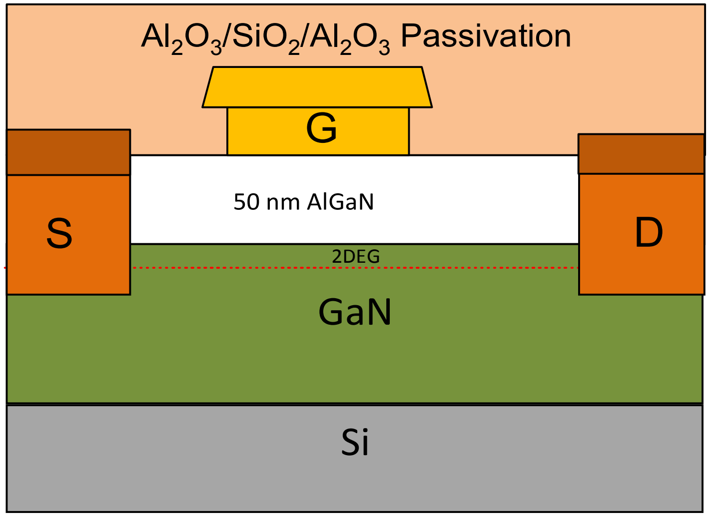
Validation of Analytical Techniques





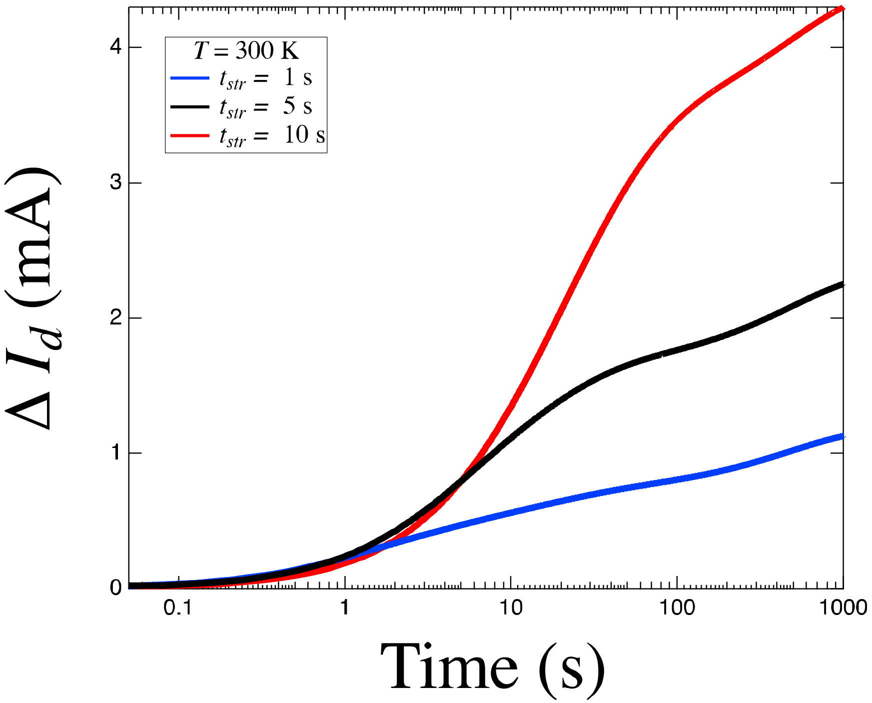
- Artificial transient representative of simultaneous trapping and emission of electrons
- Corresponding time-constant spectrum shows both trapping and emission processes are recoverable with accuracy

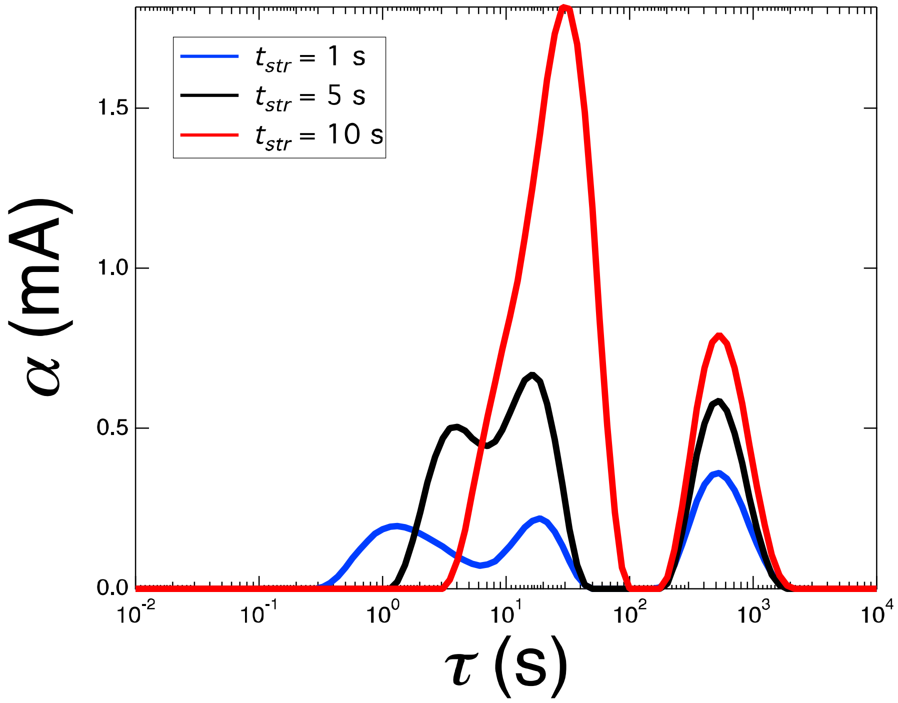
Off-State Stress Schottky-Gated HEMTs



- 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

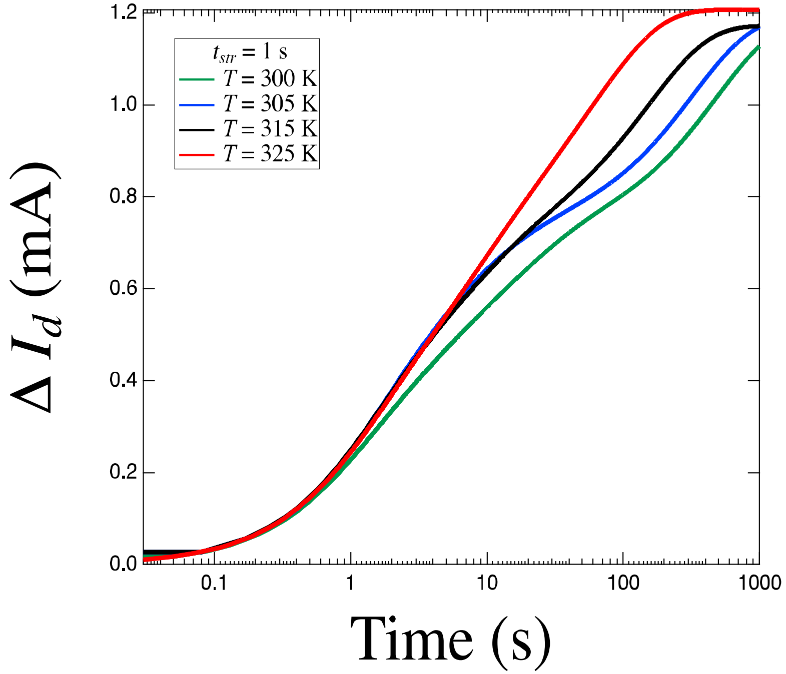


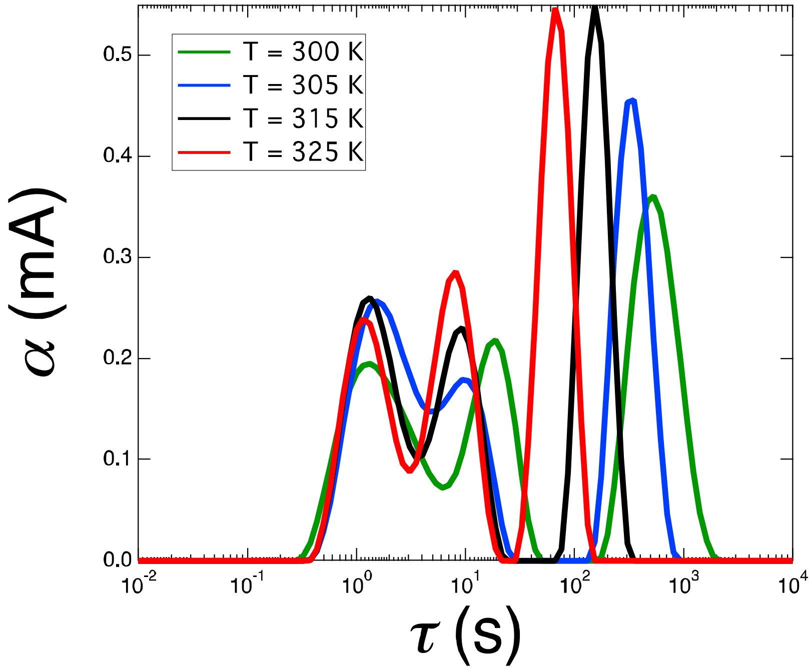


- Large ΔI_d (> 1 mA @ T = 300 K) observed following off-state stress
- ΔI_d increases for longer stress time

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

Temperature Dependent Off-State Parametric Shifts

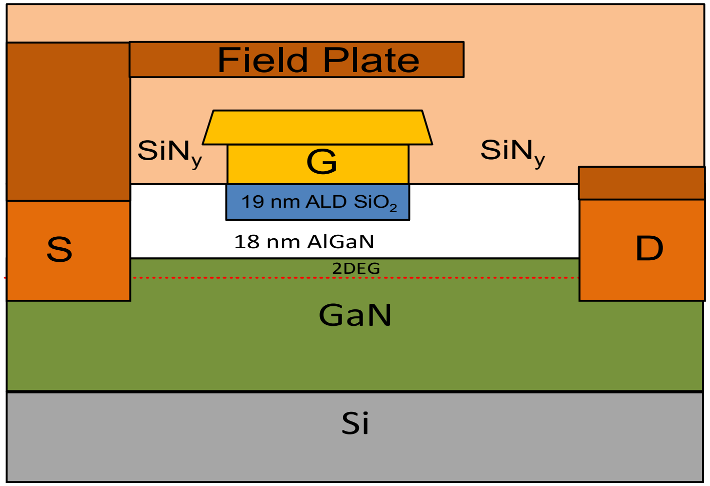




- Large ΔI_d (> 1 mA @ T = 300 K) observed following off-state stress
- ΔI_d increases for increasing temperature
- Recovery of I_d increases at longer times for higher temperature

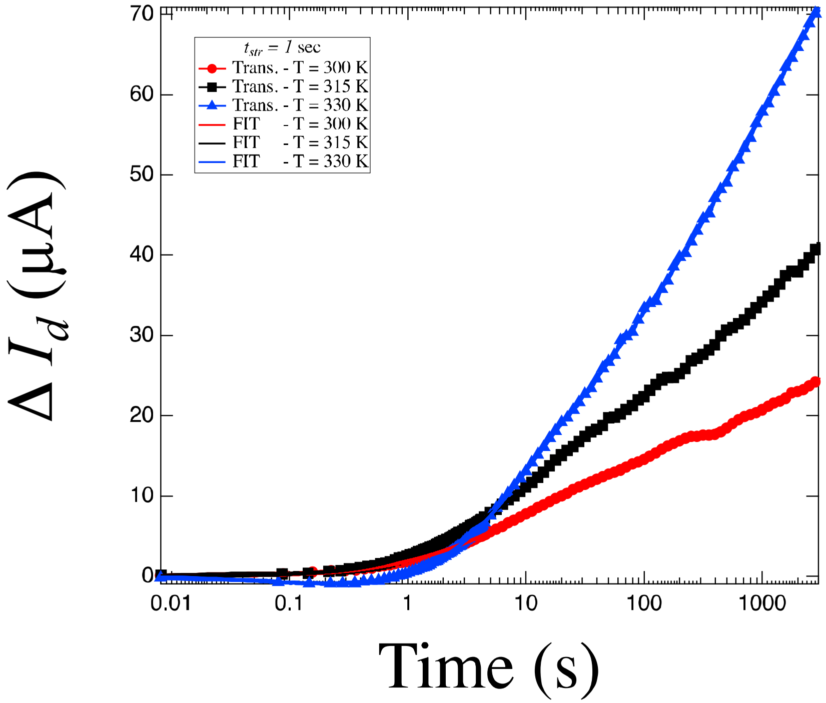
- Spectrum reveals two processes
- Broad stress-time dependent process shows no temperature dependence between 300 K and 325 K
- Slower process exhibits temp. dependence with E_a = 0.57 eV

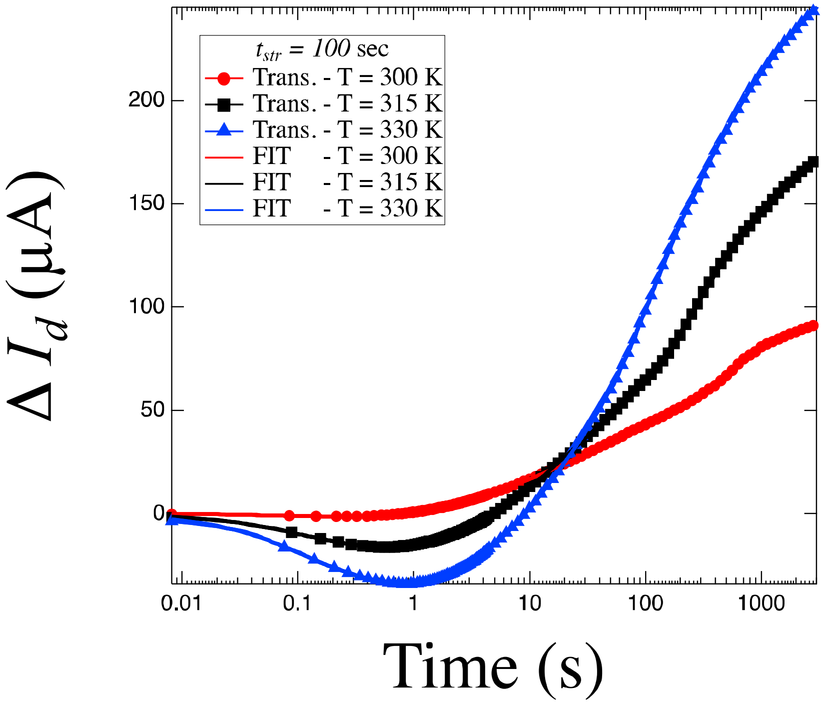
Off-State Stress MOS-HEMT Devices



- 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

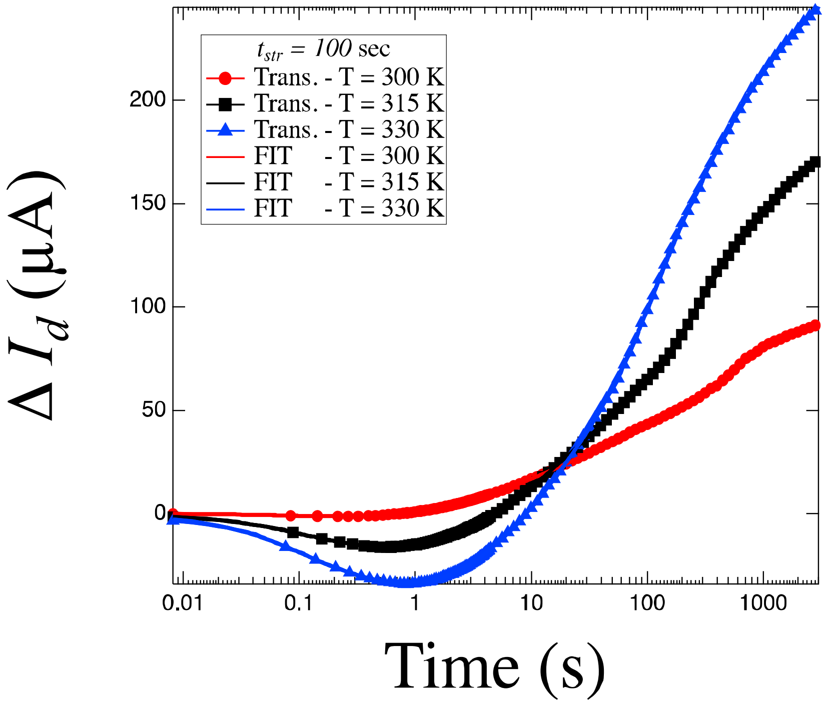


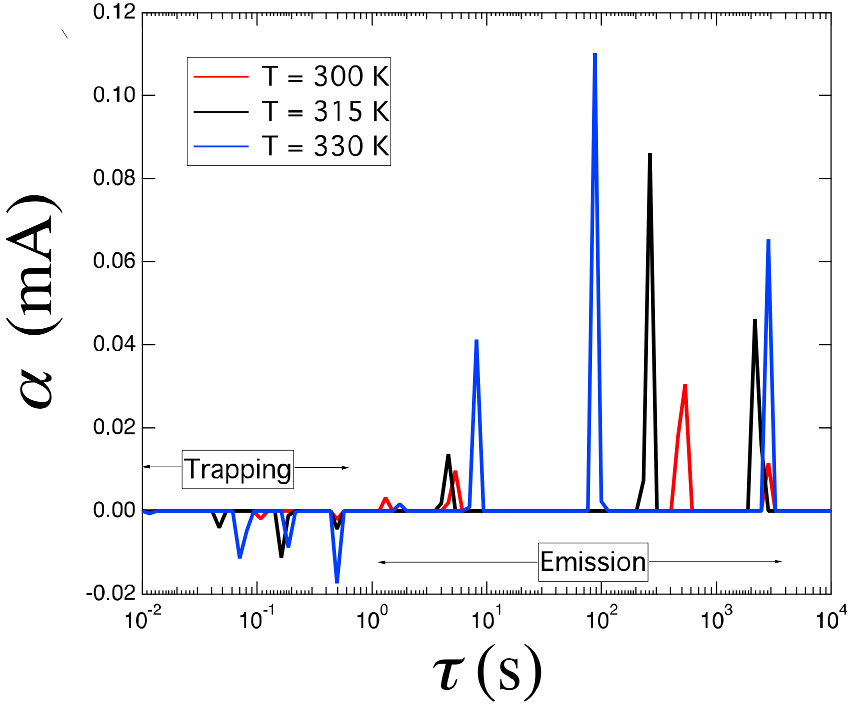


- ΔI_d following off-state stress observed to be much smaller in MOS-HEMT devices
- Increasing temp. leads to larger ΔI_d
- Recovery transient at T = 330 K shows initial decrease followed by positive recovery

- 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

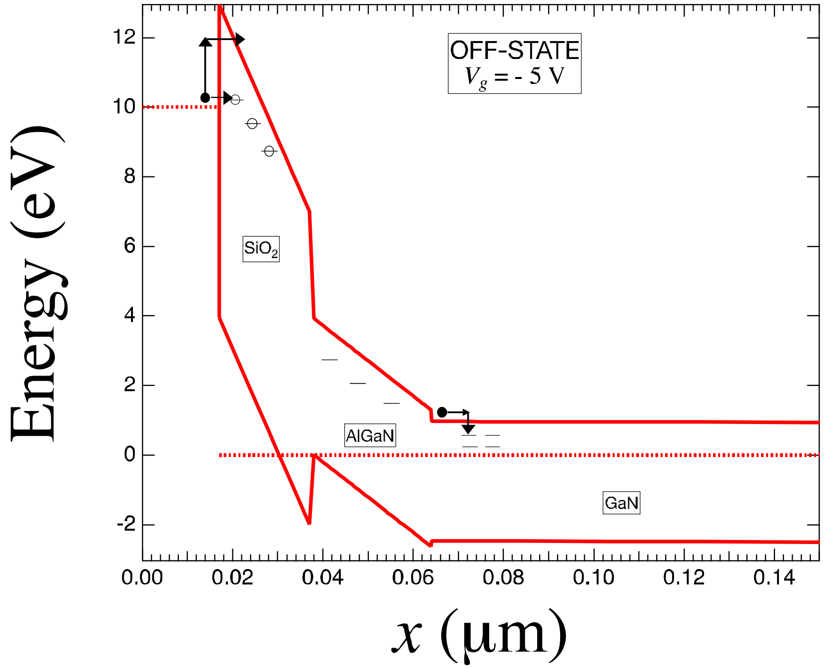




- Electron trapping leads to decreasing I_d
- Detrapping leads to increasing I_d
- Results suggest electron trapping at short recovery times (< 10 s) and emission for longer times

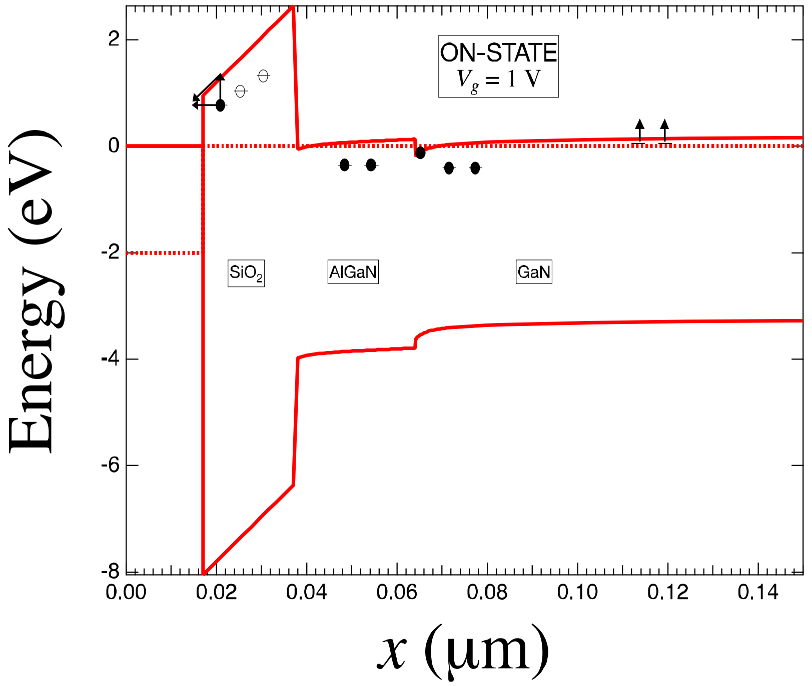
- Time constant spectrum reveals the presence of concurrent trapping and emission processes
- Temperature dependent peak present with E_a = 0.58 eV

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