SAND2020-14242PE

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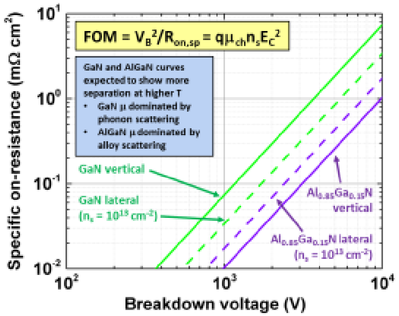
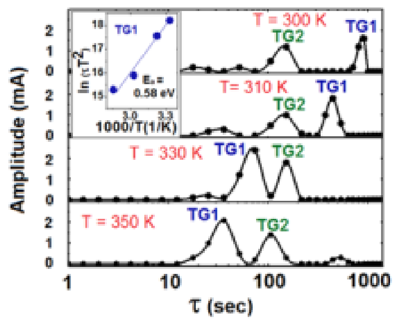
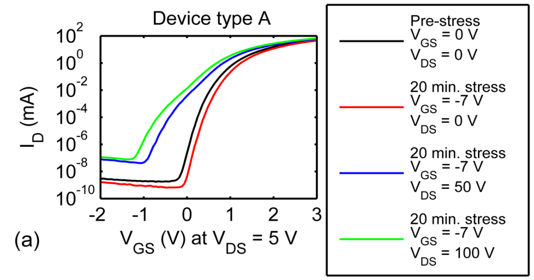
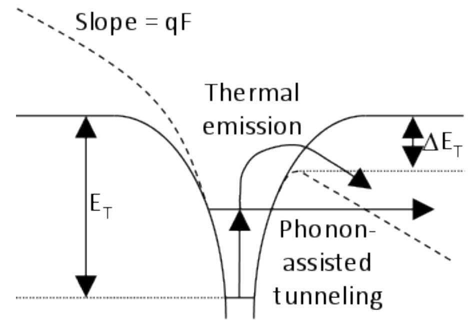
Sandia National Laboratories









GaN Power HEMT Reliability Work at Sandia National Labs

Presentation to 5N Plus

Bob Kaplar, December 22, 2020

This work was supported by DOE OE (Drs. Imre Gyuk and Mike Soboroff)

Outline

1. Introduction
2. Work with MIT on AlGaN/GaN HEMT reliability
3. Work with HRL on AlGaN/GaN HEMT reliability

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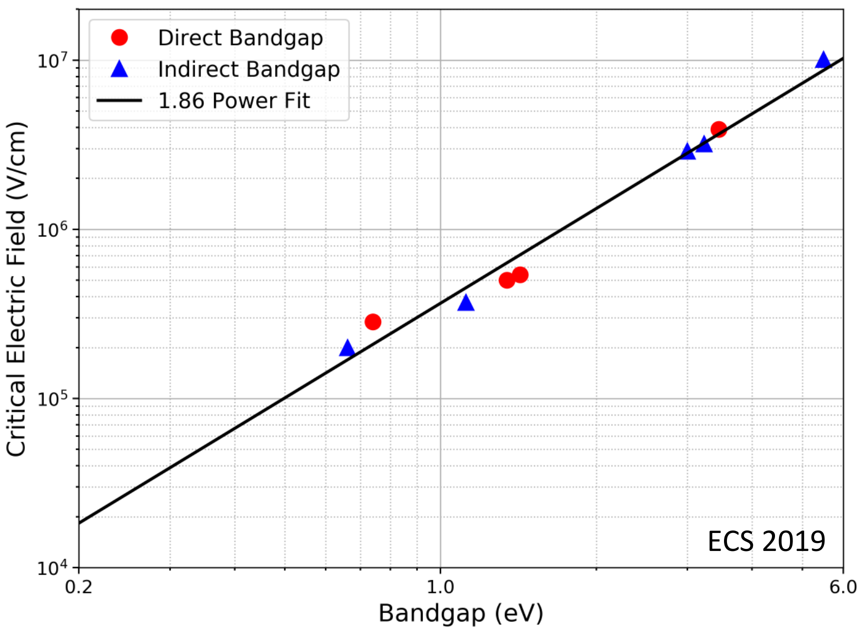
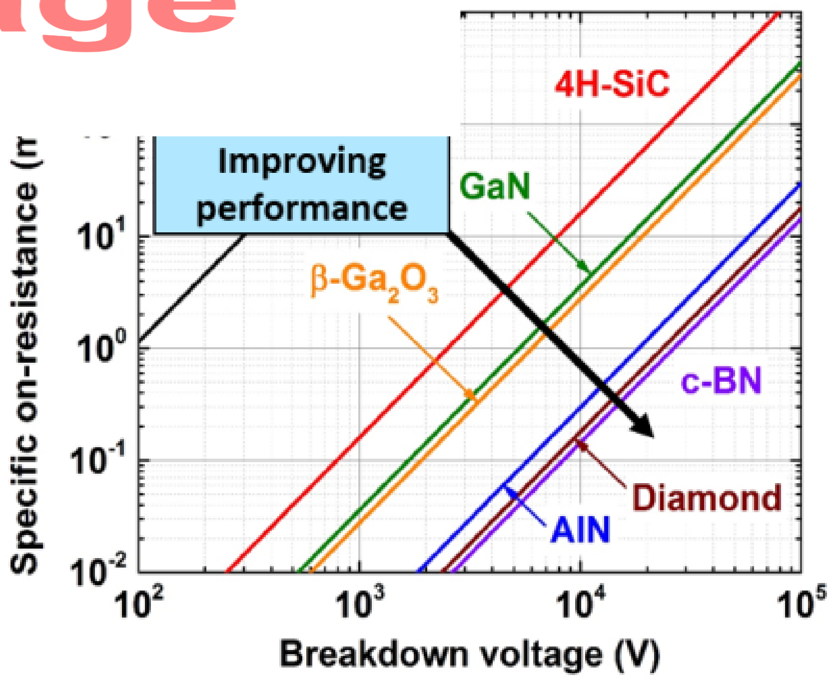
Critical Electric Field Scales with Bandgap and Determines Unipolar FOM

- **Critical electric field is believed to follow a power-law with bandgap*:** $\mathcal{E} \sim$
- **Normalizing to doping and PT/NPT yields γ ~ 1.9**
- **Implies strong de**



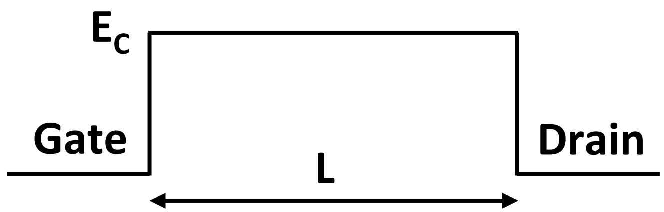


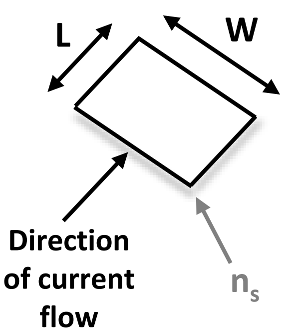
* Hudgins et al., *IEEE Trans. Power Elec.* **18(3)**, 907 (2003)

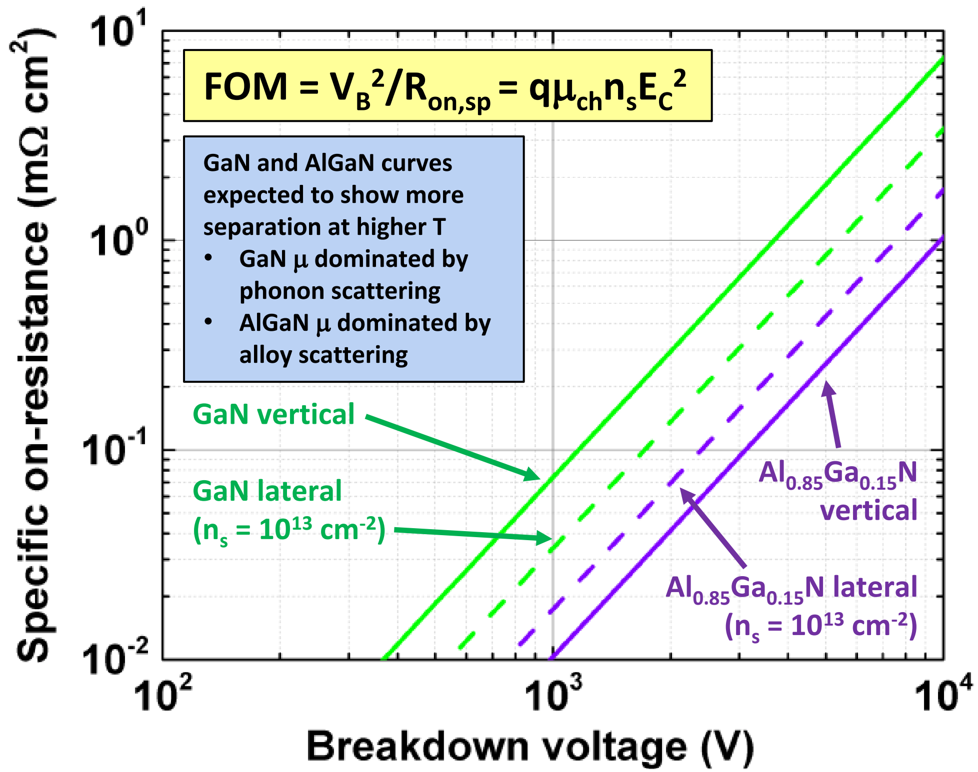
Tsao et al., *Adv. Elec. Mat*. **4**, 1600501 (2018)

Lateral Power Device Figure of Merit (Applicable to HEMTs)

- **Not as widely known as the unipolar FOM**
- **Unipolar (vertical) FOM is often incorrectly used for lateral devices**

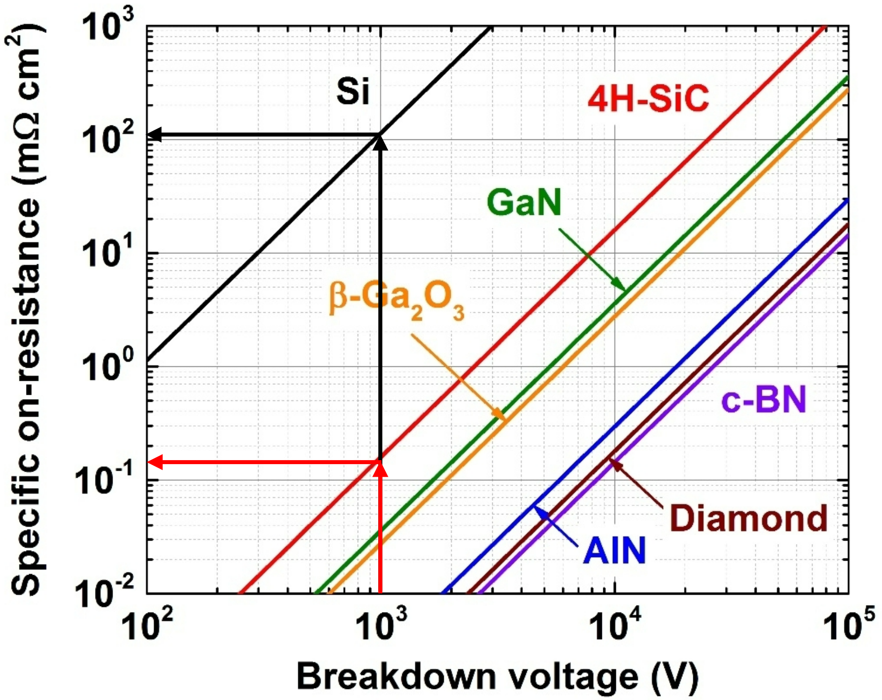






- **Proportional to E_C^2 rather than E_C^3, but high n_s can result in high FOM**

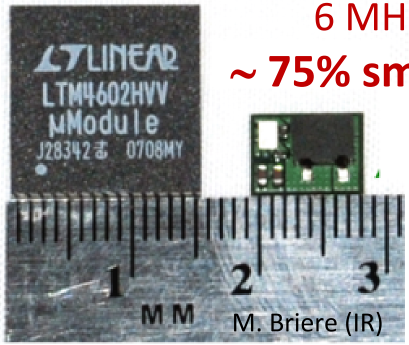
How Do WBGs and UWBGs Lead to Higher Switching Frequency and Lower Loss?



- For equivalent breakdown voltage, get lower $R_{on}A$ for (U)WBG device
  - For same R_{on}, (U)WBG device can have *smaller area*
  - Smaller area results in *less capacitance*
  - Gives a *faster switching transient* and *lower loss per switching cycle*

Si
15x15mm²
100 kHz

GaN
6x9mm²
6 MHz
~ 75% smaller

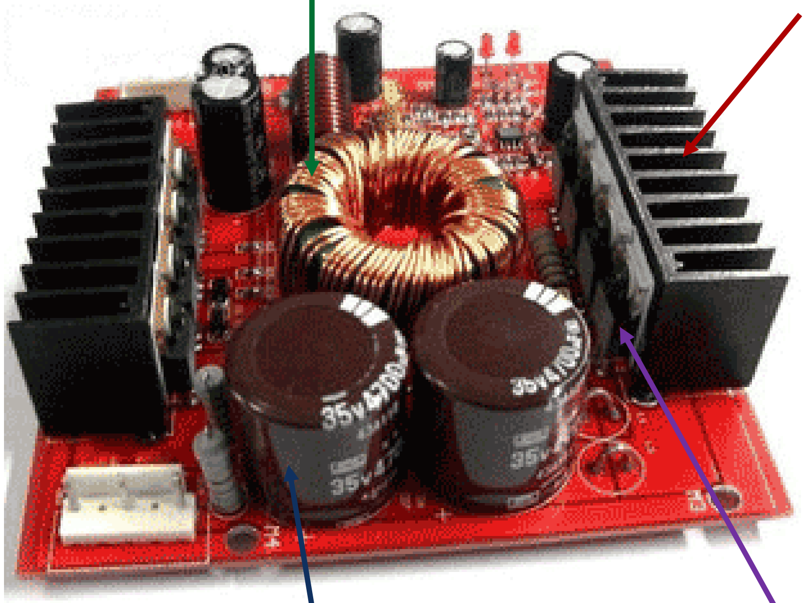


1.2 kV, 12 A switch

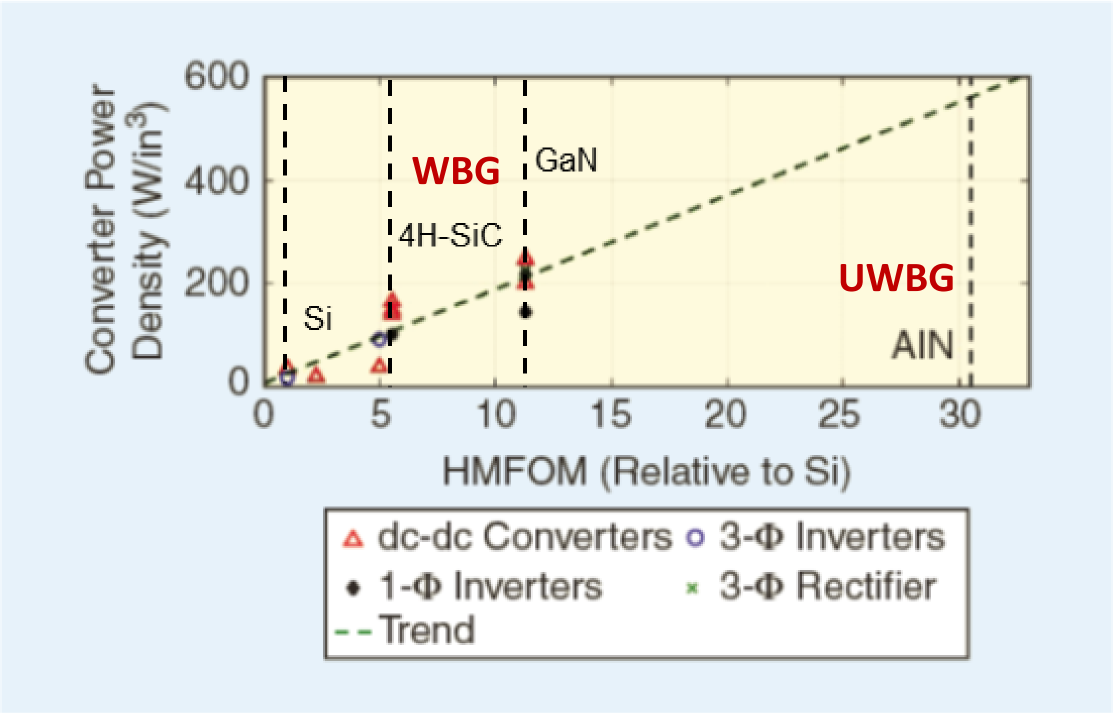
The scaling that results from the properties of WBG and UWBG materials can be utilized to optimize for switching frequency, conduction loss, and switching loss

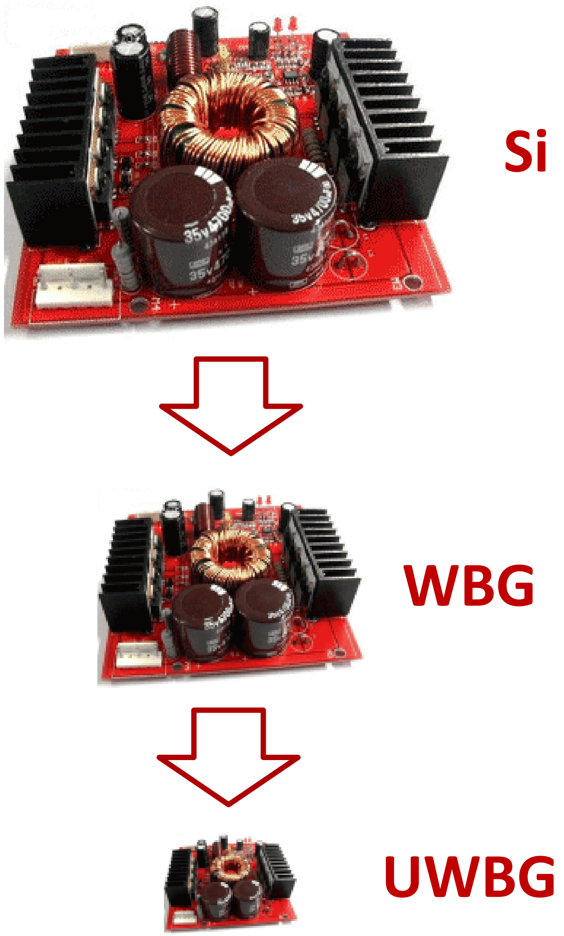
Power Converter Size is Determined by Passive Elements

- Passive elements and thermal management comprise the bulk of the volume and mass of a power converter
- These can be reduced in size using WBG semiconductors due to faster switching and reduced loss



Power Density Scaling with Semiconductor Material Properties



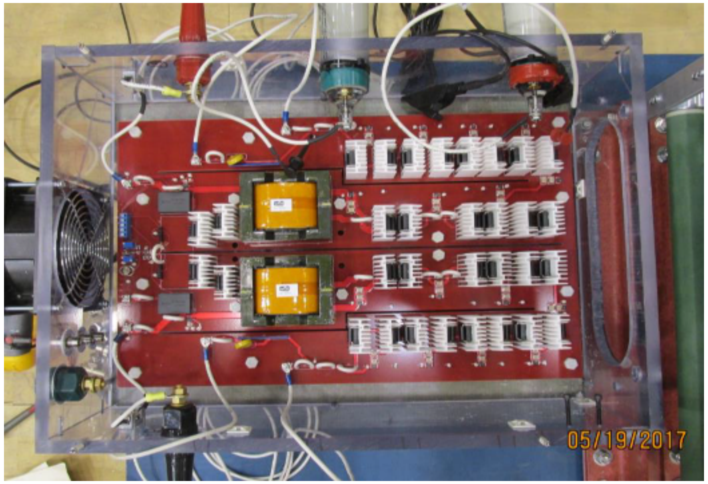


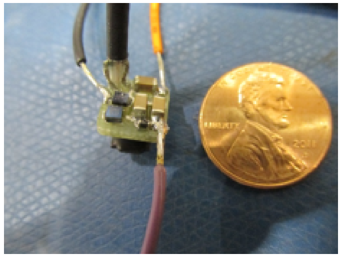
Relative Figures of Merit:

- **Vertical UFOM = $\varepsilon\mu_n E_C^3$**
- **Huang Material FOM = $E_C \mu_n^{1/2}$**
- **HM-FOM seems to be a good predictor of power density**

R. J. Kaplar, J. C. Neely, et al., *IEEE Power Electronics Magazine (March 2017)*

Efficient and Compact Power Conversion Enabled by WBG Semiconductors



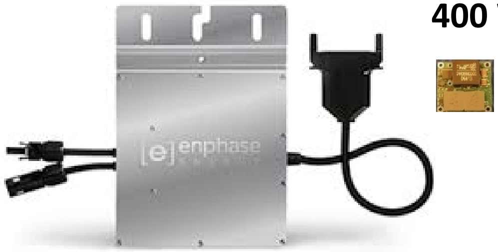


SNL GaN HEMT "Coin Converter"
90 V, 90 mA → 215 W/in^3

SNL SiC hybrid switched-capacitor boost converter (ARPA-E)

- First prototype: 0.5 kV → 10.1 kV (gain = 16.8) at 2.6 kW, 95.3% efficient, 410 in^3
- Second prototype: +2% efficiency, 55% volume

SNL GaN HEMT microinverter
400 W in 2.4 in^3 → 167 W/in^3



Over an order of magnitude improvement in power density is enabled by use of GaN power transistors compared to Si

SOA commercial microinverter
250 W in 59 in^3 → 4.2 W/in^3

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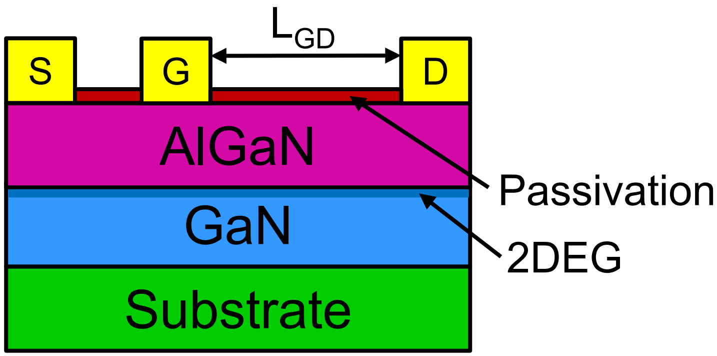
High-Voltage AlGaN/GaN HEMTs Fabricated at MIT



High Electron Mobility Transistor:

- Designed and fabricated at MIT
- Polarization induces high-μ channel
- Normally-on device
- L_{GD} and Al% control V_{BD}

	Device 1	Device 2	Device 3	Device 4
Maximum V_{BD}	1800 V	1800 V	500 V	500 V
V_{TH}	-3.6 V	-3.6 V	-1.8 V	-1.8 V
Barrier	50 nm $Al_{0.15}Ga_{0.85}N$	50 nm $Al_{0.15}Ga_{0.85}N$	20 nm $Al_{0.26}Ga_{0.74}N$	20 nm $Al_{0.26}Ga_{0.74}N$
Passivation	$Al_2O_3/SiO_2/Al_2O_3$	None	$Al_2O_3/SiO_2/Al_2O_3$	None
C-doped buffer	Yes	Yes	No	No

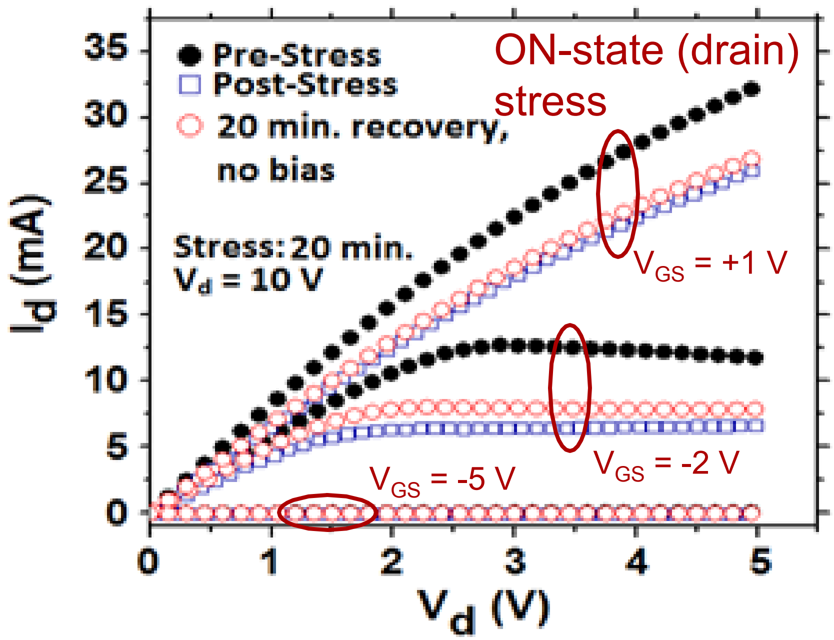
$L_G = 2\ \mu m$, $L_{GS} = 1.5\ \mu m$, $L_{GD} = 1.5$ to $40\ \mu m$

All devices grown on (111) Si by MOCVD

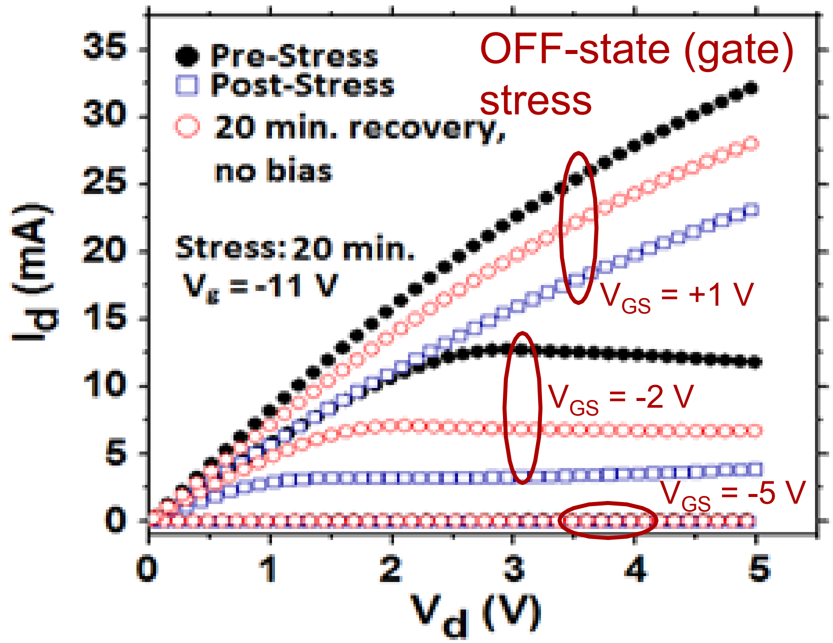
S. DasGupta et al., IEEE TED 59(8), 2115 (2012)

ON-State vs. OFF-State Stress

Passivated $Al_{0.15}Ga_{0.85}N/GaN$ sample



Stress: V_{DS} = 10 V, V_{GS} = 0 V (ON)

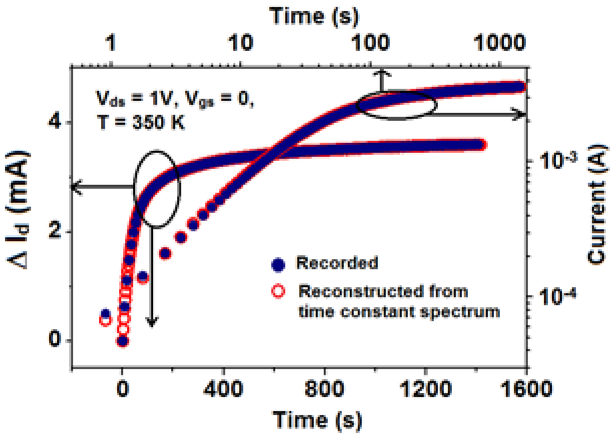


Stress: V_{DS} = 0 V, V_{GS} = -11 V (OFF)

ON-state stress (drain bias) results in much slower recovery than OFF-state stress (gate bias)

S. DasGupta et al., IEEE TED 59(8), 2115 (2012)

Recovery Current Transient Analysis Following Gate Stress



Fitting of recovery transient amplitudes A_i with fixed τ_i:

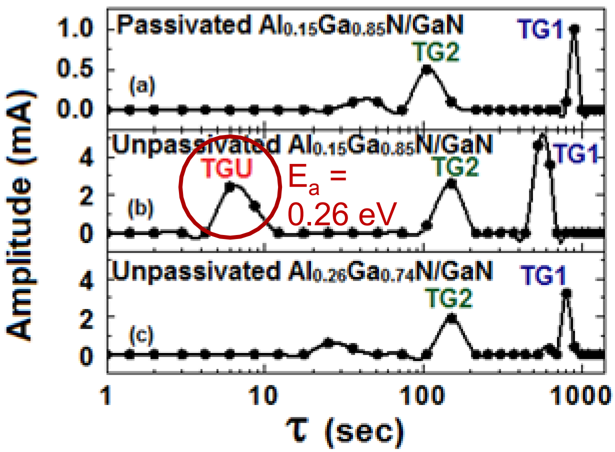
$$\Delta I_d = \sum_i A_i \left[1 - exp\left(-\frac{t}{\tau_i}\right)\right]$$

Peaks in time constant spectra are indicative of different traps in different samples

$$\Delta I_d = \sum_i A_i \left[1 - exp\left(-\frac{t}{\tau_i}\right)\right]$$

Passivated $Al_{0.26}Ga_{0.74}N/GaN$ temperature dependence

TG1 is thermally activated; TG2 is not. Why?

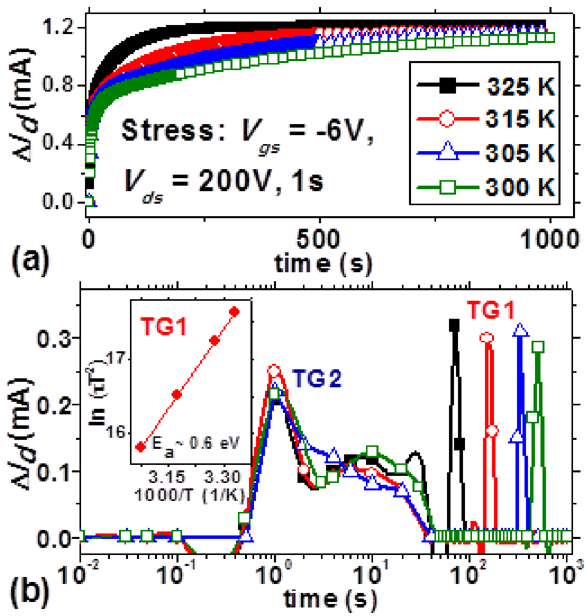


Comparison of other samples; note TGU only for unstable sample

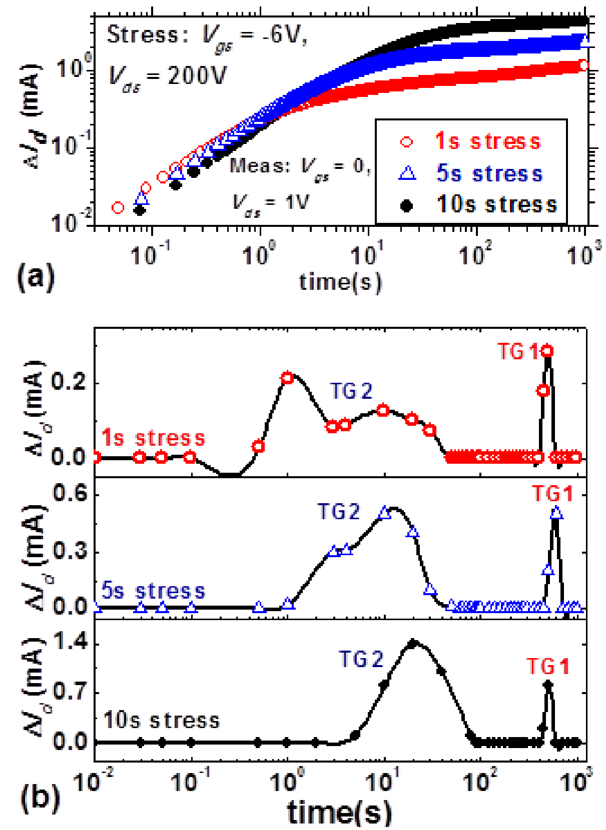
S. DasGupta et al., IEEE TED 59(8), 2115 (2012)

Temperature- and Stress-Time-Dependence of Degradation

Newer samples: 50 nm barrier, thicker passivation, V_T = -4.1 V



Stress time fixed, vary temperature

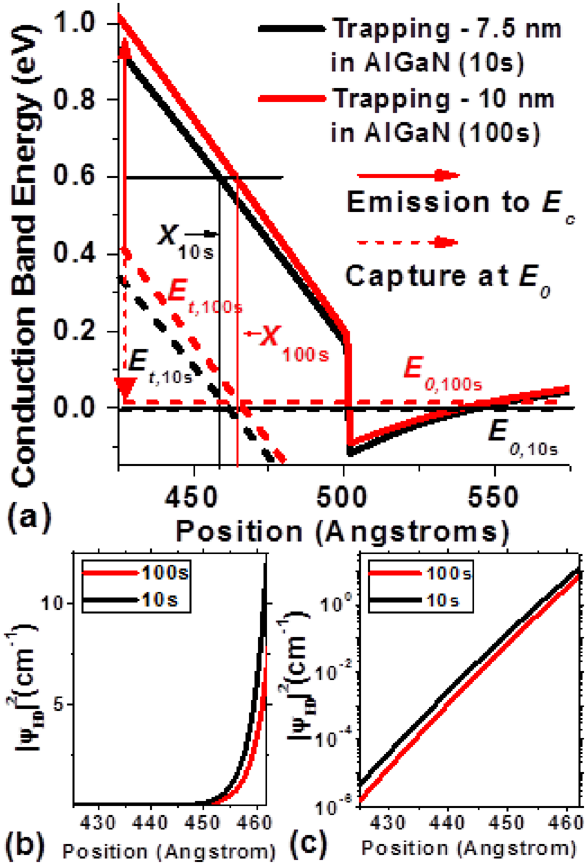


Vary stress time, temperature fixed

TG1 shows clear thermally activated behavior, but TG2 is insensitive to temperature

S. DasGupta et al., IEEE TED 59(8), 2115 (2012)

Deep-Level / 2DEG Quantum Well Interaction Model

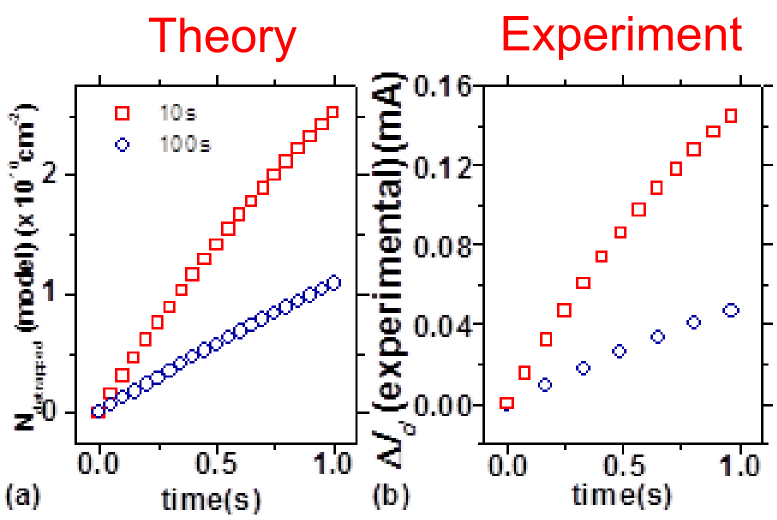


Our model proposes that a single deep level in the AlGaN barrier (E_C – 0.6 eV) may emit electrons in two different ways, resulting in two different peaks:

1. To the AlGaN CB (Arrhenius)
2. To the 2DEG wavefunction (insensitive to temperature)

Longer stress times raise the CB edge in the AlGaN, reducing the spatial depth over which the 2DEG wavefunction overlaps with the deep level

Proposal: Electrons Are Directly Captured Into Multiple 2DEG QW States



Time constant for capture of electron from deep level to 2DEG tail:

$$1/\tau_n(x) = \left|\psi_n(x)\right|^2 D_{2D}\sigma v_{th}$$

ψ_n = nth QW wavefunction (cm$^{-1/2}$)
D_{2D} = In-plane 2DEG DOS (cm^{-2})
σ = Capture cross section (cm^2)
v_{th} = Thermal velocity (cm/s)

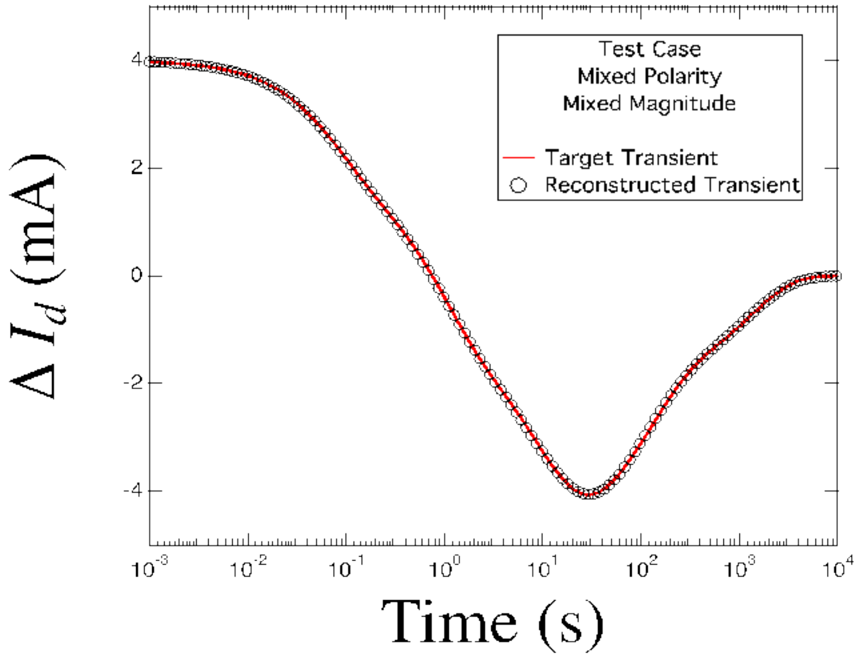
Overall recovery time constant may be tuned by wavefunction engineering (barrier height, etc.) to be much shorter than the bulk emission time; *reliability may thus be controlled by device design*

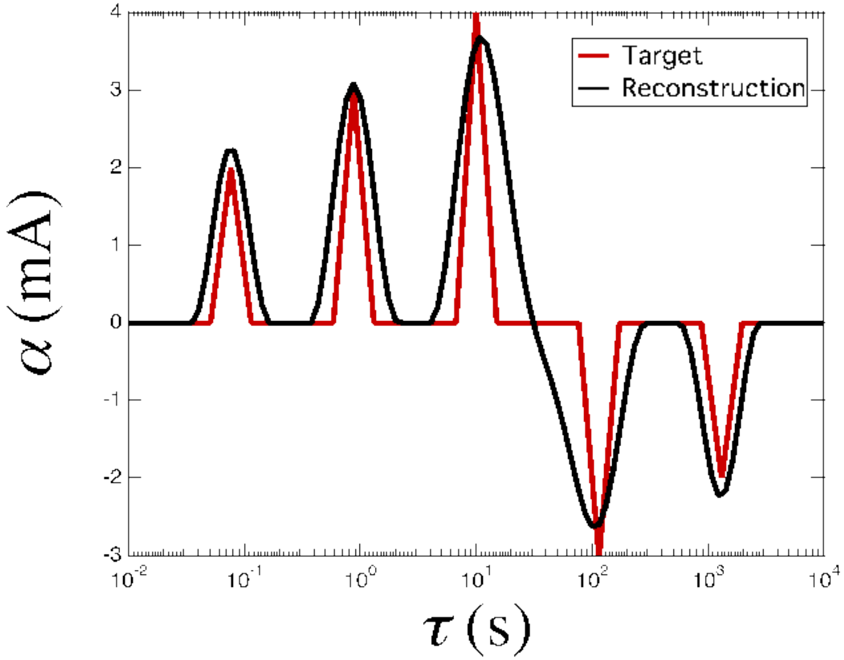
Sum time constants for each 2DEG level plus thermal term to get overall emission rate:

$$\frac{1}{\tau(x)} = \frac{1}{\tau_e} + \sum_n \frac{1}{\tau_n(x)}$$

What About Negative Peaks Due to Trapping?

$$\Delta I_d = \sum \alpha_i \left(1 - e^{-t/\tau_i}\right) \Longrightarrow y_{fit} = \min\left(|y - A\alpha|^2 + \left|\frac{d}{dt}A\alpha\right|^2 \right)$$

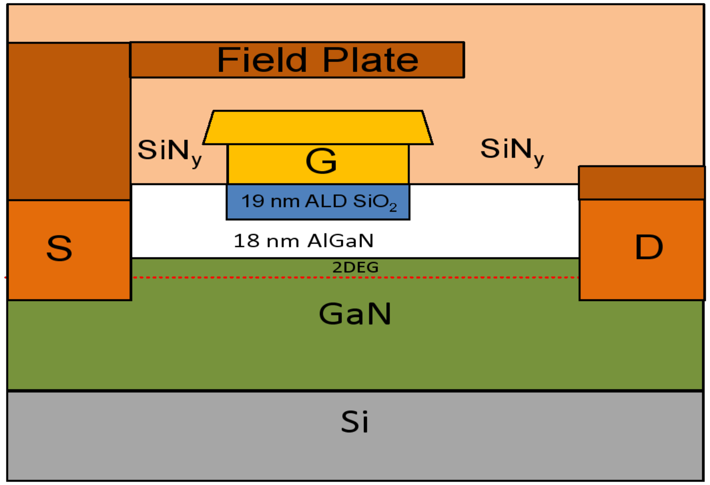




- **Artificial transient representative of simultaneous trapping and emission of electrons**
- **Corresponding time-constant spectrum shows both trapping and emission processes are recoverable**

M. P. King et al., Proc. 53rd IRPS (2015)

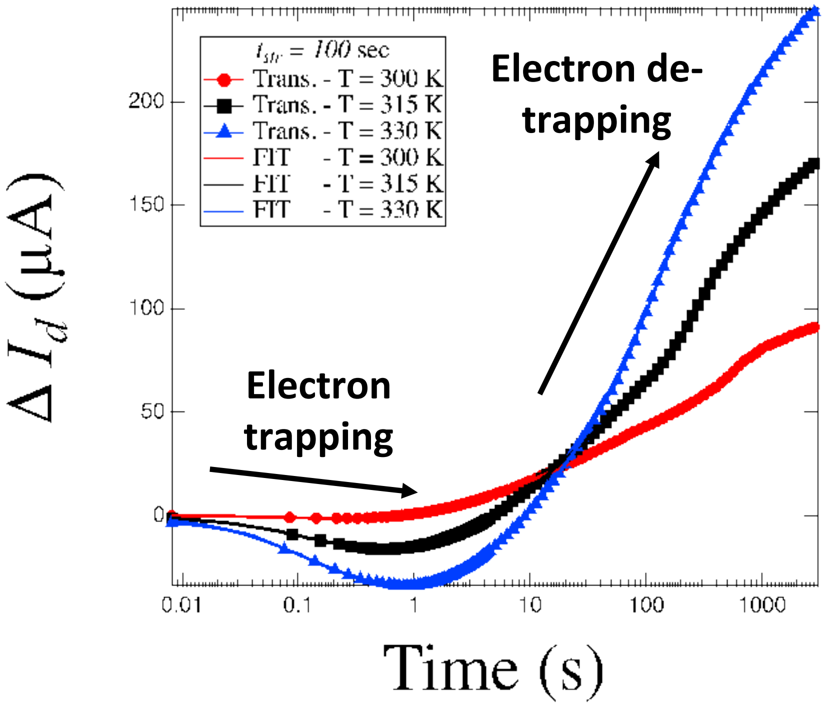
Off-State Stress
MOS-HEMT Devices

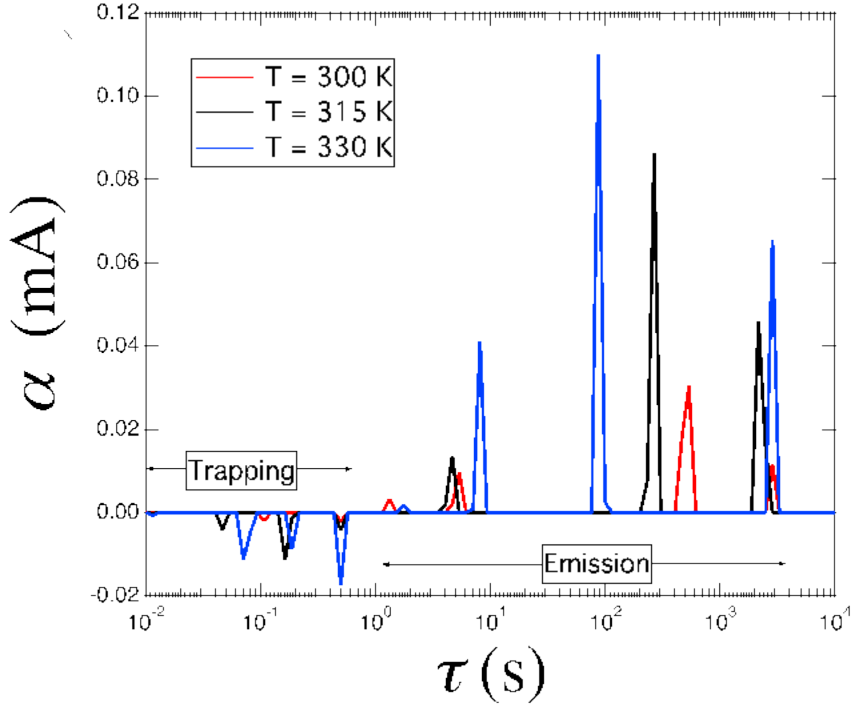


- **Stress-time and temperature dependent off-state parametric shifts in I_d**
- **Off-state stress conditions**
  V_{gs} = -5 V
  V_{ds} = 100 V
- **Recovery-state**
  V_{gs} = 1 V
  V_{ds} = 0.1 V

M. P. King et al., Proc. 53rd IRPS (2015)

Temperature Dependent Off-State Parametric Shifts





- Electron trapping decreases I_d
- De-trapping (emission) increases I_d
- Suggests electron trapping dominates at short recovery times (< 10 s) and emission dominates 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

M. P. King et al., Proc. 53rd IRPS (2015)

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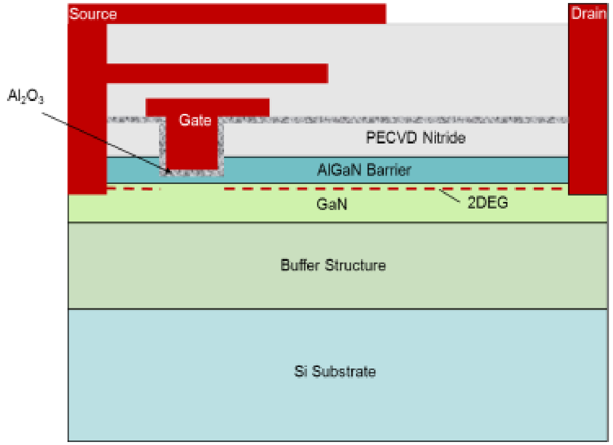
Collaboration with Sameh Khalil group

AlGaN/GaN HEMT Process Splits and Stress Response

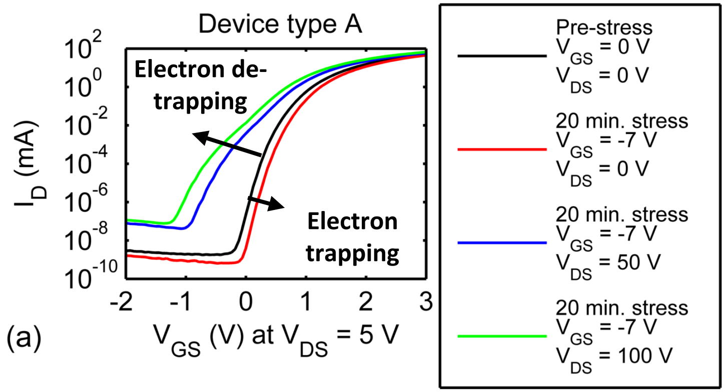


Gate stack process splits

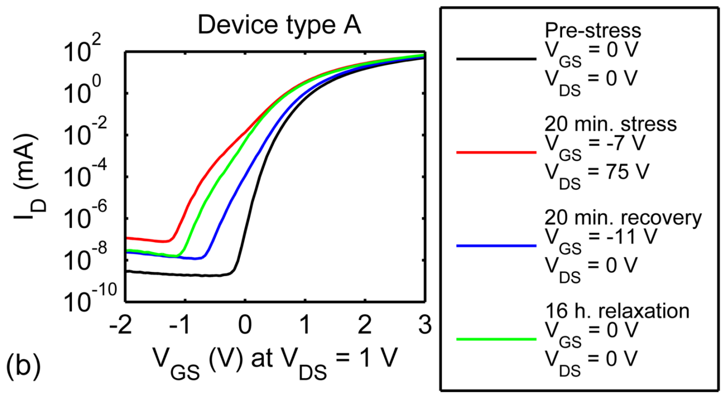
Device Type	Gate Oxide (Al_2O_3)	Gate Stack AlGaN
A	Yes	Present (t ~ 5 nm)
B	No	Residual (t < 1 nm)
C	No	Present (t ~ 5 nm)

Different electrical stress may results in both electron trapping and de-trapping (i.e. emission)

Different stresses on different devices

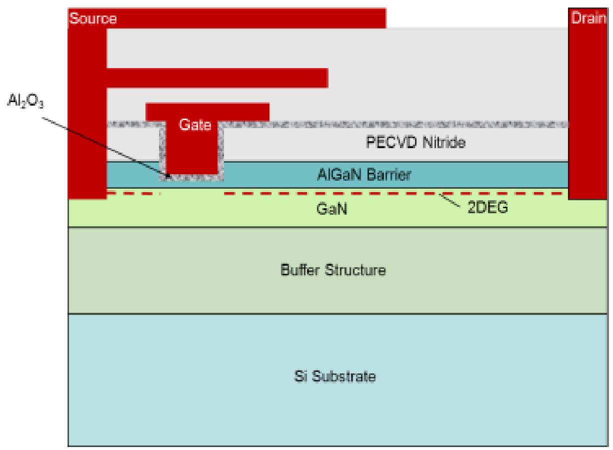


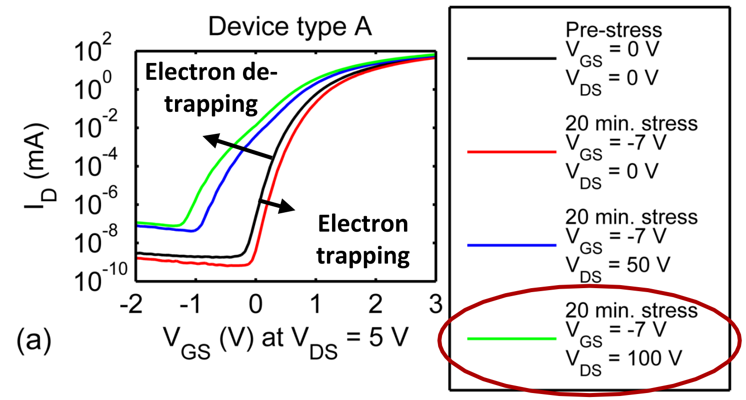
Sequential stresses on the same device



R. J. Kaplar et al., Proc. 26th ISPSD, 209 (2014)

Different Process Splits Have Different Responses to Off-State Stress





Gate stack process splits

Device Type	Gate Oxide (Al_2O_3)	Gate Stack AlGaN
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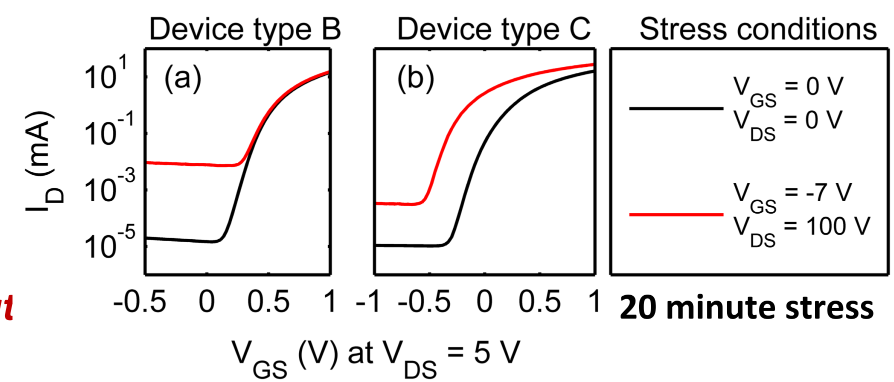
C	No	Present (t ~ 5 nm)



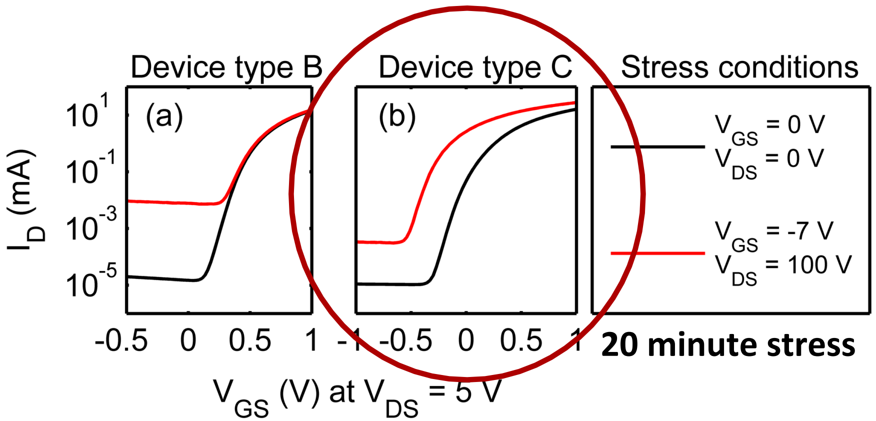
The lack of a V_T shift in device type B suggests that the defects responsible for instability are in the AlGaN portion of the gate stack

R. J. Kaplar et al., Proc. 26th ISPSD, 209 (2014)

A Reversal from Electron Trapping to De-Trapping is Observed

Gate stack process splits

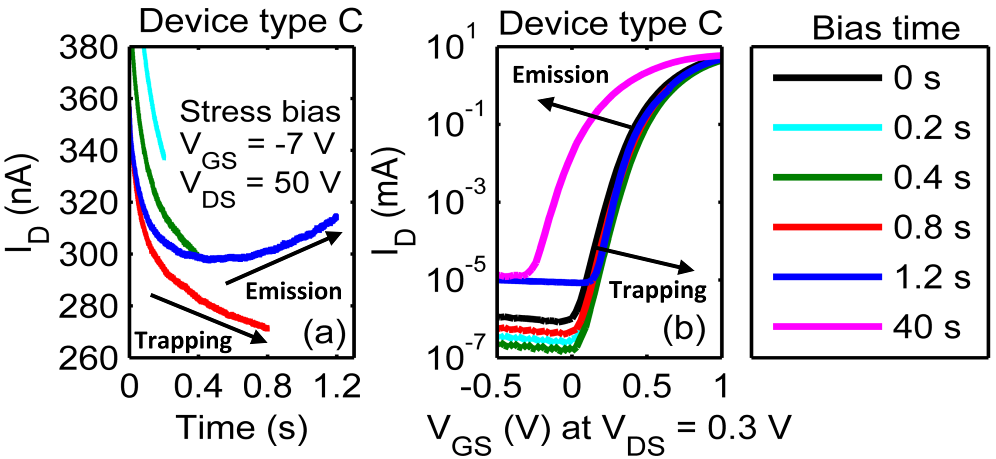
Device Type	Gate Oxide (Al_2O_3)	Gate Stack AlGaN
A	Yes	Present (t ~ 5 nm)
B	No	Residual (t < 1 nm)
C	No	Present (t ~ 5 nm)



Blocking stress at short times results in *reduction* in I_D → *Positive* V_T shift (electron trapping)

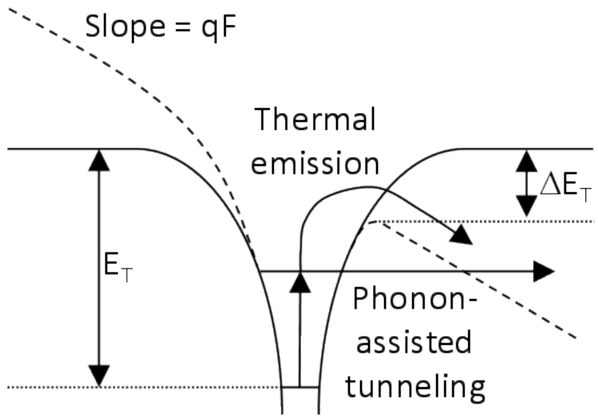
This is in contrast to stress for long times, which shows an increase in I_D → *Negative* V_T shift (electron de-trapping)

This is explained by a transition from electron trapping to emission with prolonged stress



R. J. Kaplar et al., Proc. 26th ISPSD, 209 (2014)

Field-Enhanced Emission Model to Explain Trapping to De-Trapping Transition



Poisson equation

$$\frac{\partial^2 \varphi(t,x)}{\partial x^2} = \frac{q n_T(t,x)}{\varepsilon}$$

Capture / emission rate equation

$$\frac{dn_T}{dt} = \left.\frac{dn_T}{dt}\right|_{capture} + \left.\frac{dn_T}{dt}\right|_{\substack{Thermal\\Emission}} + \left.\frac{dn_T}{dt}\right|_{\substack{Phonon-assisted\\Tunneling}}$$

Expressions for capture and emission mechanisms

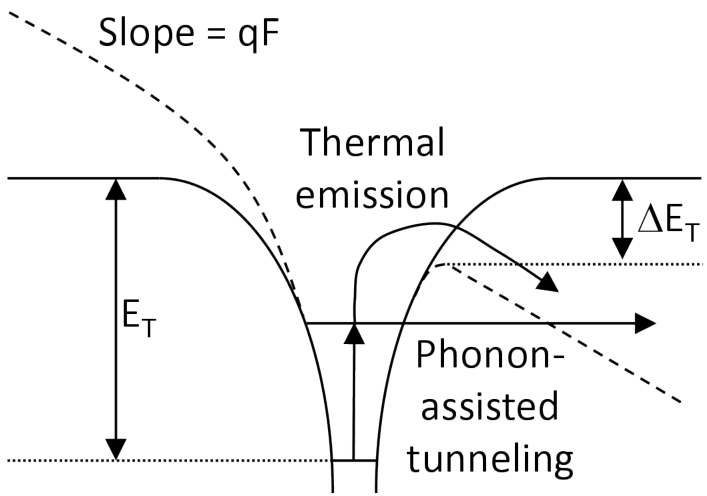
$$\left.\frac{dn_T}{dt}\right|_{capture} = \sigma_n v_{th}(N_T - n_T)n = \sigma_n v_{th}(N_T - n_T)n_0 exp\left(\frac{-E_B}{kT}\right)$$

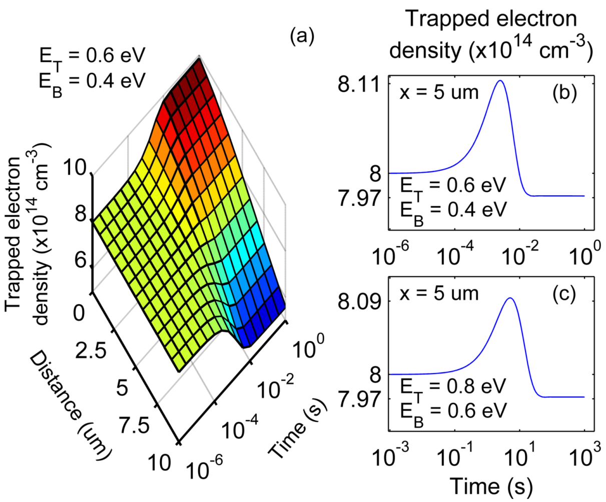
$$\left.\frac{dn_T}{dt}\right|_{\substack{Thermal\\Emission}} = -\sigma_n v_{th} N_C exp\left((-(E_T - \Delta E_T))/kT\right) n_T(t,x) \text{ with } \Delta E_T = q\sqrt{q\left|\frac{\partial\varphi}{\partial x}\right|/\pi\varepsilon}$$

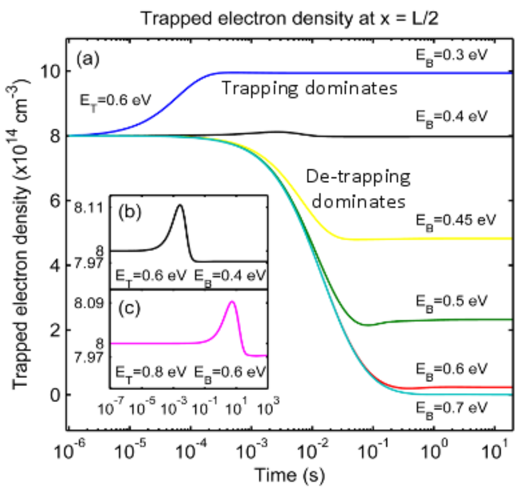
$$\left.\frac{dn_T}{dt}\right|_{\substack{Phonon-assisted\\Tunneling}} = -\sigma_n v_{th} N_C exp\left(\frac{-E_T}{kT}\right)\left[\int_{\Delta E_T/kT}^{E_T/kT} exp\left[z - z^{3/2}\left(\frac{8\pi\sqrt{m_n^*(kT)^3}}{3qh|\partial\varphi/\partial x|}\right)\left(1-\left(\frac{\Delta E_T}{zkT}\right)^{5/3}\right)\right]dz\right] n_T(t,x)$$

R. J. Kaplar et al., Proc. 26th ISPSD, 209 (2014); S. G. Khalil et al., Proc. 52nd IRPS, CD.4 (2014)

1D Field-Enhanced Emission Model Results





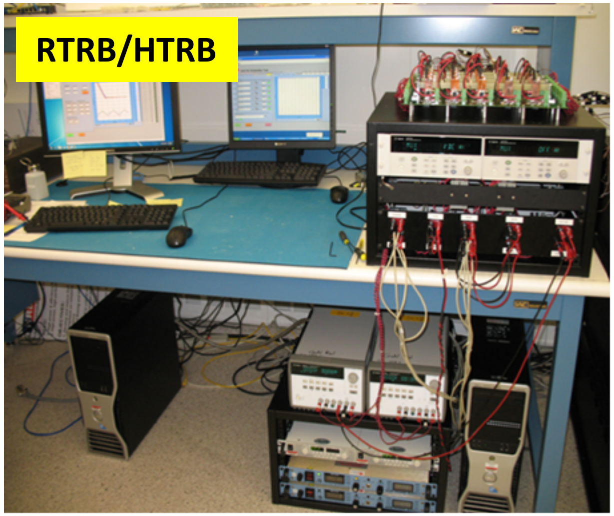


Simplified 1D model is able to qualitatively explain trapping to de-trapping transition!

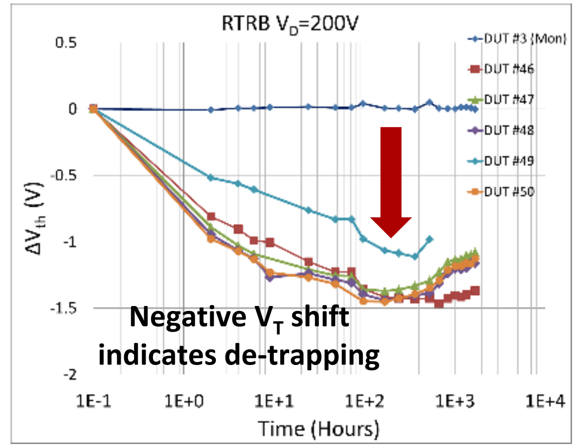
Trapped electron density vs. position and time

R. J. Kaplar et al., Proc. 26th ISPSD, 209 (2014); S. G. Khalil et al., Proc. 52nd IRPS, CD.4 (2014)

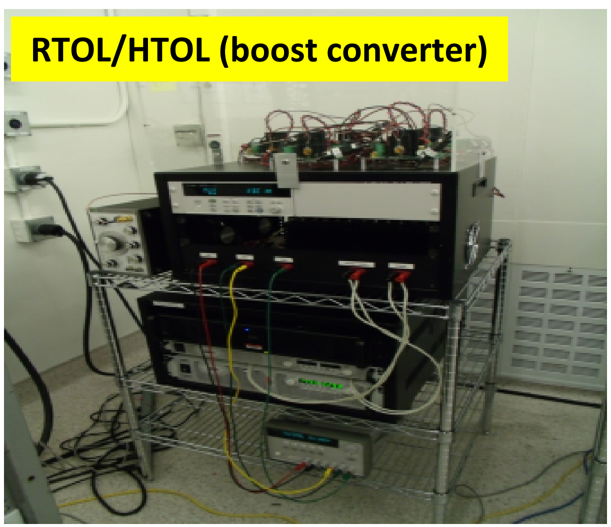
Correlation with Reverse Bias and Operating Life Testing



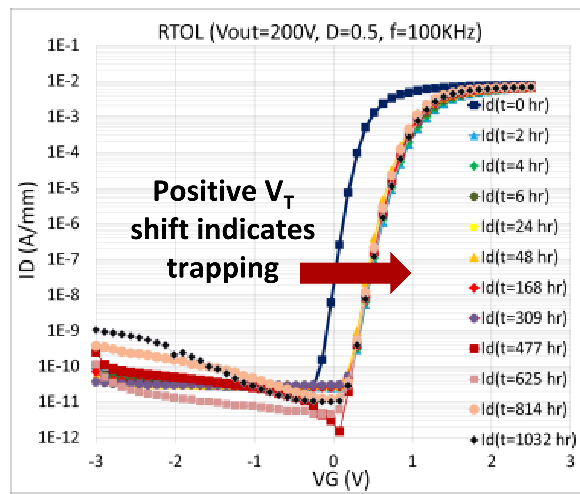
RTRB



DC stress



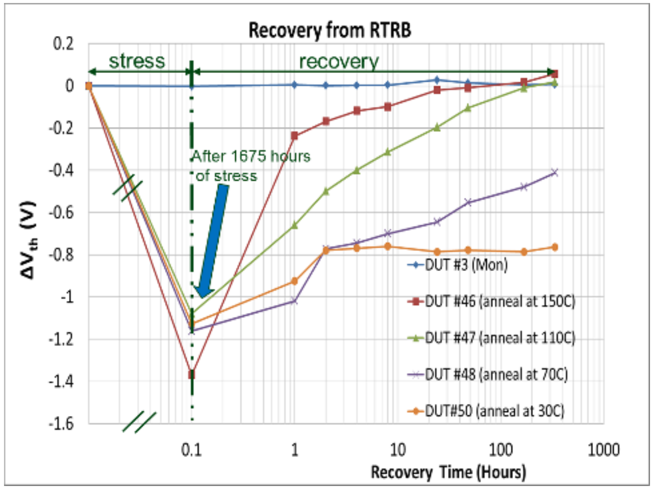
RTOL



AC stress

S. G. Khalil et al., Proc. 52nd IRPS, CD.4 (2014)

Temperature-Dependence of Reliability Stress



Recovery from RTRB stress:

- **Positive V_T shift indicates electron capture**
- **Temperature dependence indicates a barrier to electron capture, consistent with model**

Working theory

- ***For RTRB/HTRB, the stress time is long so a negative V_T shift resulting from electron de-trapping is observed***
- ***For RTOL/HTOL, the effective stress time is short (during blocking bias conditions) so a positive V_T shift resulting from electron trapping is observed***

S. G. Khalil et al., Proc. 52[nd] IRPS, CD.4 (2014)

Summary

- **Physics-based investigations of AlGaN/GaN HEMT reliability with MIT and HRL, in both cases focused on parametric shifts due to electron capture and emission**
- **Temperature-dependent and independent signatures are observed**
- **A transition from electron capture to emission explains many observations**
- **Coupling of device design and electric field distribution to defects is of critical importance**

The contributions of all past and present collaborators are gratefully acknowledged