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Reliability Considerations for Al-rich Aluminum Gallium Nitride Power Switching Transistors

Albert Baca, Brianna Klein, Chad Stephenson, Andrew Armstrong, Andrew Allerman, Erica Douglas, Torben Fortune, Albert Colon, and Robert Kaplar

Sandia National Laboratories
Albuquerque, NM USA

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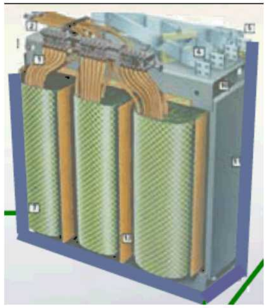
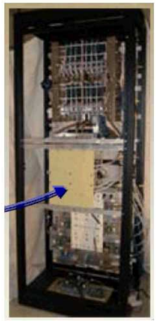
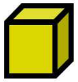
Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Conduction loss-based metrics for incumbent and emerging devices in power conversion
- Early History with depletion-mode transistors
- Demonstration of enhancement-mode transistors
- Reliability Considerations for Al-rich AlGaN transistors
- Summary

UWBG semiconductors for Power Electronics

Silicon	SiC	UWBG ($E_G > E_G$ (GaN))
		
• 2.7 MVA • 6 tons • 10 m^3	• 2.7 MVA • 2 tons • 6.5 m^3	• 2.7 MVA • <1 ton • <1 m^3

- Electrification of sensors, weapons and propulsion demand >100 kV, >1000 kA, or >100 MW
- Requires higher voltage, power density, and thermal margin than SiC or GaN provides

Albert Baca - agbaca@sandia.gov

Conduction Loss Figure of Merit for Lateral and Vertical Devices

Basis for FOM: Conduction Loss: Greater voltage requires lower doping and longer drift region (double whammy)

Baliga FOM (Vertical)

$$\frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_{crit}^3$$

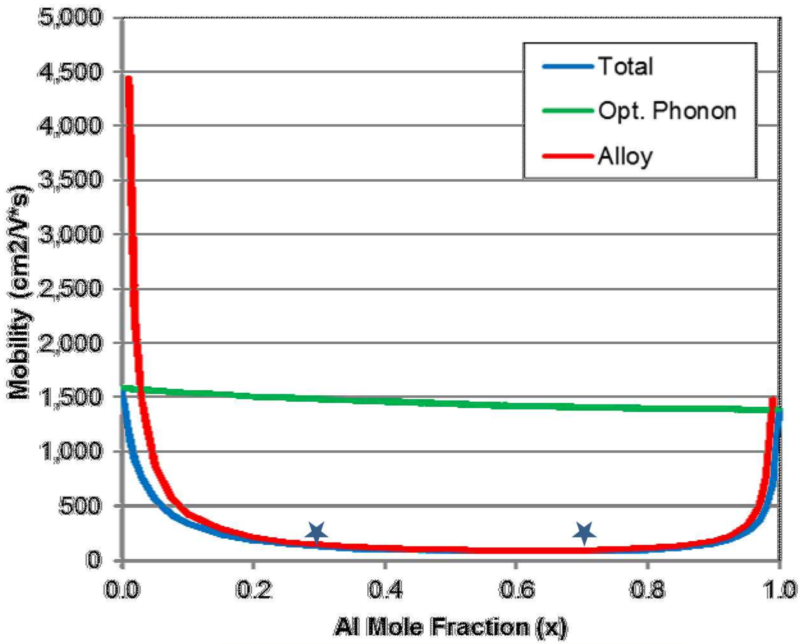
Lateral FOM

$$\frac{V_{br}^2}{R_{on,sp}} = q\mu n_s E_{crit}^2$$

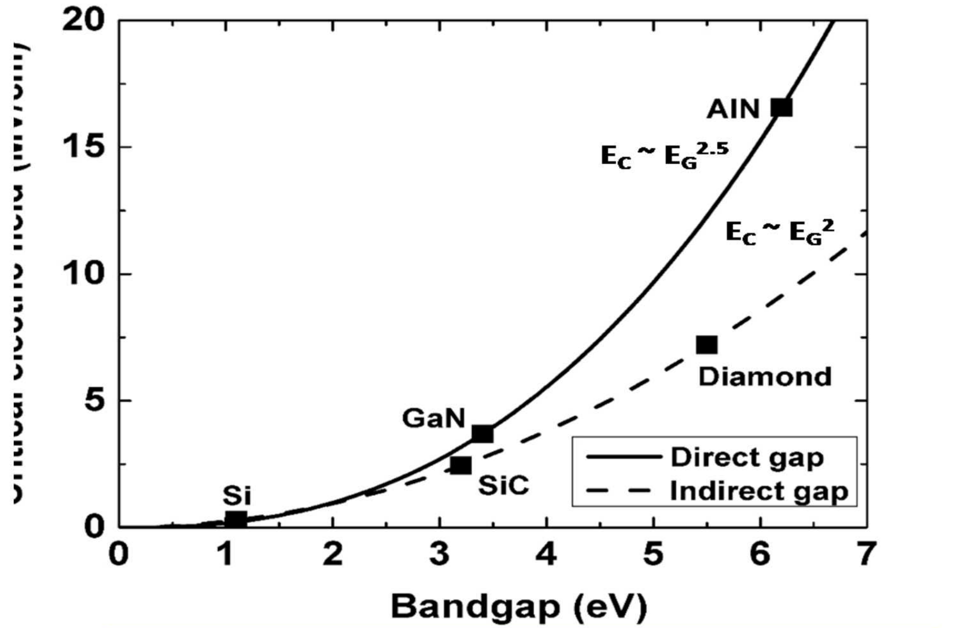
Parameters and FOM values are different – Lateral and Vertical devices are different

FOMs can be compared – they are measured similarly

FOM Critical Parameters and Al Mole Fraction (x) in $Al_xGa_{1-x}N$



Coltrin *et al.*, JSST 6, S3114 (2017)

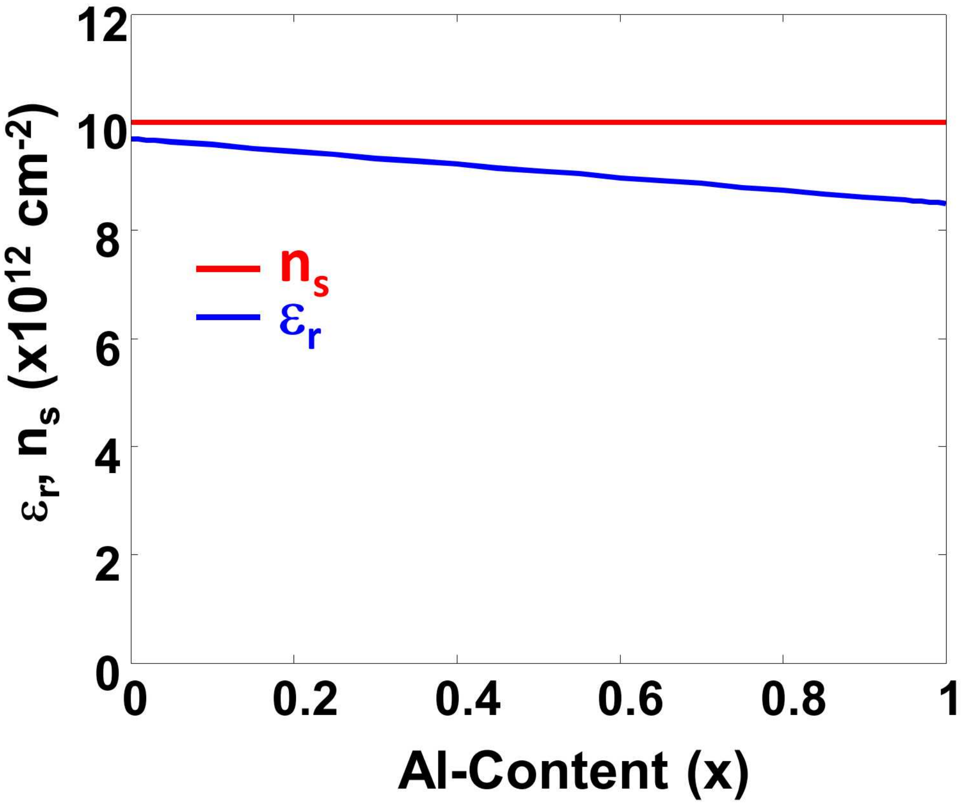


Based on Hudgins *et al.*, *IEEE Trans. Power El*. 18, 907 (2003)

Ternary alloy scattering considerably reduces the FOM for 0.1 < x < 0.9

E_C considerably increases the FOM for x > 0

Other FOM Parameters and Al Mole Fraction (x) in $Al_xGa_{1-x}N$



These parameters have a lesser dependence on Al-content

Figure of Merit Comparisons for Lateral and Vertical Devices

Basis for FOM: Conduction Loss: Greater voltage requires lower doping and longer drift region (double whammy)

Baliga FOM (Vertical)

$$\frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_{crit}^3$$

Lateral FOM

$$\frac{V_{br}^2}{R_{on,sp}} = q\mu n_s E_{crit}^2$$

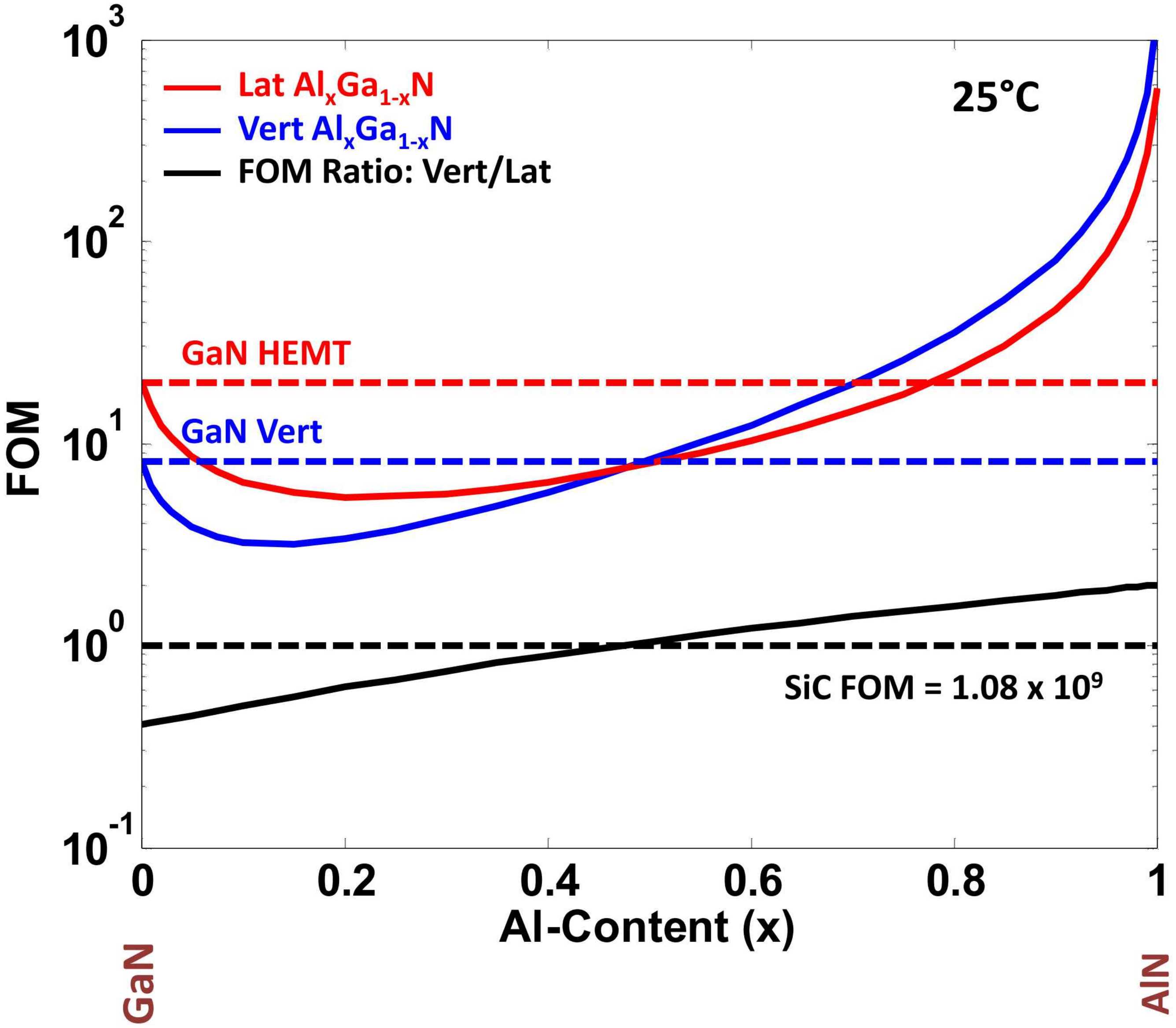
$\mu {E_C}^2$ *common factor which increases with x & with EG*

$\frac{1}{4}\varepsilon E_{crit}$ *compares to* qn_s

Common factor increases either FOM with E_G

Extra factor increases BFOM(E_G) more strongly than LFOM(E_G)

$Al_xGa_{1-x}N$ Lateral and Vertical Device FOM (Normalized to SiC)



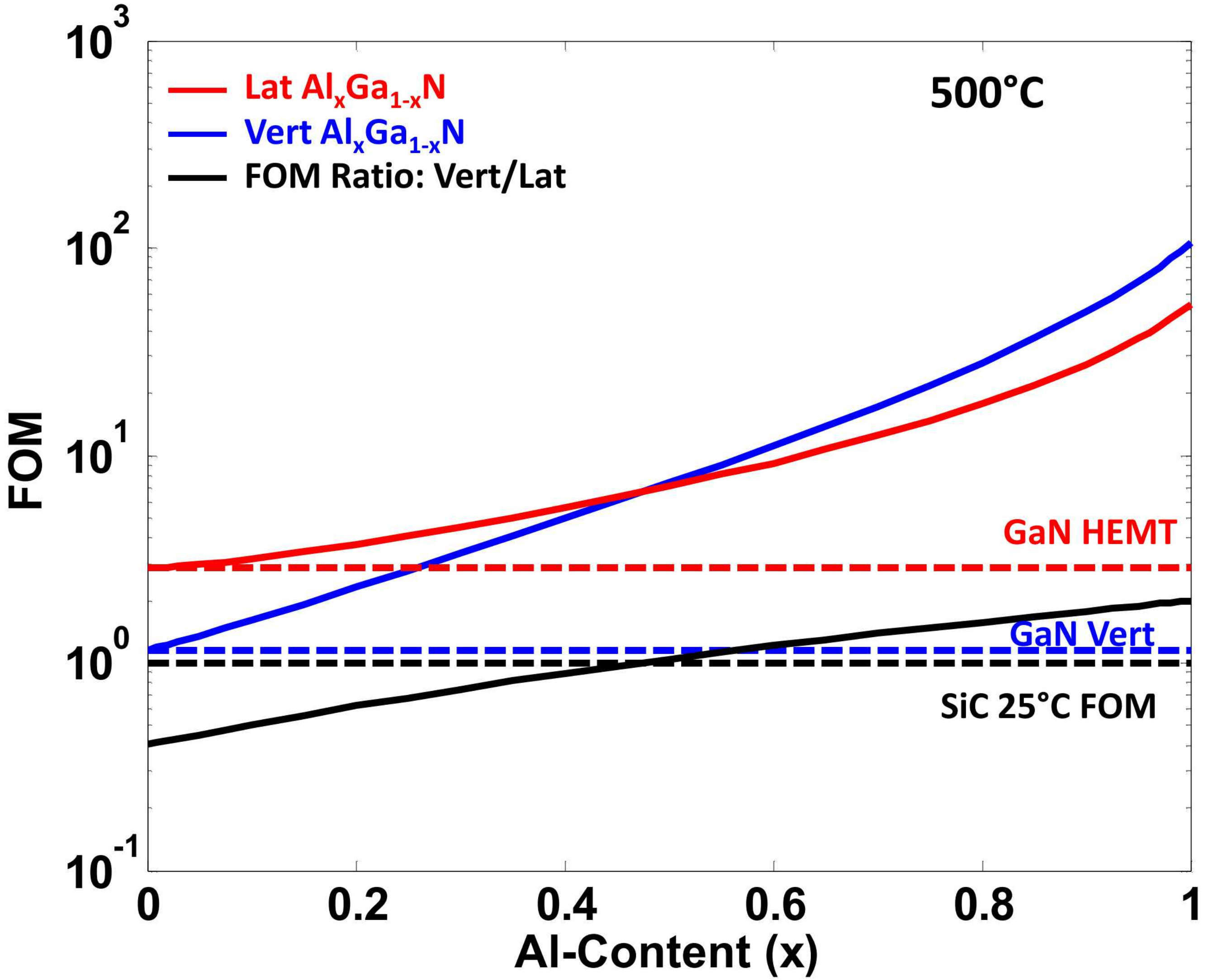
$Al_xGa_{1-x}N$ FOM payoff is greatest at high x (AlN)

FOM payoff increases with temperature

BUT …

Challenges increase exponentially with x, for both lateral & vertical devices

500°C $Al_xGa_{1-x}N$ Lateral and Vertical Device FOM (Normalized to SiC)



$Al_xGa_{1-x}N$ FOM has good payoff at all x for 500°C operation

BUT …

Challenges increase exponentially with T, for WBG and UWBG devices

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Conduction loss-based metrics for incumbent and emerging devices in power conversion
- Early History with depletion-mode transistors
- Recent demonstration of enhancement-mode transistors
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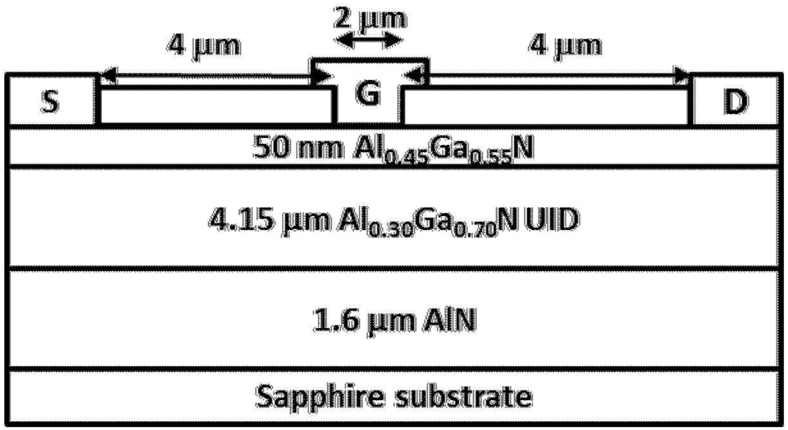
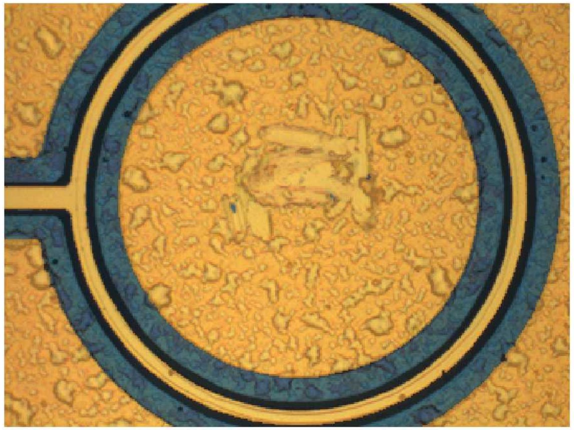
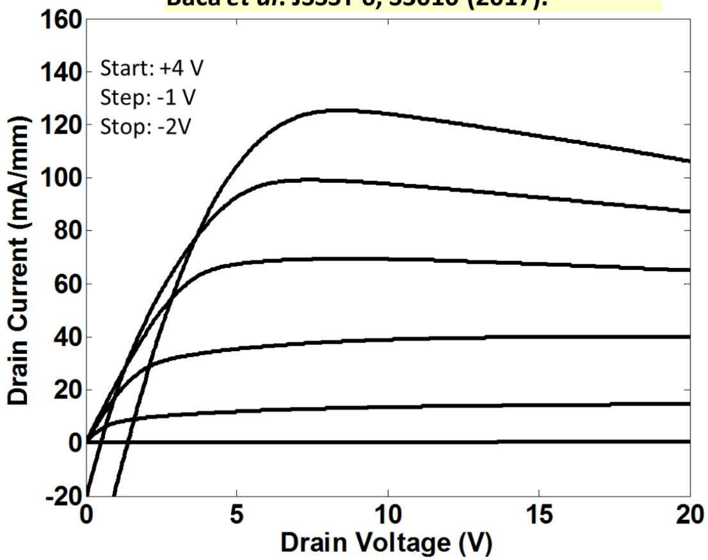
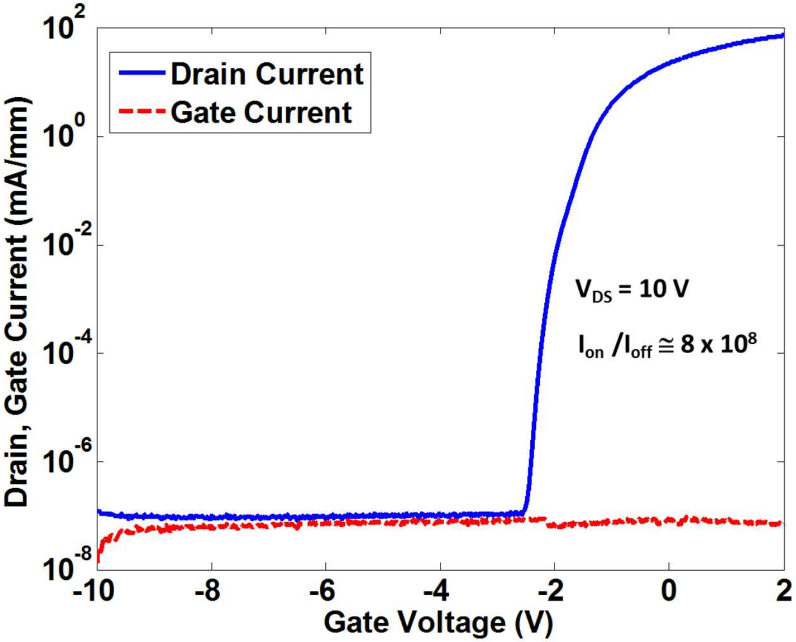
D-mode $Al_{0.45}Ga_{0.55}N$/ $Al_{0.3}Ga_{0.7}N$ "45/30" HEMT

Baca *et al*. JSSST 6, S3010 (2017).



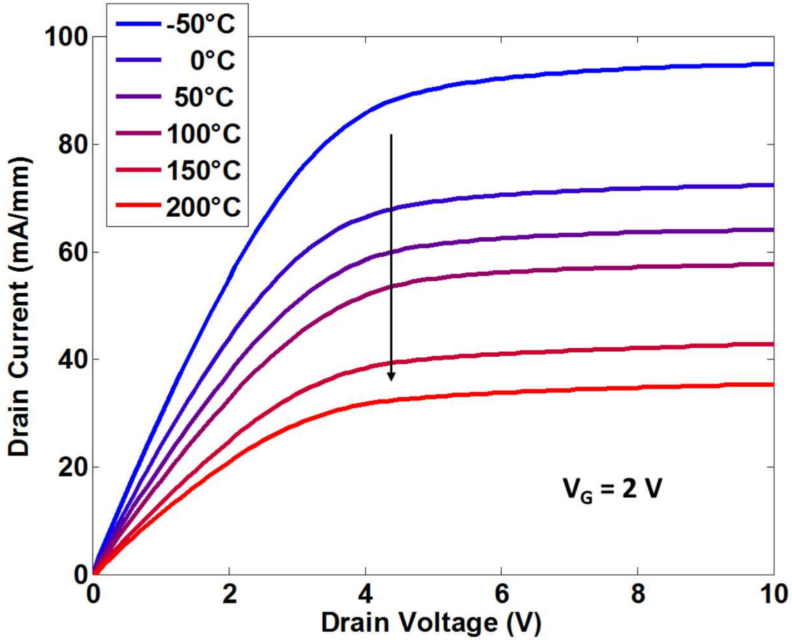




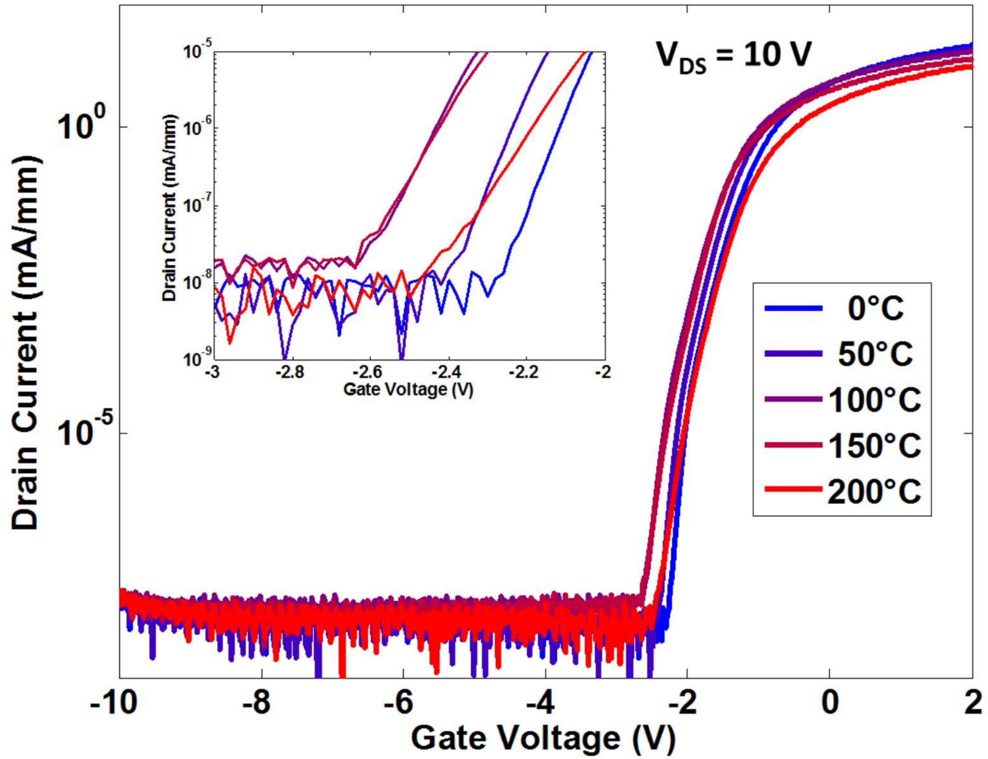


- *Linear through the origin I-V*
    - *due to ~2.5 x 10^{-5} Ω-cm^2 Ohmic contacts*
- *Exceptional I_{DMAX}/I_{DMIN} ratio (I_{ON}/I_{OFF}) of 8 x 10^8*
- *Very low gate leakage*

Temperature Dependence of "45/30" Transfer and Output Characteristics

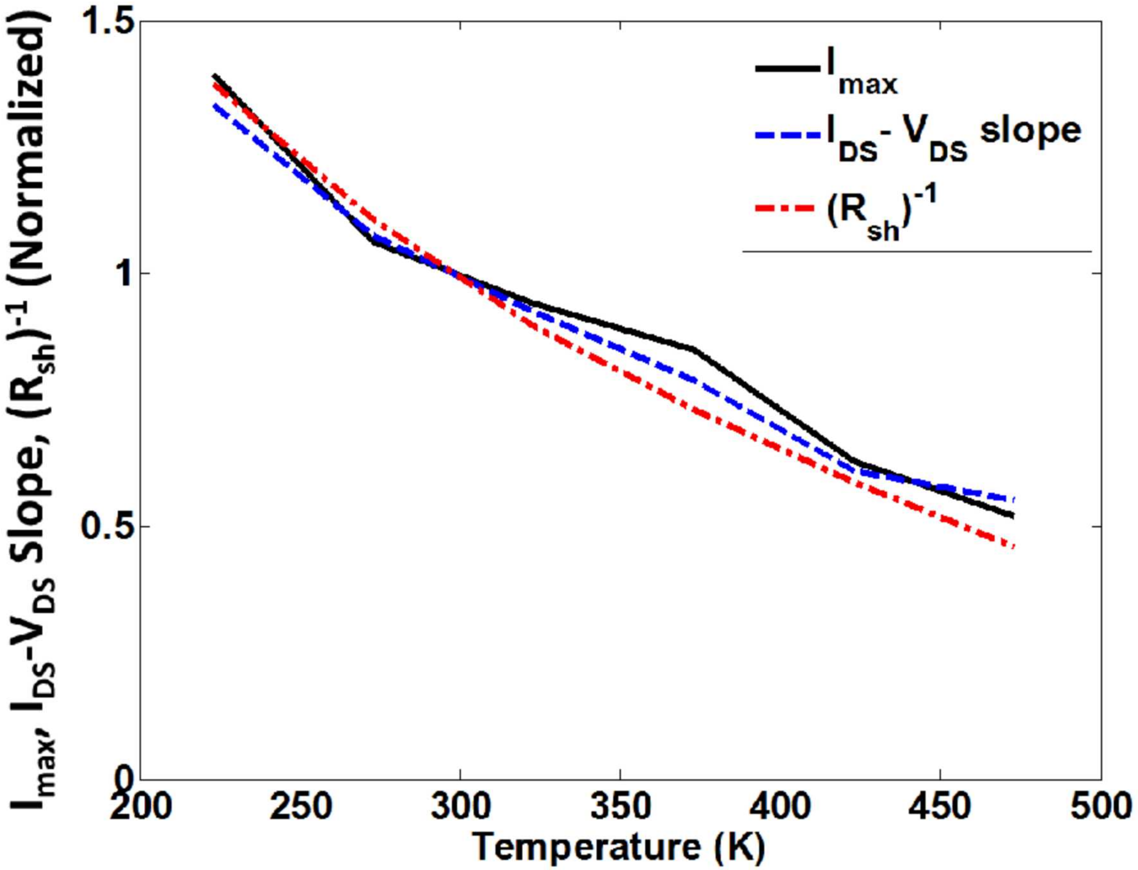


Baca *et al*. JSSST 6, S3010 (2017).



- ***Drain current decreases monotonically with temperature***
- ***Exceptionally low leakage current is invariant with temperature***
- ***Subthreshold slope varies slightly with temperature***

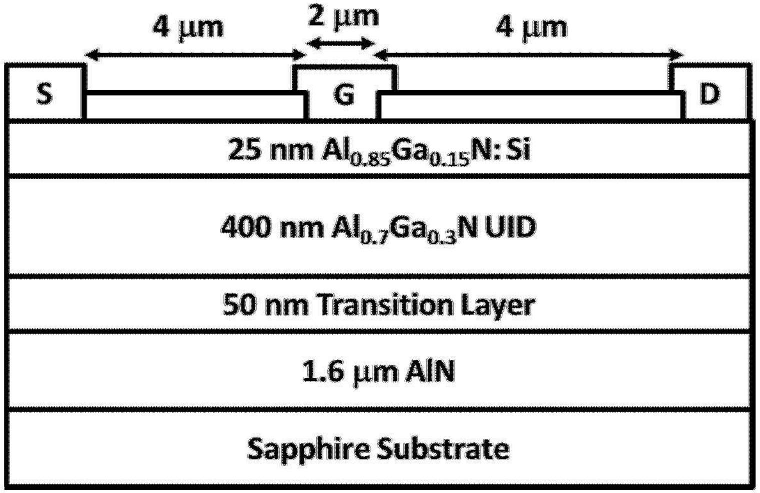
Temperature Dependence of "45/30" Imax Consistent with Mobility-Dominated Transport

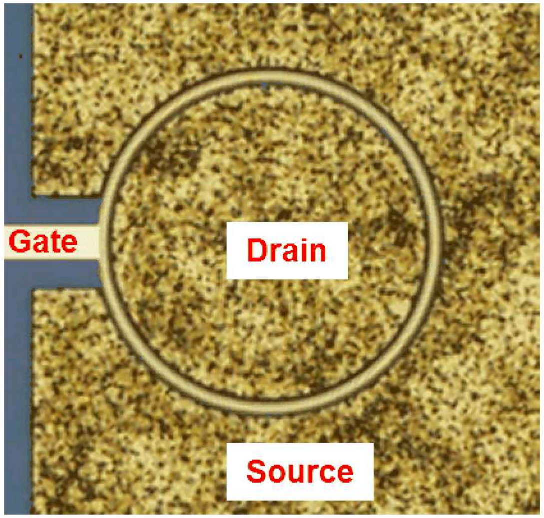


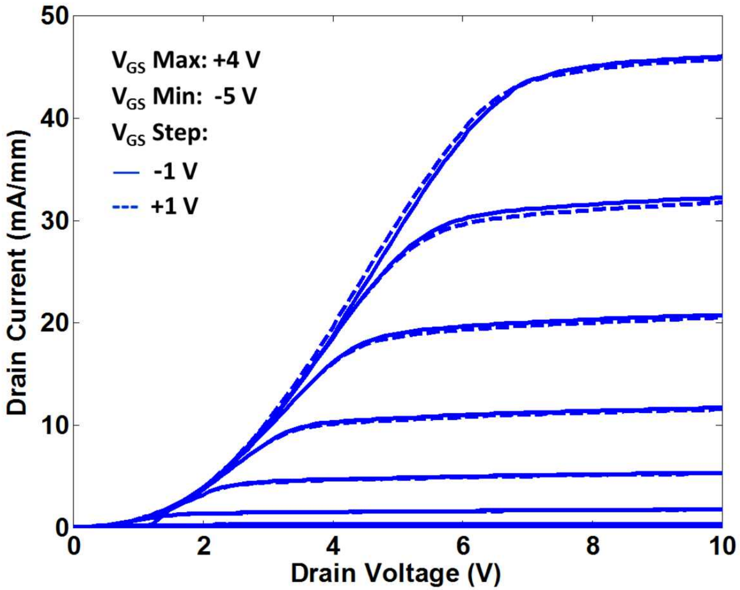
Baca *et al*. JSSST 6, S3010 (2017).

- ***I_{max}, I_{DS}-V_{DS} slope, and $(R_{sh})^{-1}$ all track with temperature – suggestive of electron mobility as the common factor***

D-mode $Al_{0.85}Ga_{0.15}N$/ $Al_{0.7}Ga_{0.3}N$ "85/70" HEMT



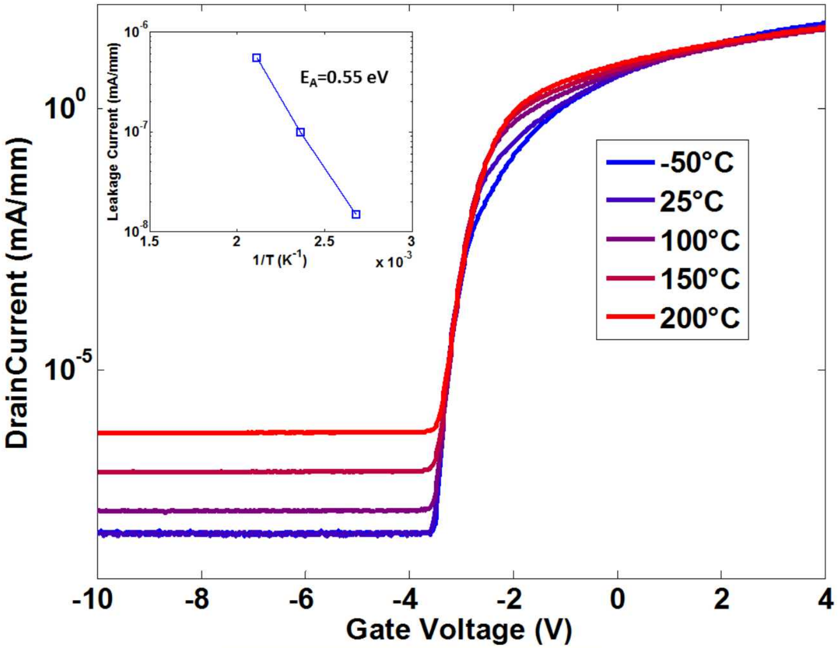




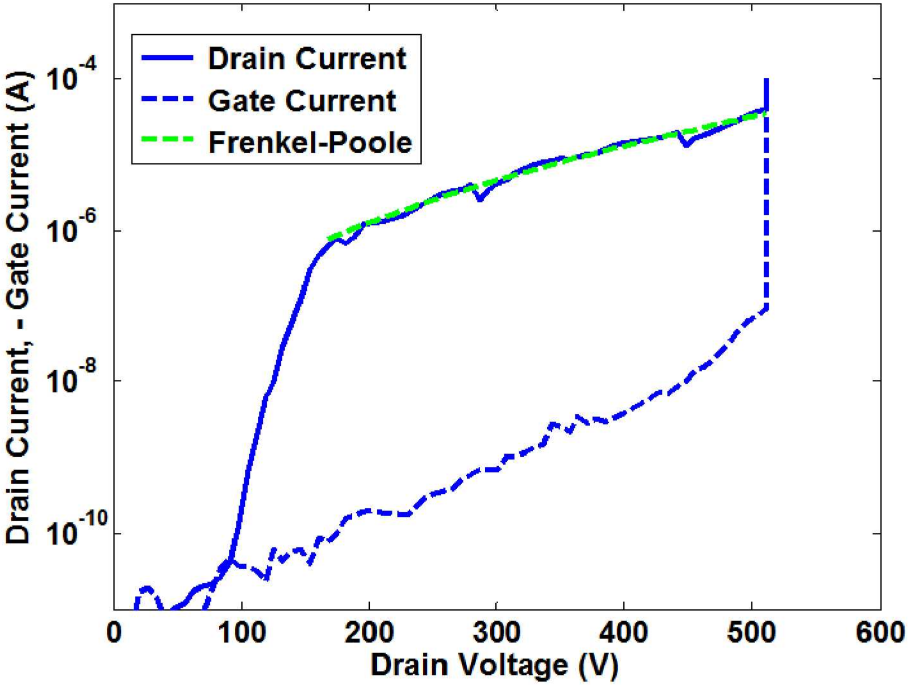
Baca *et al*. JSSST 6, Q161 (2017).

- ***Very little hysteresis***
- ***Difficulty of Ohmic contact formation leads to offset voltage and limitation of drain current potential (beyond mobility concerns)***

Exceptional Leakage Characteristics over Temperature in D-mode "85/70" HEMT

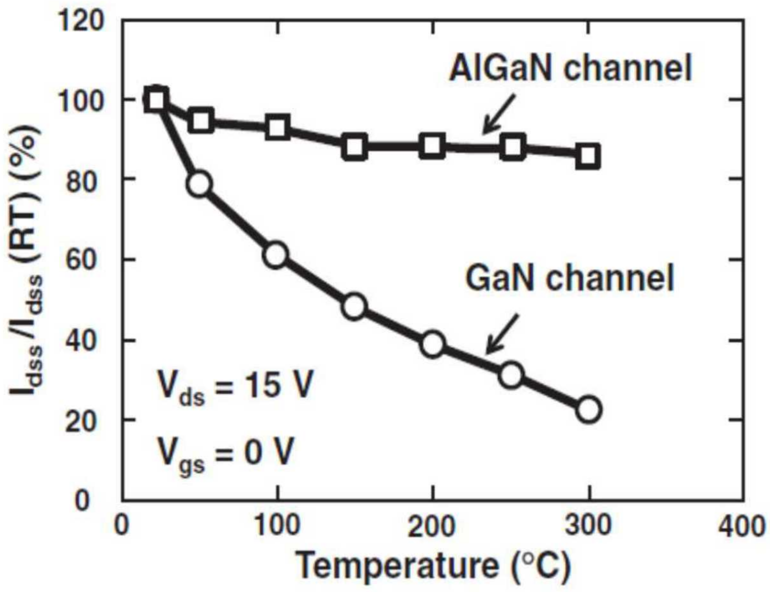


Baca *et al*. JSSST 6, Q161 (2017).



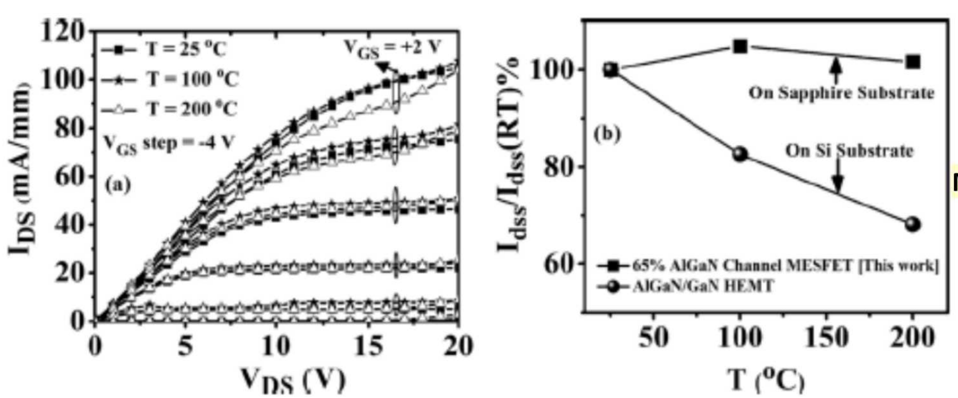
- ***Exceptional ratio I_{on}/I_{off} ratio of 8 x 10^9 at -50°C***
- ***Exceptionally low leakage current that increases with temperature and E_A = 0.55 eV***
- ***Breakdown voltage exceeds 500 V and drain leakage current is consistent with Frenkel-Poole conduction***

Modest I_D (T) Decline Observed by Outside Researchers



86/51 HEMT

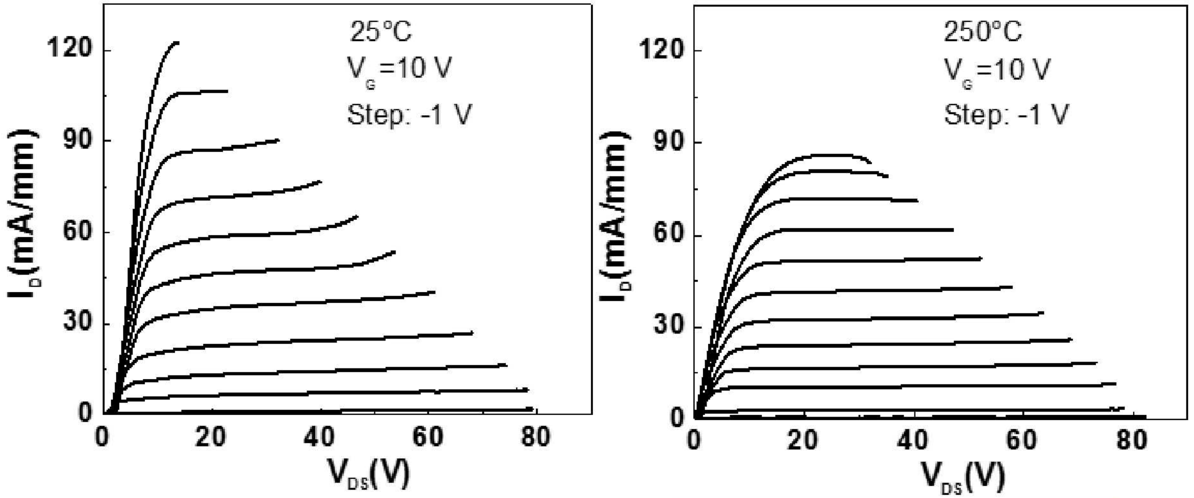
Tokuda *et al.*, *Appl. Phys. Exp.* 3, 121003 (2010)

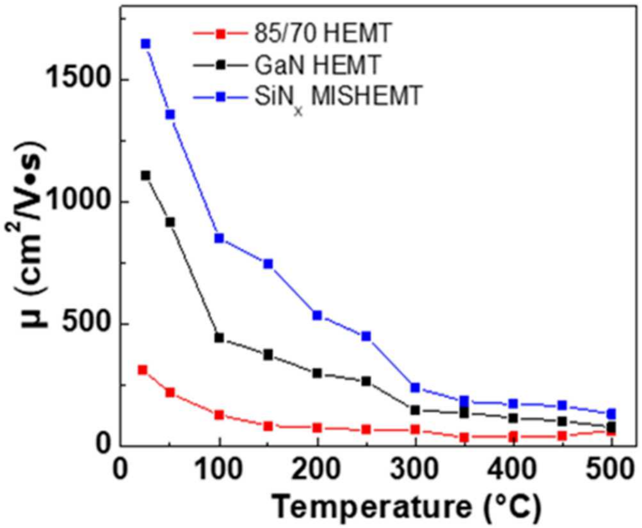


$Al_{0.65}Ga_{0.35}N$ MESFET

Muhtadi *et al.*, *Appl. Phys. Lett.* 110, 193501 (2017)

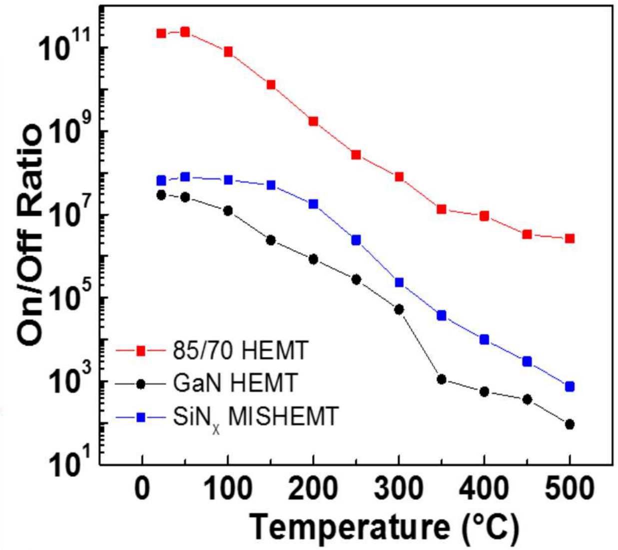
Trend of Modest I_D(T) decline extends to 500°C in "85/70" HEMT





UF/Sandia Collaboration:
Carey *et al.*, *IEEE JEDS* 7, 444 (2019).

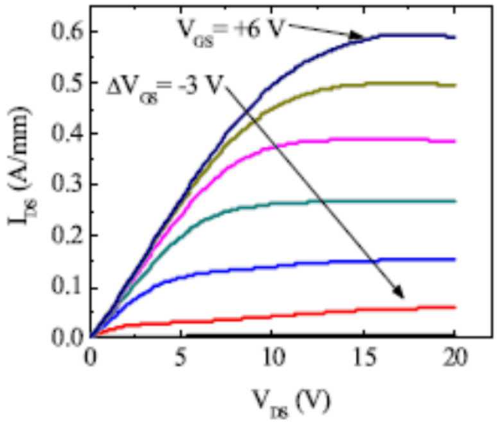
- ***I_D exceeds 120 mA/mm at 25°C***
- ***Retain excellent I_D and at over 50 mA/mm when operated at 500°C***
- ***Al-rich HEMT maintains excellent On/Off ratio at 500°C and GaN doesn't***
- ***I_{ON}/I_{OFF} extrapolation to 600-800°C looks fine for in 85/70 HEMTs, but untenable for AlGaN/GaN***



High Current Density D-mode HEMTs

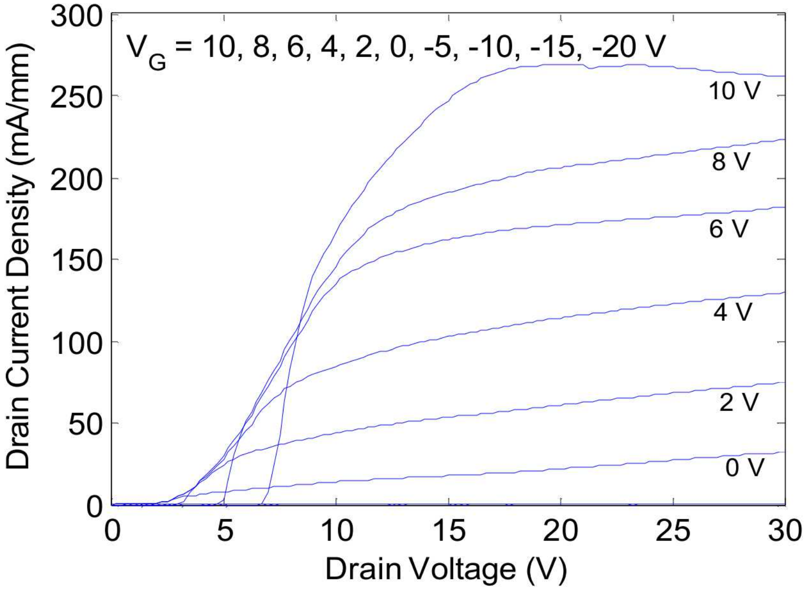
65/40 D-mode MOS-HEMT

Hu *et al*. EDL 39, 1568 (2018)



Long channel device, d-mode, larger n_s with very negative V_{TH}, and 600 mA/mm

85/70 D-mode HEMT, 90 nm gates



Slightly d-mode, > 250 mA/mm, higher electric fields with L_{SG} = 0.5 μm, L_{GD} = 2.0 μm

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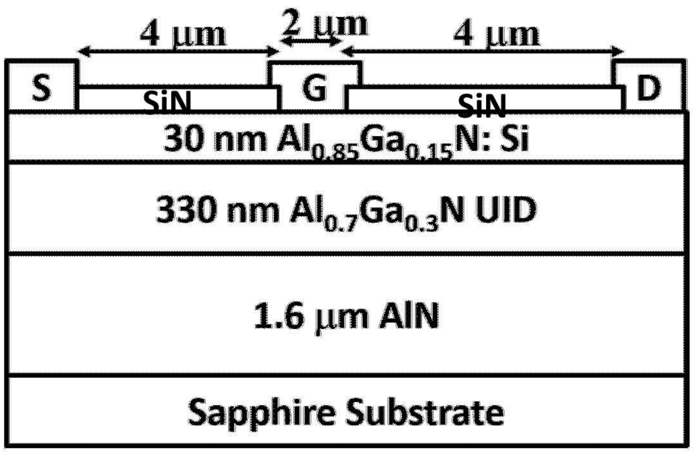
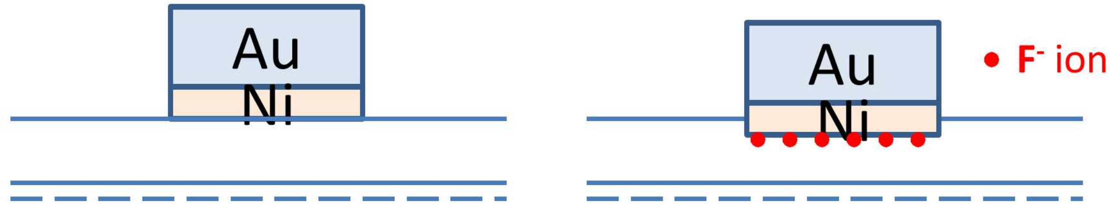
E-mode $Al_{0.7}Ga_{0.3}N$ using *F-Plasma* Treatment

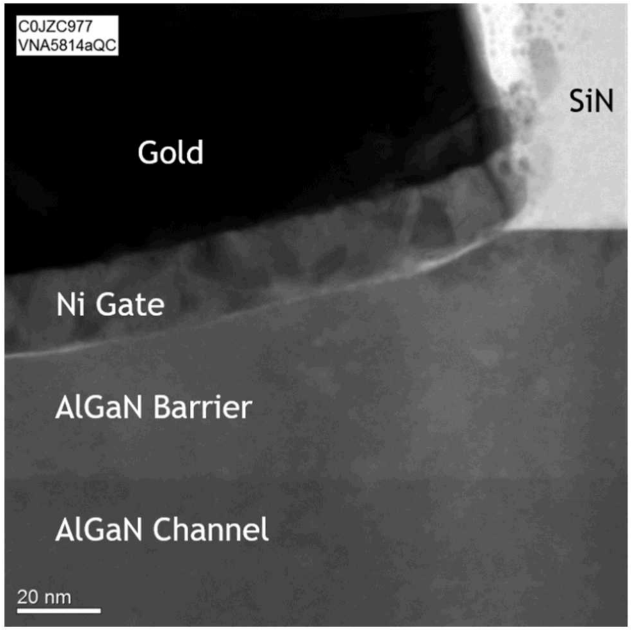


Motivated by Cai *et al.*, *IEEE Trans. El. Dev*. 53, 2223 (2006)



D-mode HEMT gate stack

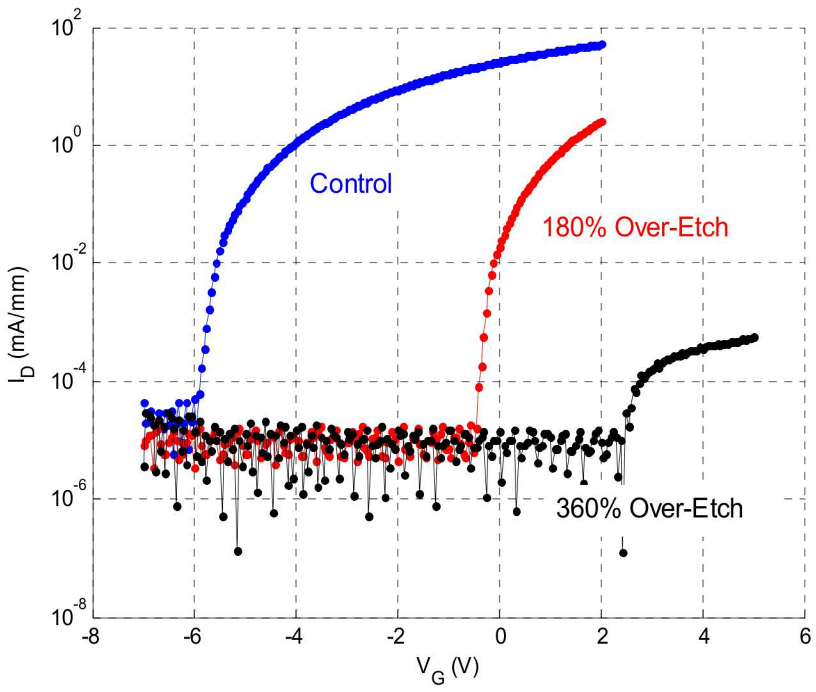
E-mode HEMT gate stack



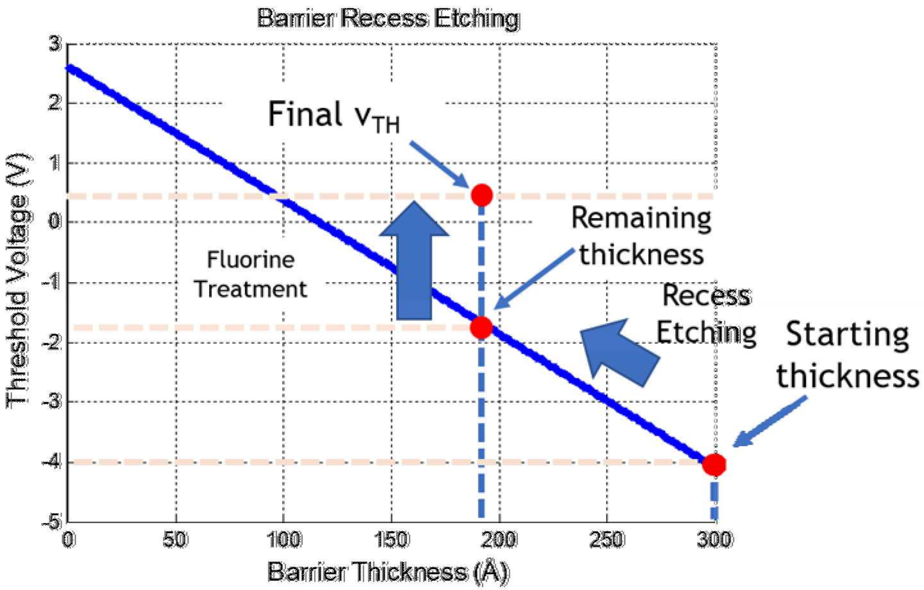
F-plasma from reactive ion etch (through SiN): combination of AlGaN etch and incorporation of *F^-* ions near the surface

E-mode $Al_{0.7}Ga_{0.3}N$ using *F-Plasma* Treatment

Klein *et al.*, *Appl. Phys. Lett.* 114, 112104 (2019)



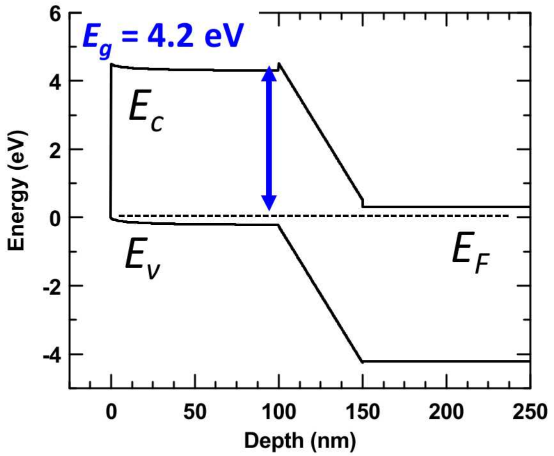
$$v_{TH} = \varphi_b - \frac{q\sigma_p t_{barrier}}{\varepsilon_r \varepsilon_0} - \Delta E_c$$



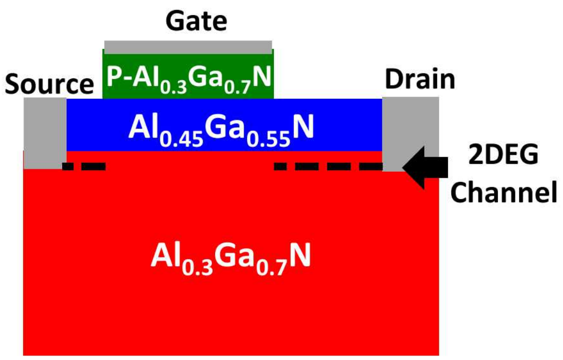
***F-plasma* from reactive ion etch (through SiN, then into AlGaN): combination of AlGaN etch and incorporation of *F^-* ions near the surface**

MIS-free E-mode AlGaN using *p*-type gate

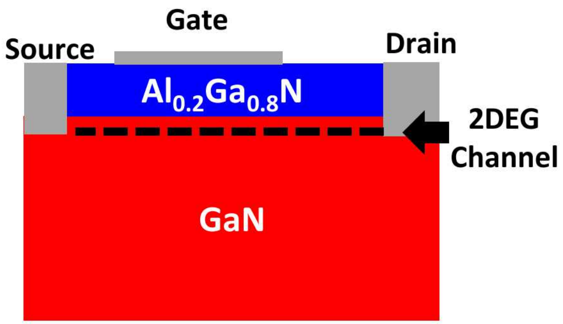
Douglas *et al.*, *J. Vac. Sci. Tech.* B37, 021208 (2019)



p-AlGaN under gate



Schottky gate



p-AlGaN under gate replaces Schottky barrier with AlGaN E_g

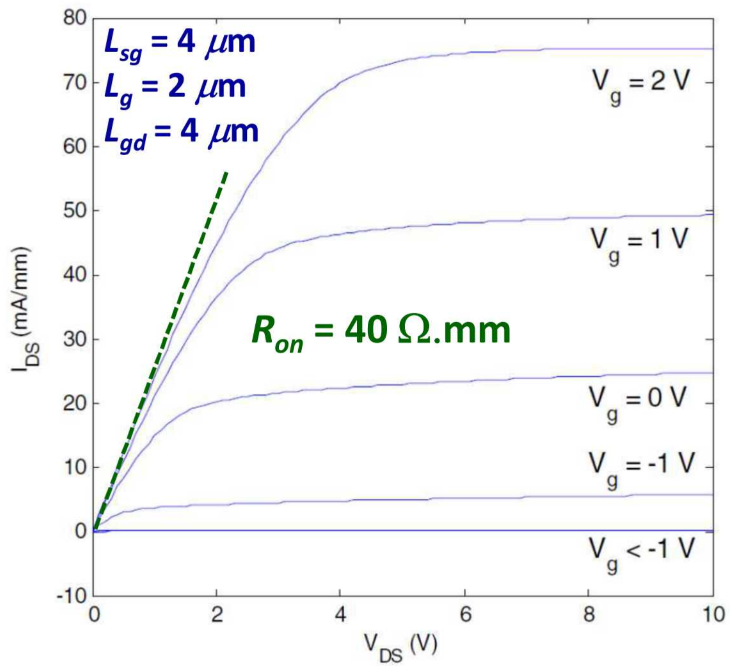
(Larger E_g enables more positive V_{th})

(Larger E_g enables larger positive V_G swing)

(MIS-free eliminates possible dielectric-induced reliability degradation)

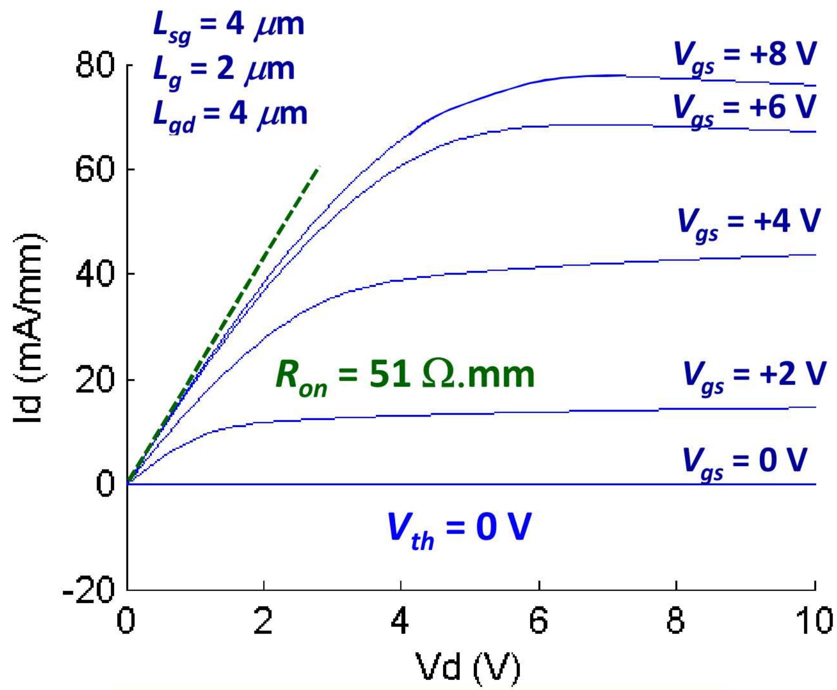
E-mode *p*-30/45/30 with high current density

I-V of D-mode 45/30 AlGaN HEMT



Klein *et al.*, *ECS JSSST* 6 S3067 (2017).

I-V of E-mode 30/45/30 AlGaN HEMT

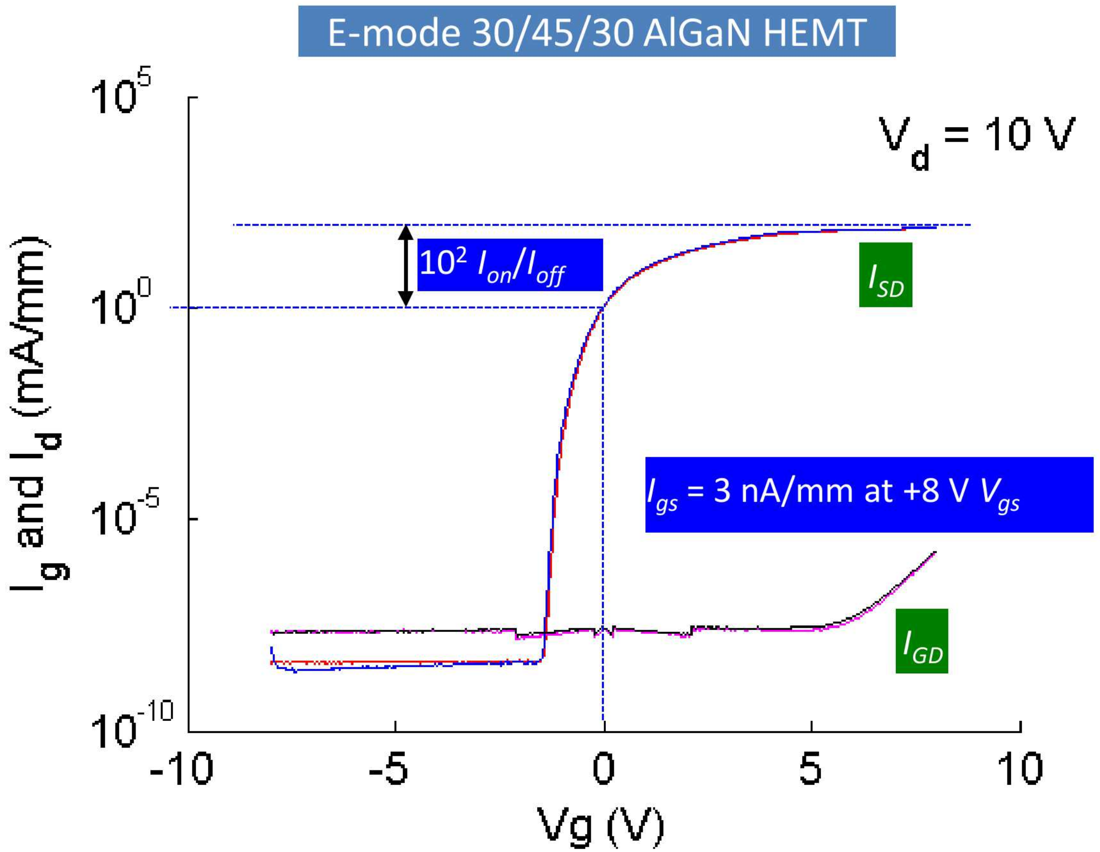


Douglas *et al.*, *J. Vac. Sci. Tech*. B37, 021208 (2019)

- V_{th} = 0 V
- Little to no degradation of $I_{DS,max}$ or $R_{on,sp}$ for E-mode *vs*. D-mode AlGaN HEMT due to Mg or etch

E-mode *p*-30/45/30 with excellent gate performance

Douglas *et al.*, *J. Vac. Sci. Tech*. B37, 021208 (2019)



- Small hysteresis (~ 80 mV)
- Vanishingly small gate current

Reliability

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- Conduction loss-based metrics for incumbent and emerging devices in power conversion
- Early History with depletion-mode transistors
- Demonstration of enhancement-mode transistors
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Generalized Reliability Issues in III-N Transistors

- Contacts
  - Ohmic, Schottky *contact degradation*
  - Interface stability
- *High Temperature Operating Life*: On-state stress, self-heating, hot electrons, capture emission effects
- *High temperature reverse bias*: off-state stress, high electric field stress, E_{Cx}, few hot electrons
- *Gate stress, forward bias*: donor and acceptor-like barrier traps, dielectric traps (for gate insulators)
- *Gate stress, reverse bias*: donor and acceptor-like barrier traps, dielectric traps (for gate insulators), high electric field stress, E_{Cz}

Early Development Cycle Reliability Issues in III-N Transistors

- Suitability of Reliability studies early in a development cycle
  - Can influence the development as one of the metrics
  - There may not be customer requirements defined
  - May not be suitable if the technology is rapidly changing
- Have you accounted for capture/emission effects?
  - If not, then you can't distinguish between permanent and reversible degradation
- Do you have a targeted question regarding a reliability or degradation topic?
  - If yes, then a targeted stress experiment may be appropriate

Reliability Issues in III-N Transistors II

- Suitability of Reliability studies early in a development cycle
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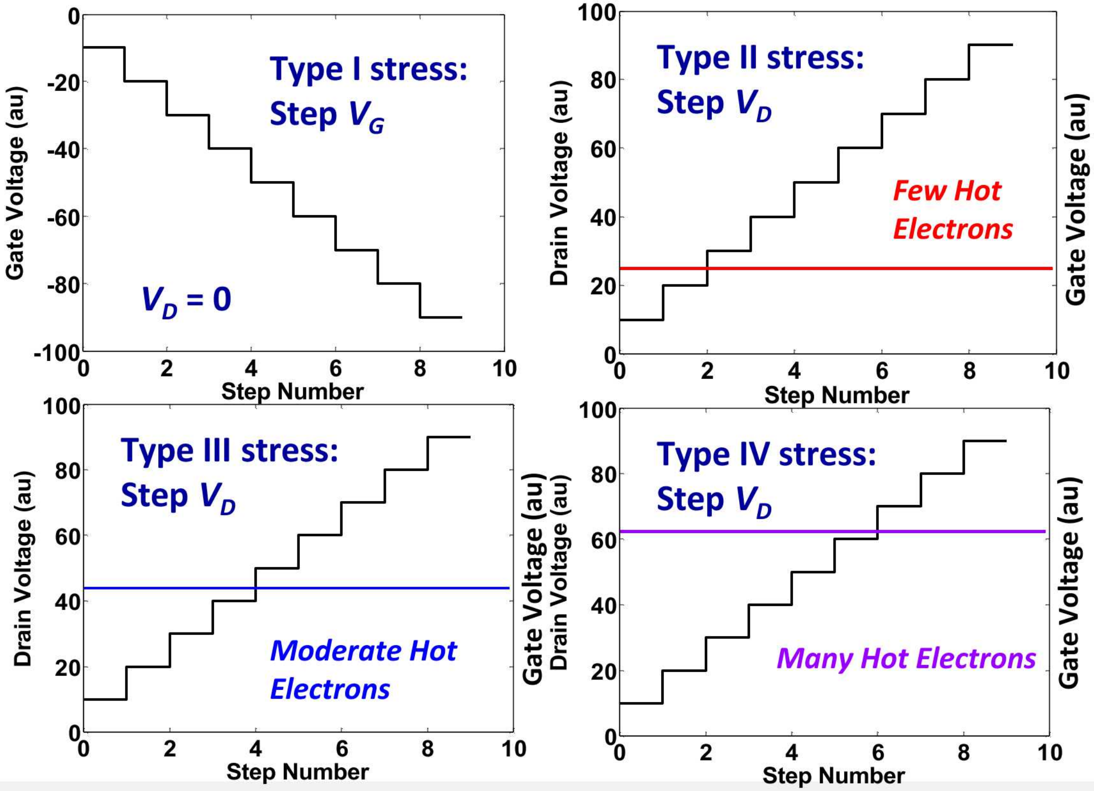
Is there value in an exploratory step-stress study?

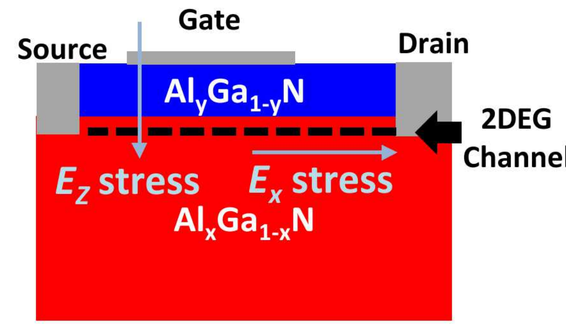
AND …

Can we learn something about Fluorine stability in Al-rich HEMTs?

Exploratory Step-Stress: Is There a Most Severe Type of Stress?

Step-Stress Experiments





From AlGaN/GaN experience:

- Dominant Type I stress: E_Z degradation may cause cracks in $Al_yGa_{1-y}N$ barrier
- Dominant Type II stress: numerous hot electron degradation
- Dominant Type III stress may distinguish between hot electron degradation and other types of E_X degradation
- Dominant Type IV stress may highlight E_X degradation effects

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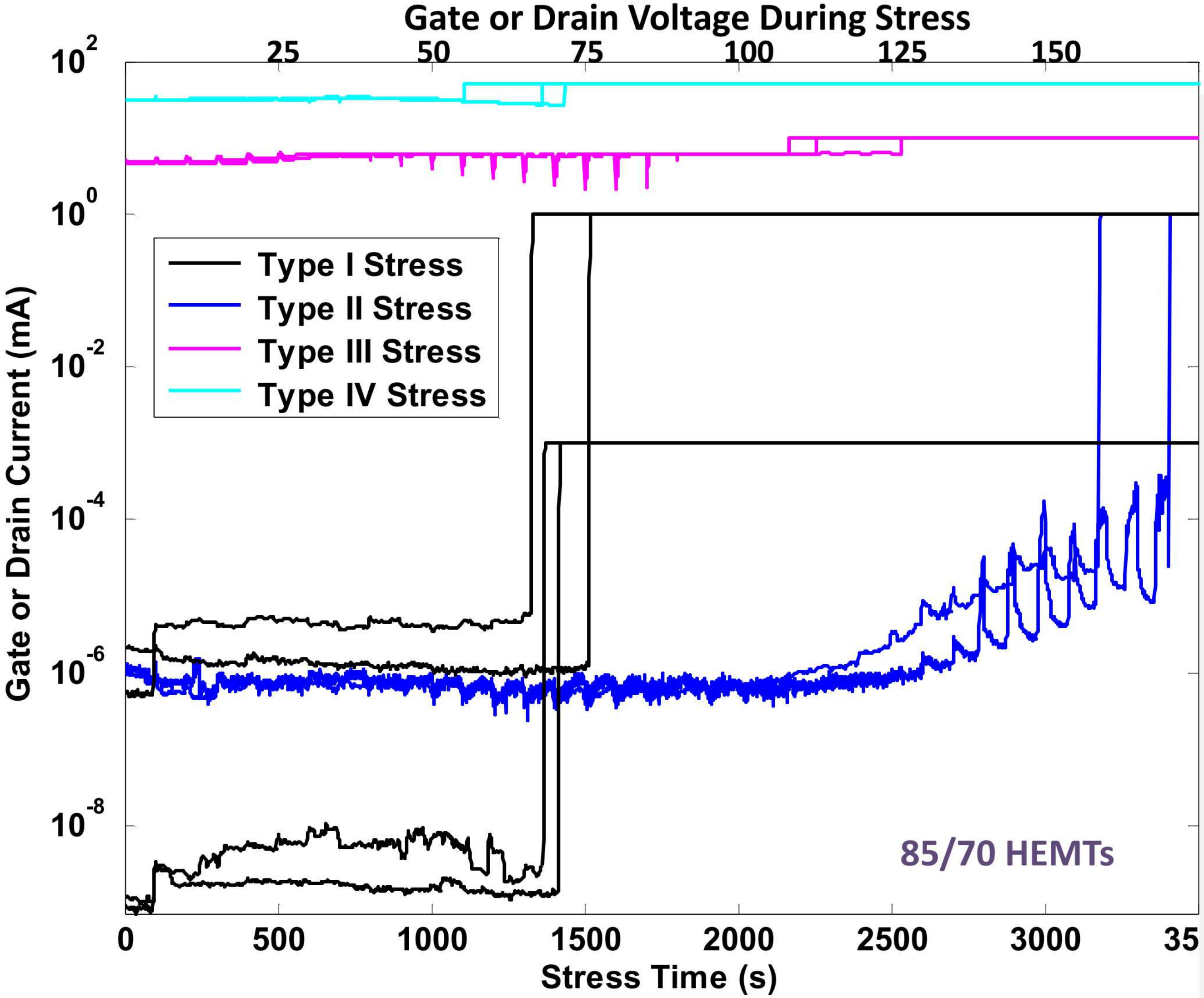
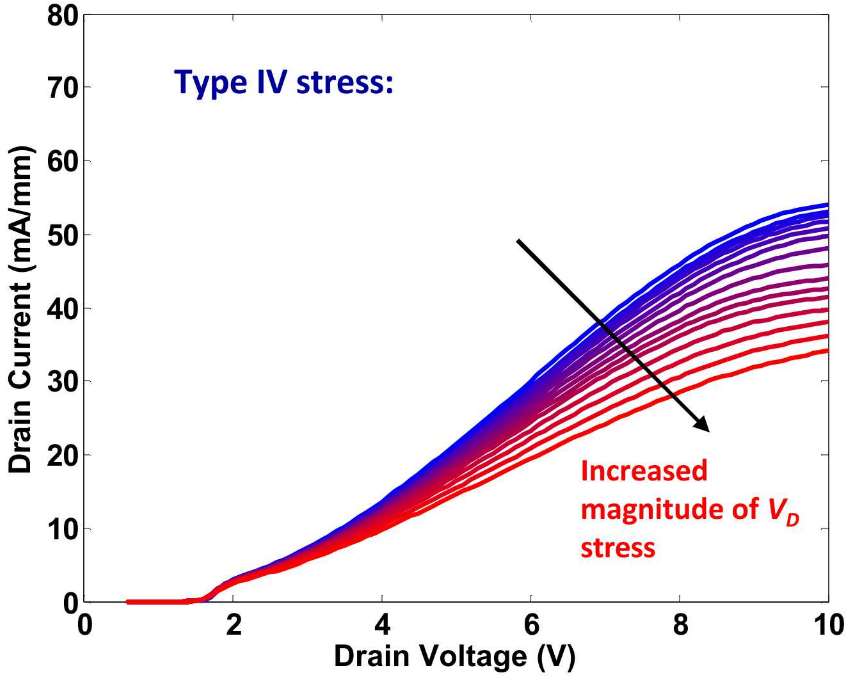
Multiple HEMTs Stressed with Types I, II, III, IV Stress

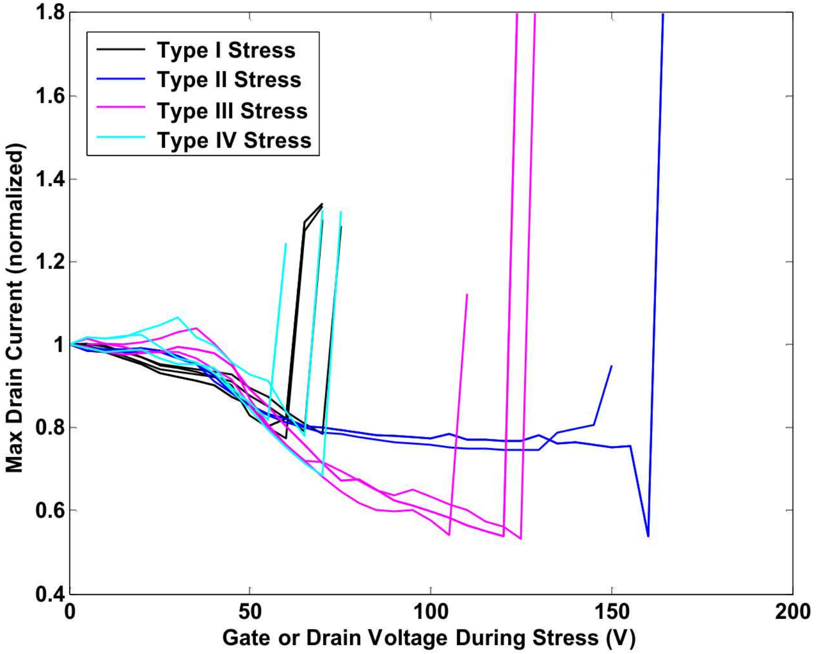


Step-Stress Experiments:

- Tested to destruction
- 100 s time window
- Interrupted the stress for electrical characterization
- Identify interesting bias points for subsequent experiments
- Hot electron stress can be very severe
- Temporal character is interesting
- Leakage current trend gets interesting as you approach destructive voltage

Stress Interruptions of 85/70 HEMTs with Types I, II, III, IV Stress

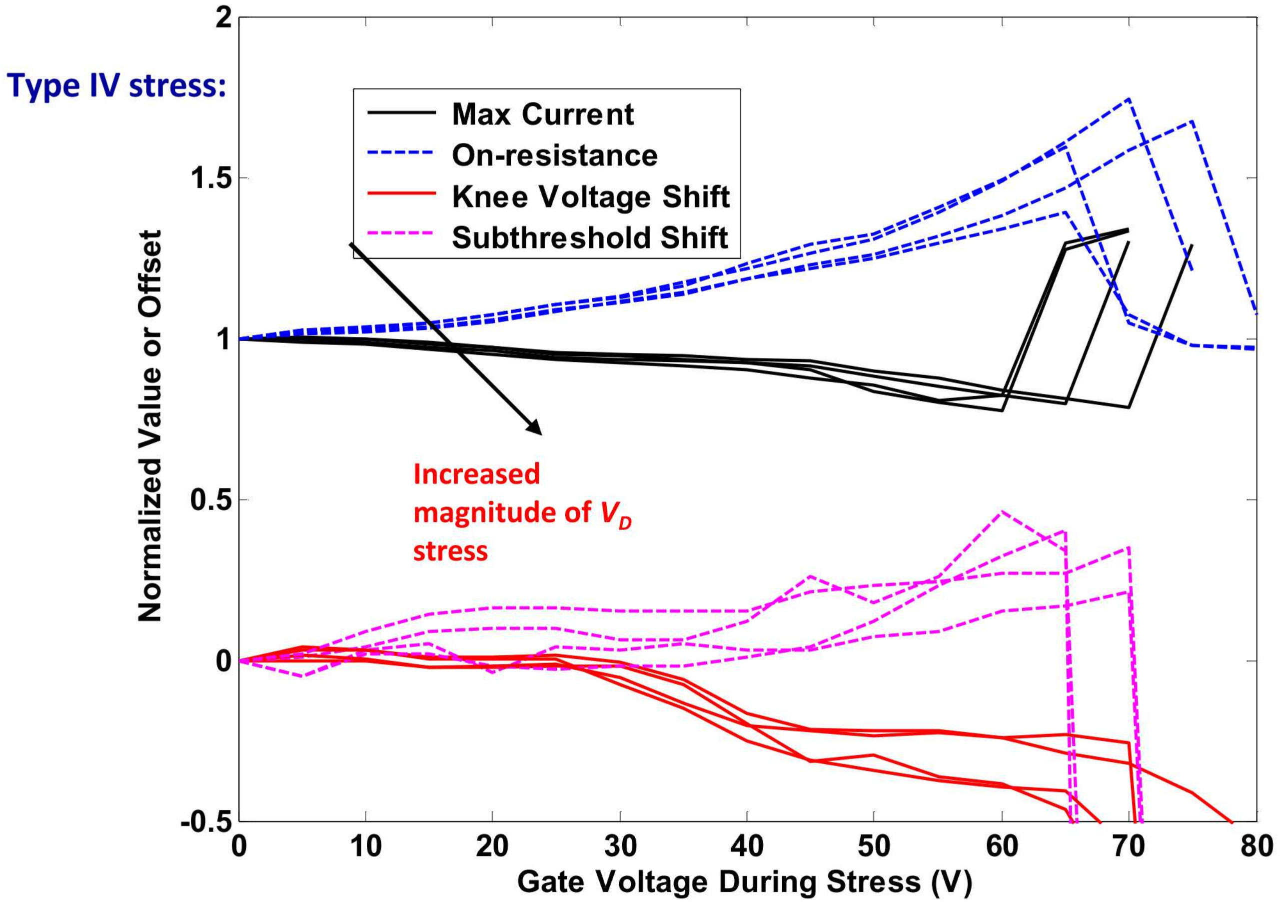




Observations from these Step-Stress Experiments:

- I_{MAX} decreases with V_D stress
- Types III, IV stress are the apparently the worst
  - Must account for reversible degradation

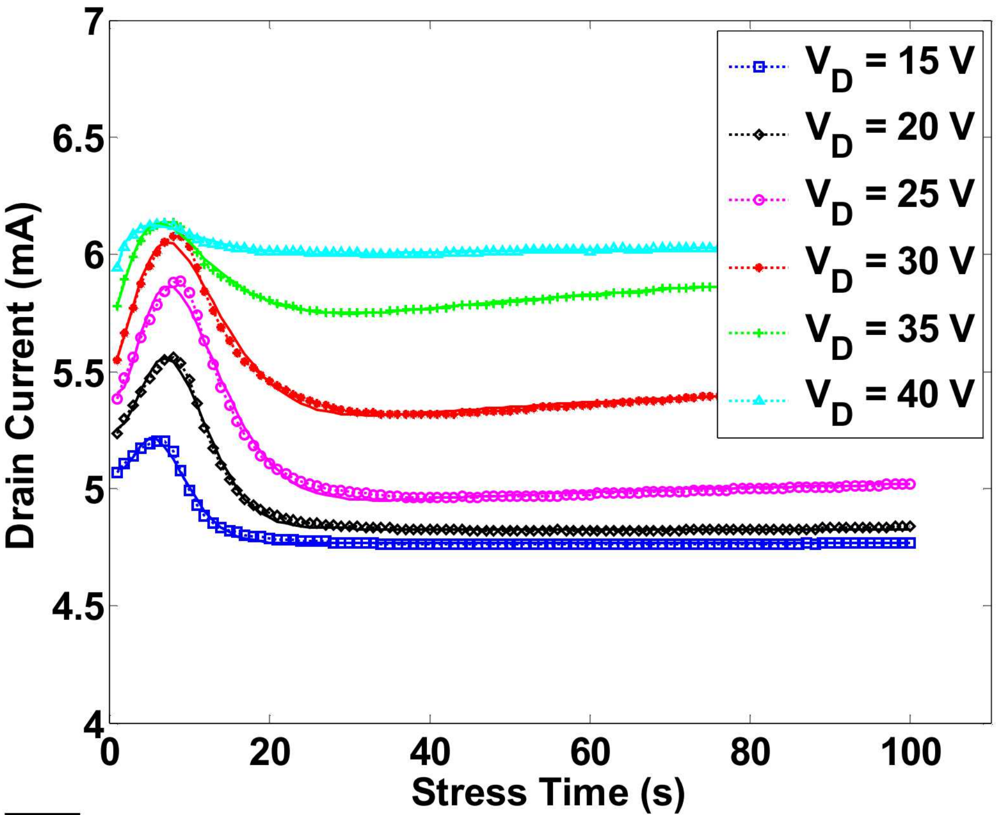
Example of 85/70 HEMT Stress Interruptions with Type IV Stress



<u>Observations from 85/70 HEMTs with Type IV Step-Stress Experiments</u>:

- I_{MAX} decreases with V_D stress, correlates with R_{ON} decrease
- Subthreshold shift increases with V_D stress
- Knee voltage stable up to 30 V stress, then shifts negative

Capture/Emission Effects Need Better Understanding



$$I = I_o + \sum A_i e^{-(t/tau)^{\beta}}$$

"Stretched" exponential, after Bisi *et al*.
***IEEE Tr. Electr. Dev.* 62, 3166 (2013)**

- **Data are symbols**
- **Lines fit to the stretched exponential**
- **100 s stress window from step-stress experiments**
- **Fitted parameters are dependent on electric field**
- **Observe both emission and capture processes which confound the experiment**
- **One solution is to run long experiments**

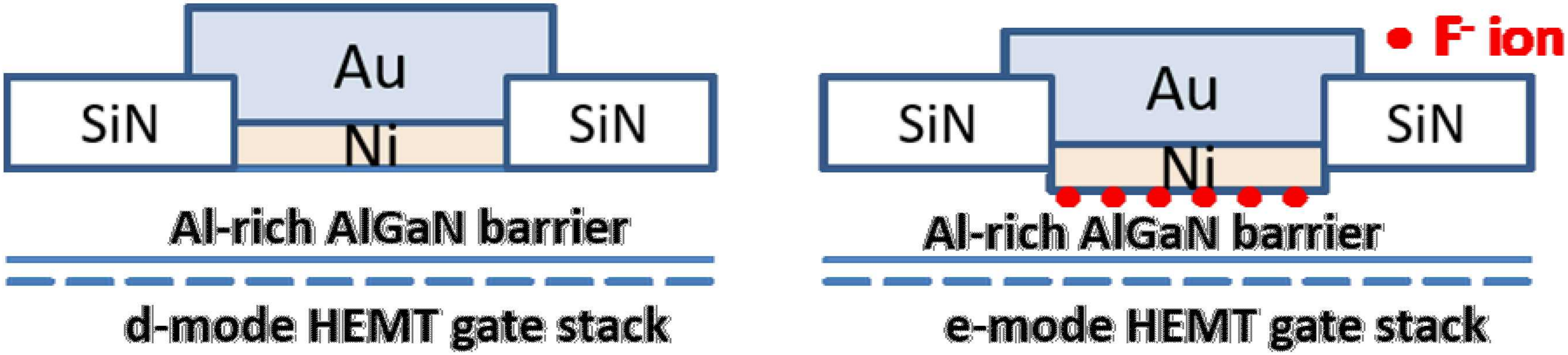
20% changes within 20 s!

Need to let the data "settle"

ALL CONCLUSIONS ARE TENTATIVE until the capture and emission effects are better understood

"Stretched" exponential, after Bisi *et al*. *IEEE Tr. ED* **62**, 3166 (2013)

Can We Learn Something about Flourine Stability in Al-rich HEMTs?



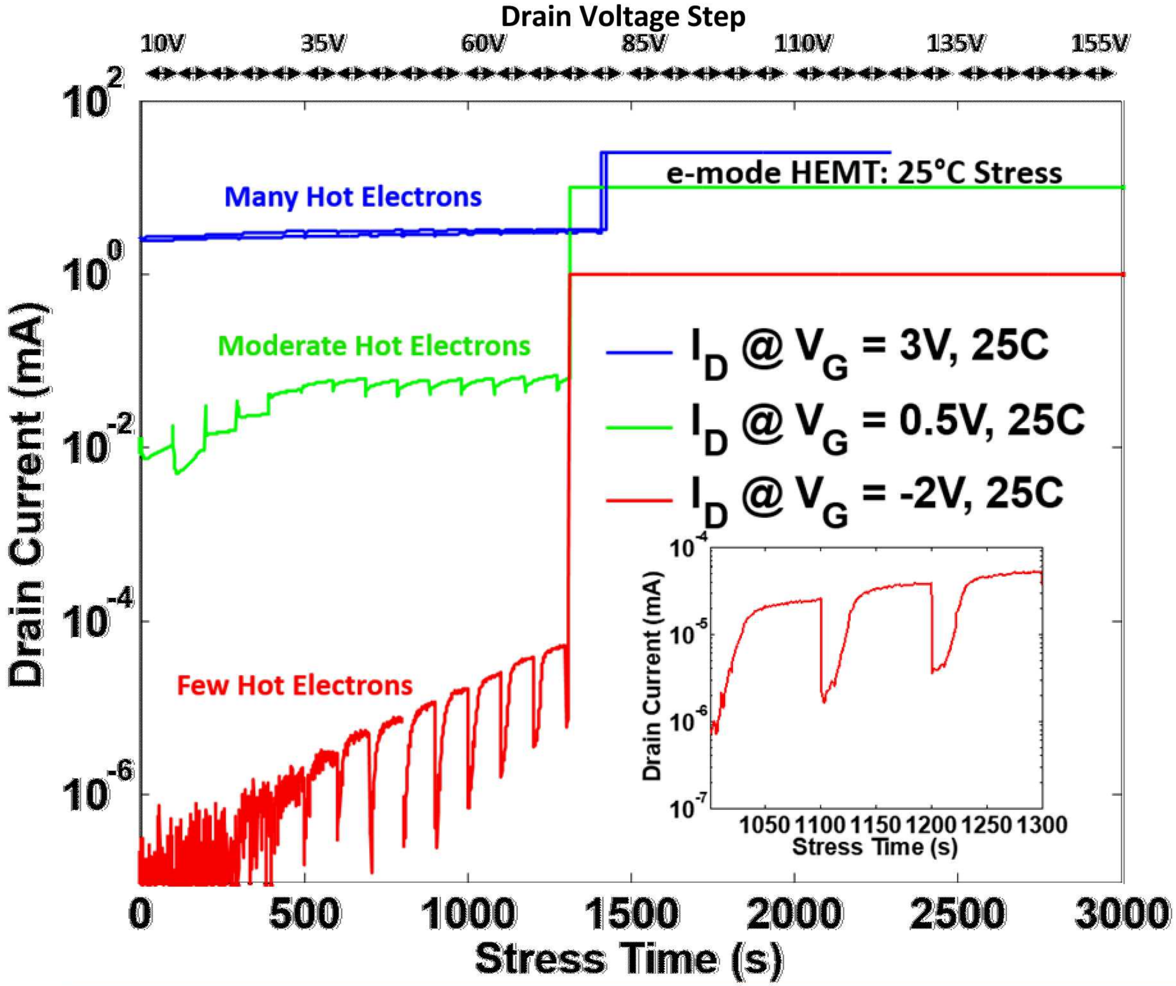
- F-treatment in AlGaN/GaN HEMTs produces e-mode transistors, yet questions about its stability/reliability persist, Cai *et al.*, IEEE Trans. El. Dev. **53**, 2223 (2006)
- If $\mathbf{F^-}$ is mobile, V_{TH} can shift considerably

- $\mathbf{F^-}$ ion stability is interesting in Al-rich transistors due to greater negative enthalpy of formation for AlF_3 (-1504* kJ/mol) compared to GaF_3 (-1163* kJ/mol)

******Inorganic Compounds: Physical and Thermochemical Data***

http://www2.ucdsb.on.ca/tiss/stretton/database/inorganic_thermo.htm

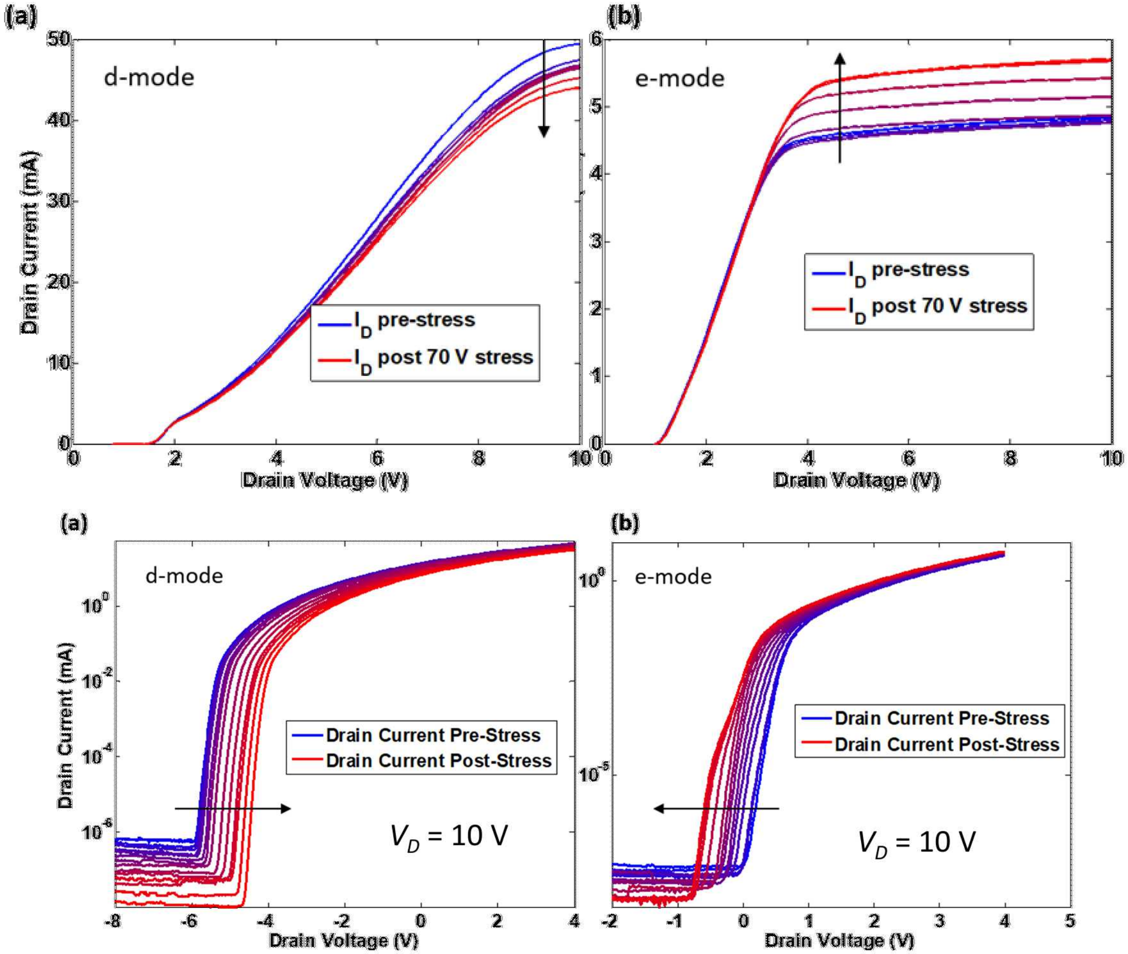
Drain current evolution for 3-types of e-mode HEMT stress experiments



Baca *et al.*, *IRPS* (2019)

- Drain current transients evident within the 100 s stress windows - reversible
- Destructive voltage similar for different V_G stress conditions
  - Hot electrons: minor role in degradation?

Evolution of e-mode 25°C output transfer and characteristics (at stress interruptions)

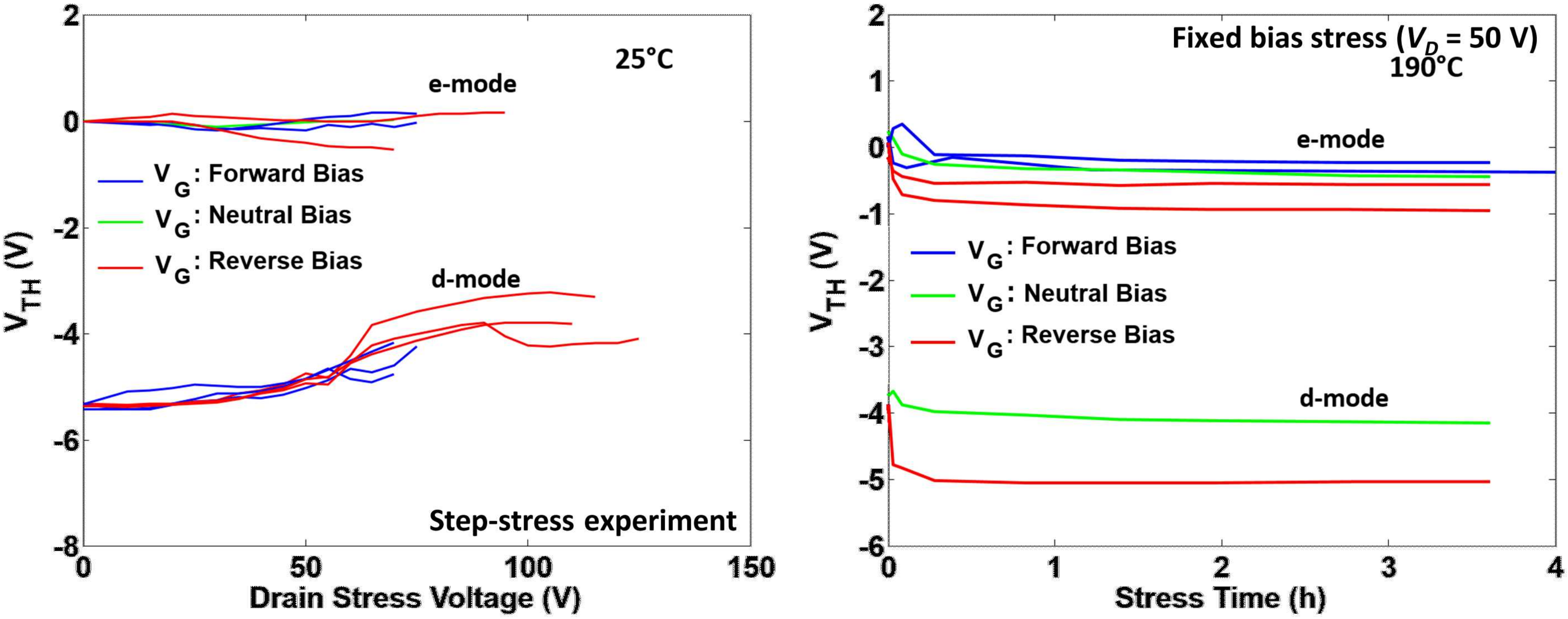


Baca *et al.*, *IRPS* (2019)

- d-mode: Stress @ V_G=-10V, step V_D
- Slight R_{ON} effect
- Larger V_{TH} effect: transient?

- e-mode: Stress @ V_G=-2V, step V_D
- Negligible R_{ON} effect
- Considerable V_{TH} effect – not fully understood

V_{TH} Trends with V_D Stress



Baca *et al.*, *IRPS* (2019)

- V_{TH} - V_D trends considerable but transient

- Constant V_D stress = 50 V: initial V_{TH} shifts
- Stabilize after 0.25 h

Takeaway:
- V_{TH} shifts affect both d- and e-mode HEMTs (common factor) undergoing reverse bias V_G stress; stabilizes in 0.3 h
- Evidence that F^- ions are stable in $Al_{0.85}Ga_{0.15}N$

Summary

- FOM analysis favors AlGaN, expecially at high temperature
- Demonstrated 500°C operation of an 85/70 HEMT with 16x improvement in FOM over GaN
- Current density exceeds 500 mA/mm with aggressive dimensions and improvements to Ohmic contacts
- Demonstrated Al-rich enhancement-mode HEMT with F-plasma treatment
- Demonstrated AlGaN-channel enhancement-mode HEMT with p^+ gate (45/30) HEMT
- Used step-stress experiments to narrow the focus of targeted reliability studies
- Showed evidence of F-Stability in 85/70 e-mode HEMT