SAND2018-11013C

Power Electronics Devices based on Al-rich Aluminum Gallium Nitride

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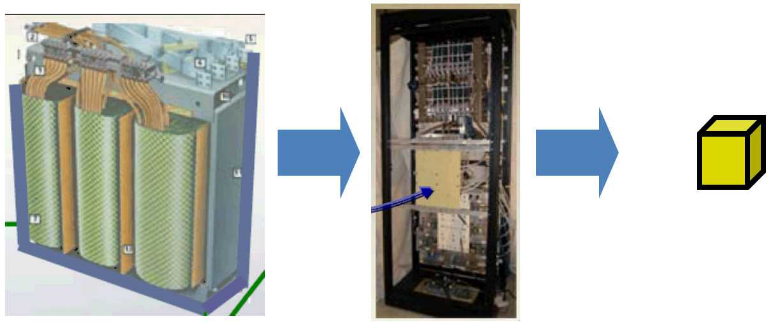
Outline

- 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
- Recent demonstration of enhancement-mode transistors
- Challenges for Al-rich AlGaN transistors
- Summary

UWBG semiconductors for Power Electronics

Silicon	SiC	UWBG



Silicon	SiC	UWBG
• 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

Figure of Merit Differs 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

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

$$\frac{1}{4}\varepsilon E_{crit} \text{ compares to } q n_s$$

For comparisons between Vertical & Lateral devices, n_s may somewhat offset E_{crit}

Numerical Comparison of GaN Lateral and Vertical Devices

Baliga FOM (Vertical):

$\varepsilon_o\ \varepsilon_r$ = (8.85 x 10^{-14})*(9) F/cm

μ = 1500 cm^2/Vs

Lateral FOM:

μ = 1500 cm^2/Vs

n_s = 1 x 10^{13} cm^{-2}

Both:

E_{crit} = 4 x 10^6 V/cm

$$\frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_{crit}^3 = 2 \times 10^{10}$$

$$\frac{V_{br}^2}{R_{on,sp}} = q\mu n_s E_{crit}^2 = 3.8 \times 10^{10}$$

Numerically similar in spite of extra E_{crit} factor

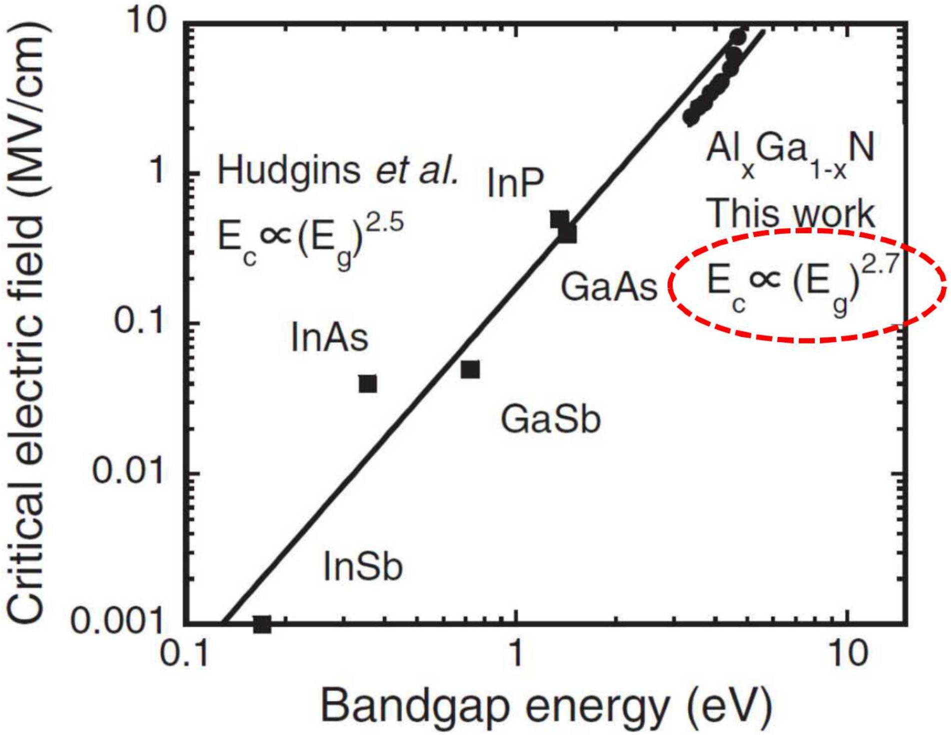
Future plots will only include (Al)GaN LFOM

Critical Electrical field scales *dramatically* with band gap

Band gap energy (E_g) is a critical material property for power electronics

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

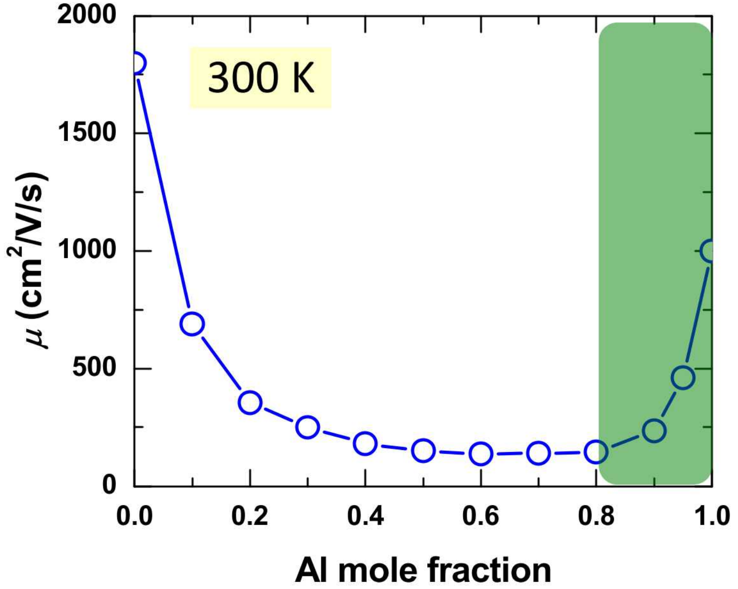
Material	E_{crit} (MV/cm)
Si	0.3
SiC	3.4
GaN	4.0
$Al_{0.3}Ga_{0.7}N$	7.3
β-Ga_2O_3	8
$Al_{0.7}Ga_{0.3}N$	12.7
AlN	17



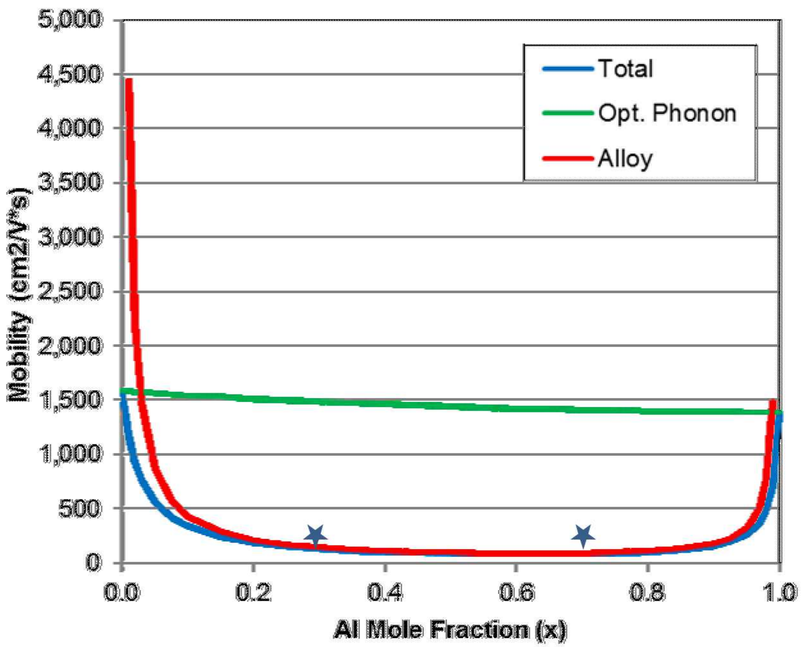
Nishikawa, *et al.*, JJAP 46, 2316 (2007).

AlGaN Alloy Mobilities are Smaller than Binary Alloys

AlGaN HEMT channel mobility



Bajaj *et al*. APL 105 263503 (2014)

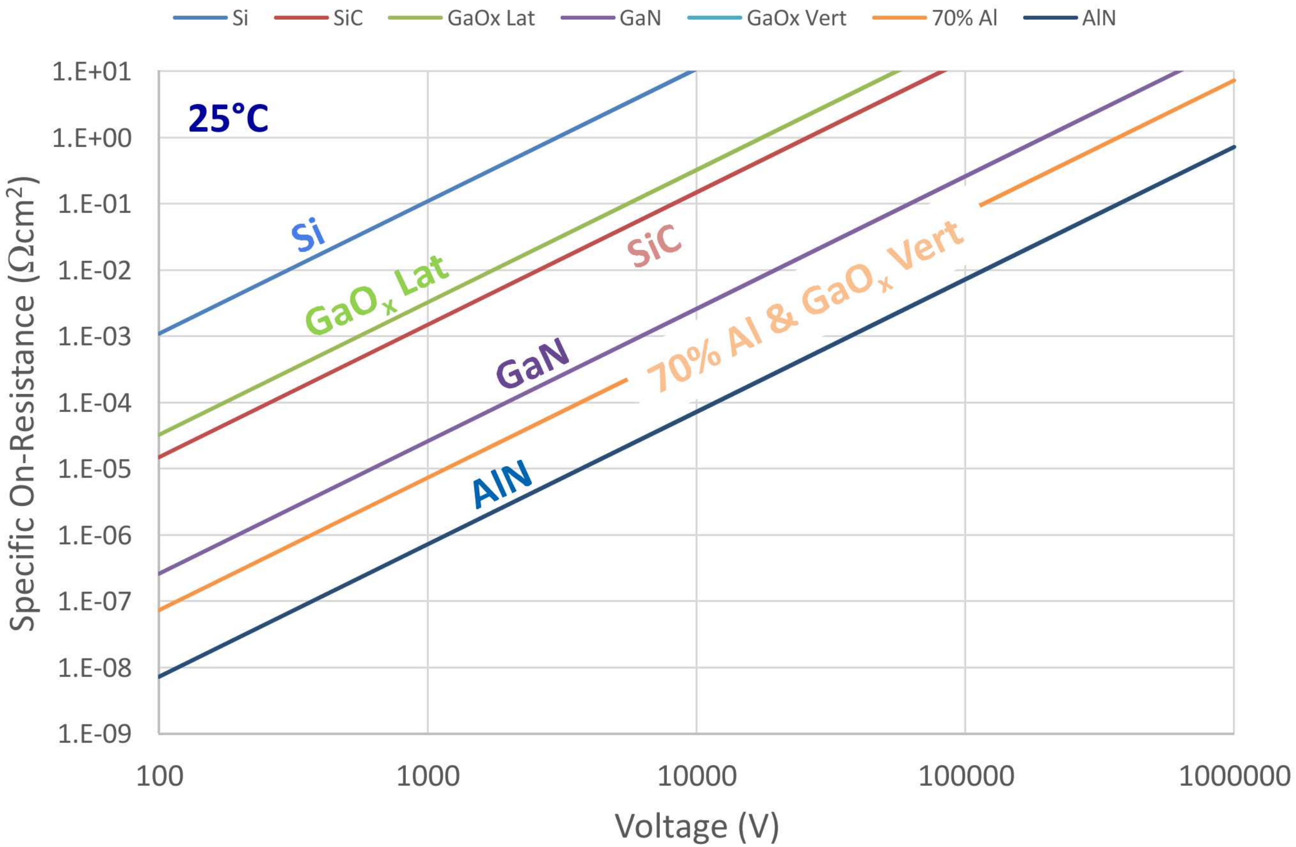


Coltrin *et al.*, JSST 6, S3114 (2017)

$Al_xGa_{1-x}N$ mobility increases markedly at x > 0.9

Binary alloy mobility drops markedly with (extreme) temperature

25°C Figure of Merit for WBG and UWBG Devices



- ***SiC & GaN are well represented in current research***
- ***Ga_2O_3 is not competitive as a lateral device – path to vertical??***
- ***Everything beyond SiC and GaN is immature***
  - ***Al-rich lateral devices – this work***
  - ***AlN least mature - doping & conductivity issues***

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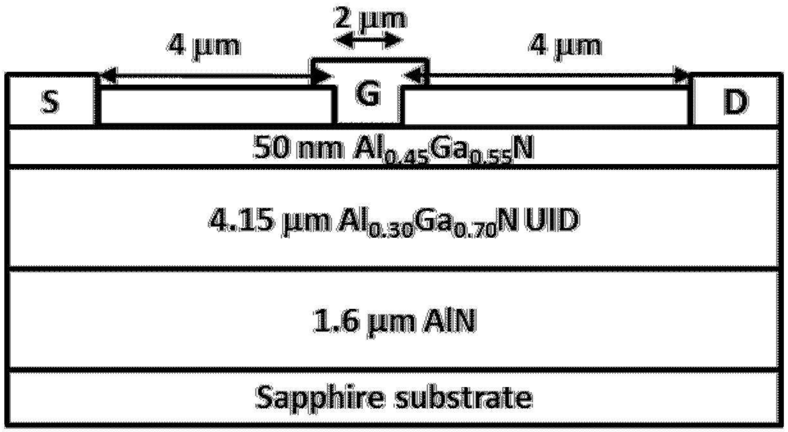
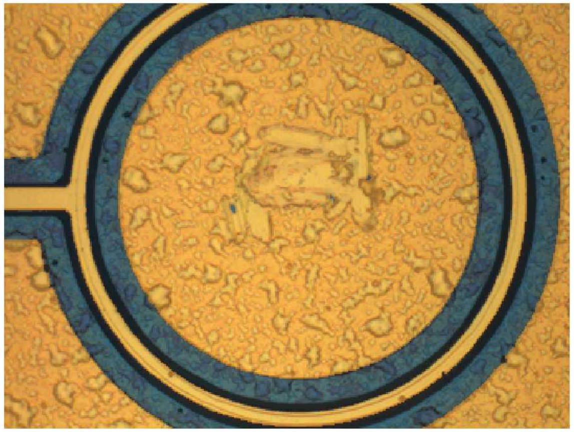
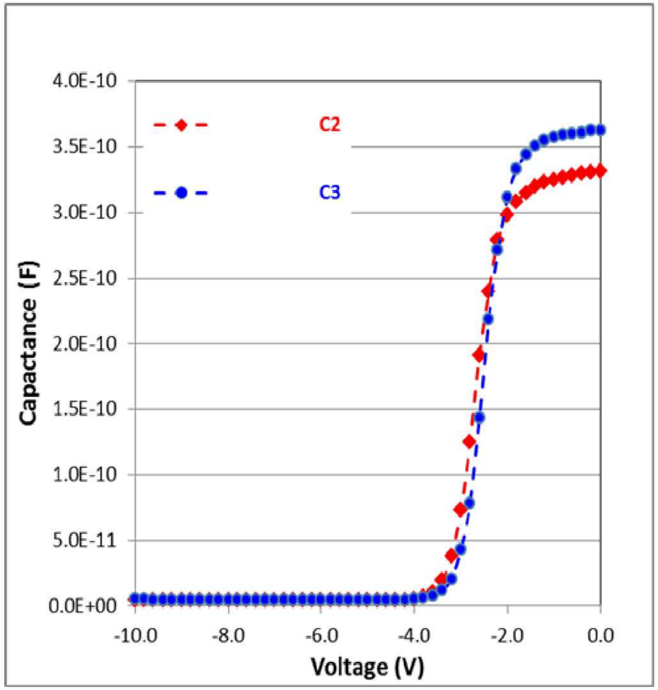
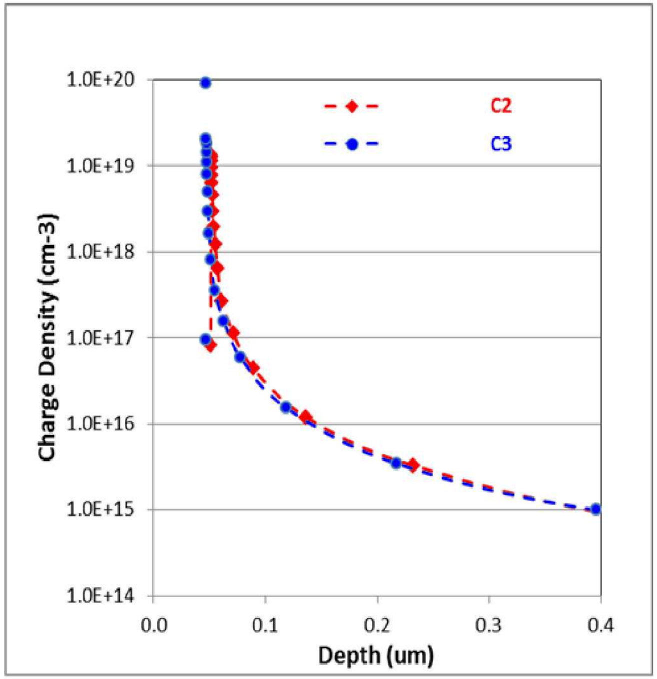
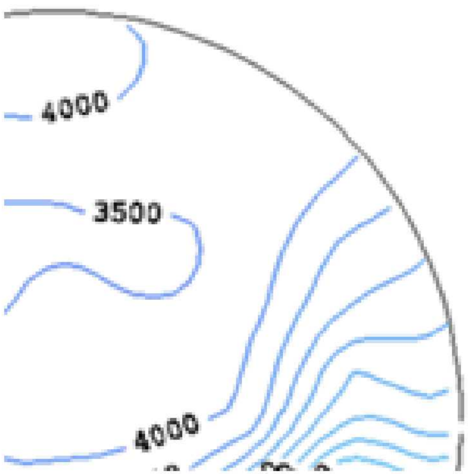
D-mode $Al_{0.45}Ga_{0.55}N$/ $Al_{0.3}Ga_{0.7}N$ HEMT



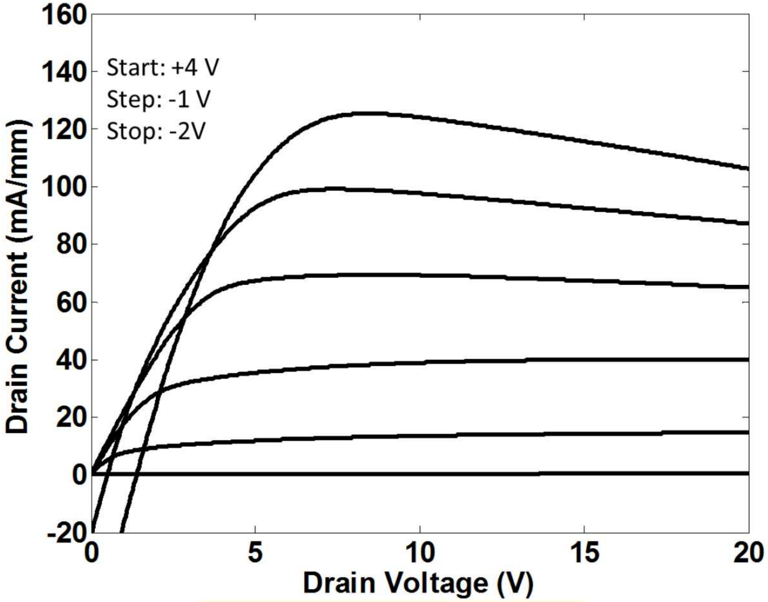




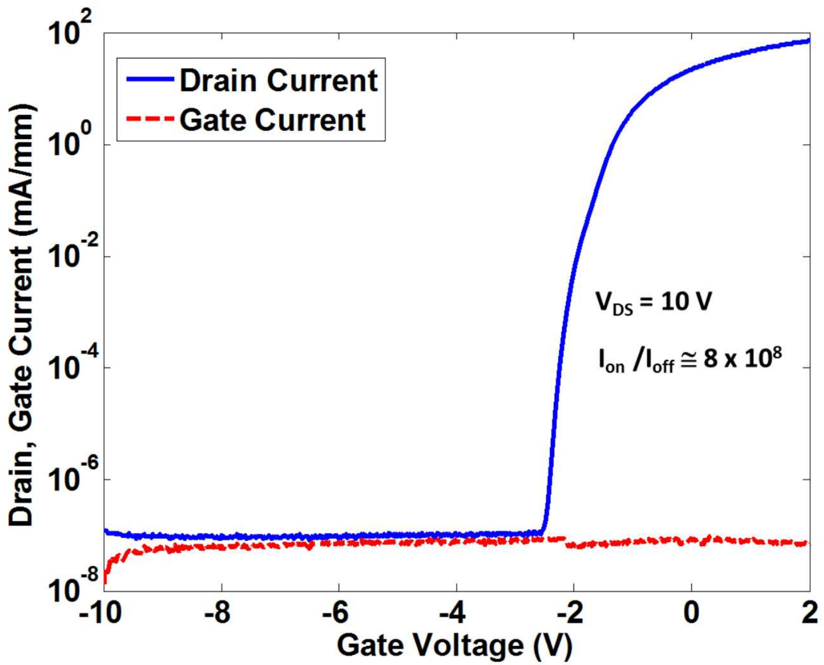




25°C Transfer and Output Characteristics for "45/30" HEMT

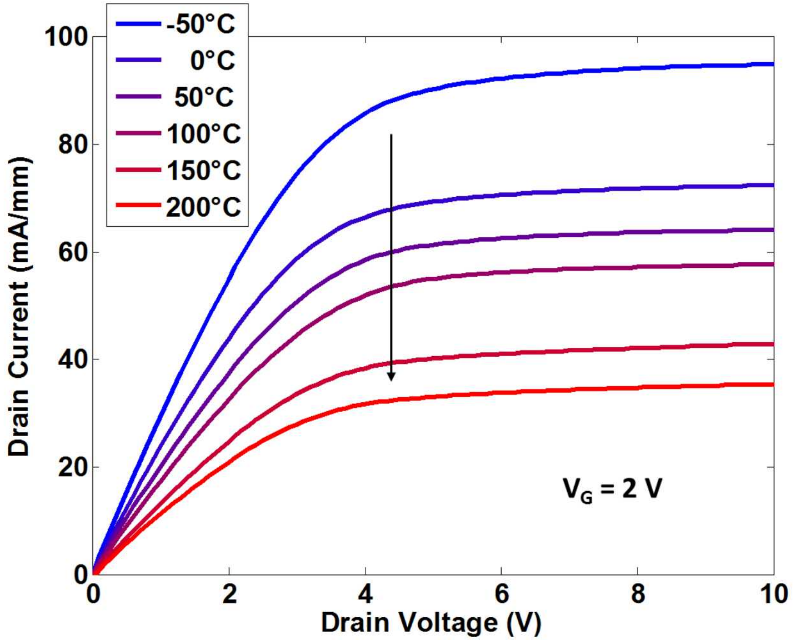


Baca *et al*. JSSST 6, S3010 (2017).

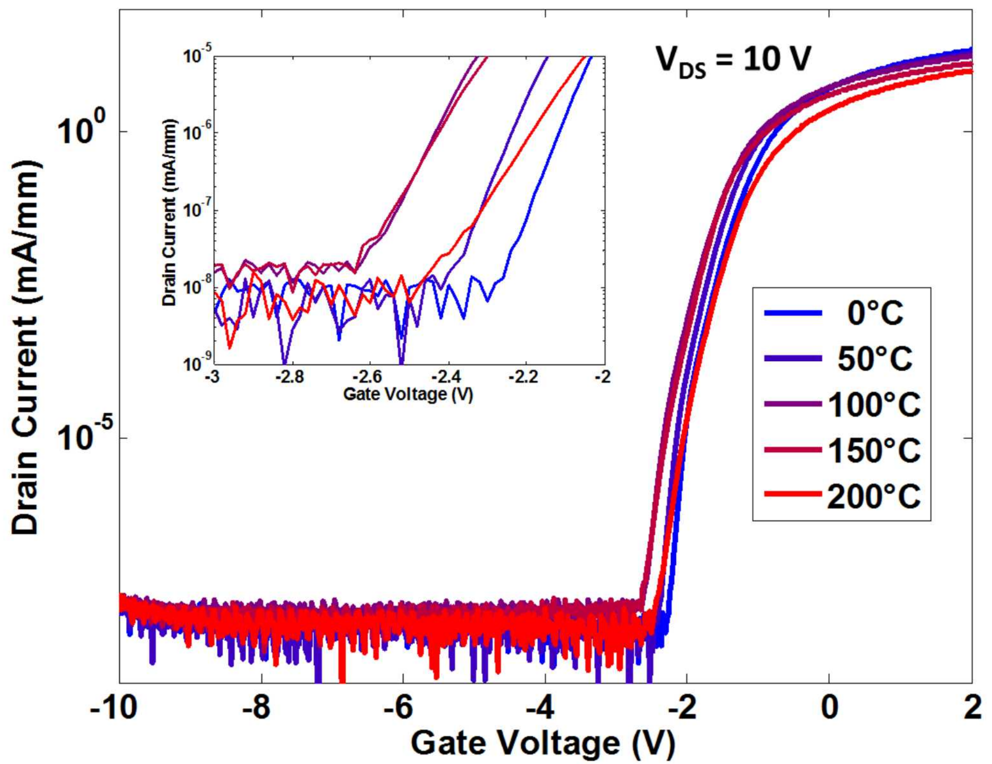


- *Linear through the origin I-V due to ~2.5 x 10^{-5} Ω-cm^2 Ohmic contacts*
- *Exceptional I_{DMAX}/I_{DMIN} ratio (I_{on}/I_{off}) of 8 x 10^8*
- *Very low gate leakage*

Temperature Dependence of “45/30” Transfer and Output Characteristics

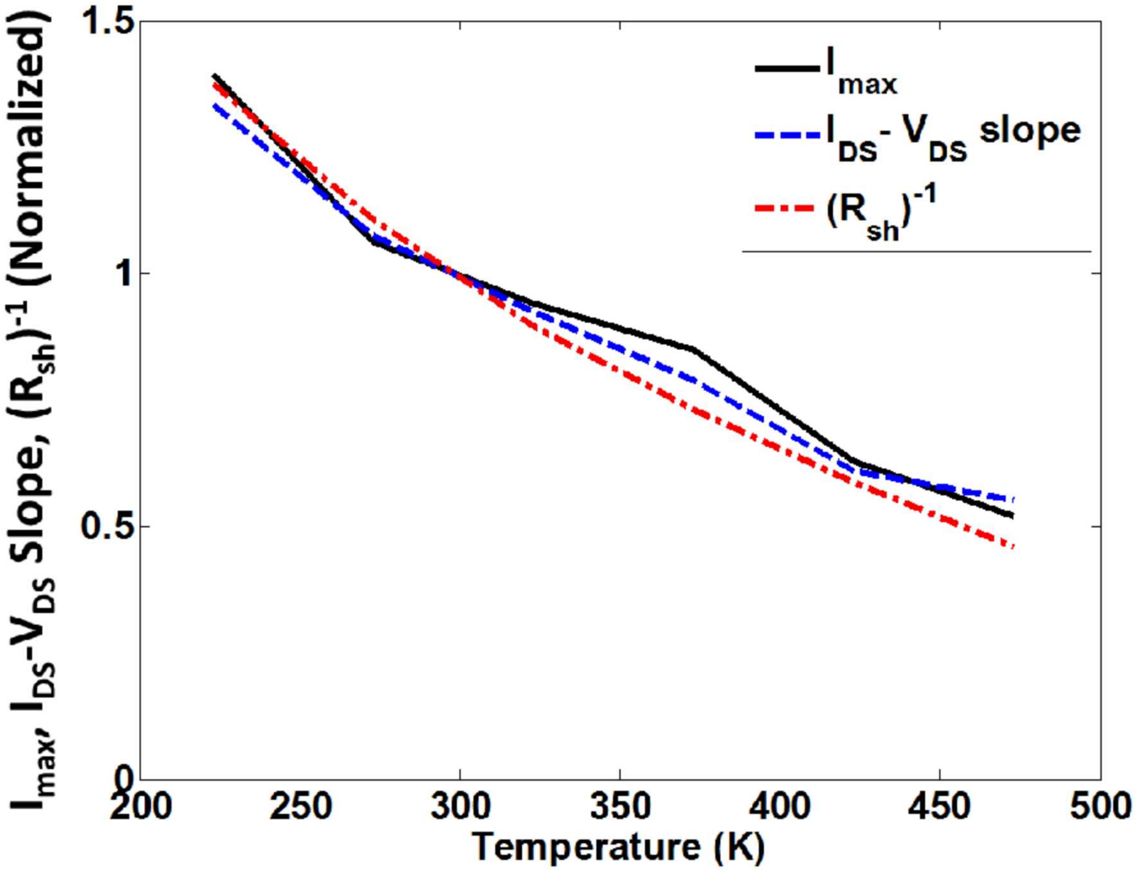


Baca *et al*. JSSST 6, S3010 (2017).



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

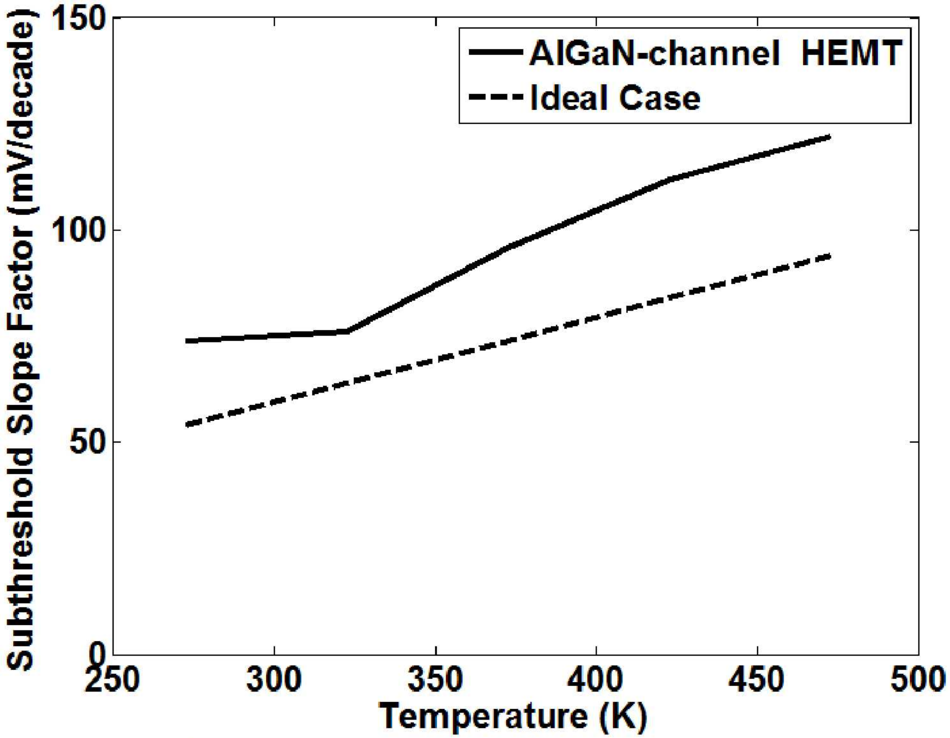
Temperature Dependence of "45/30" Imax Consistent with Mobility-Dominated Transport



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***

Temperature Dependence of "45/30" Subthreshold Slope Factor is Near Ideal



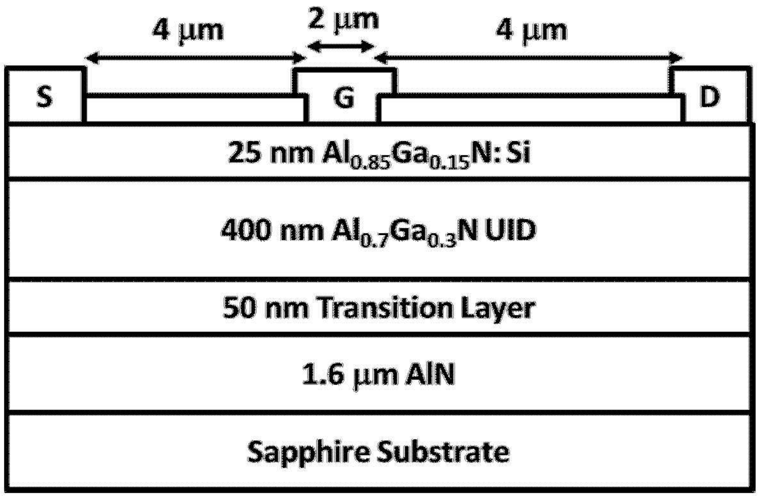
Baca *et al*. JSSST 6, Q161 (2017).

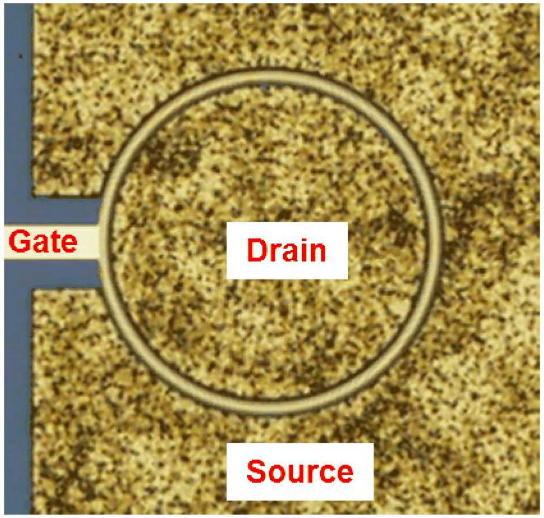
$$S = \left(\frac{kT}{q} ln10\right)\left(1 + \frac{qD_{it}}{C_i}\right)$$

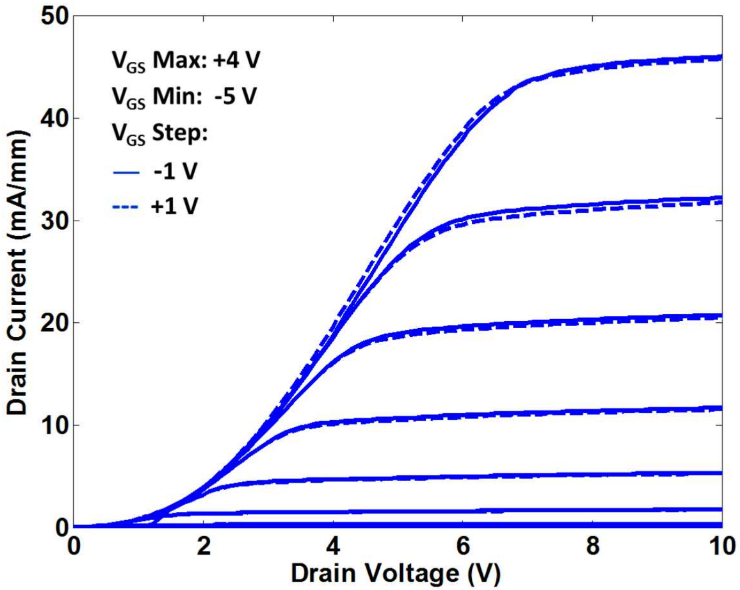
$$S = T\left(\frac{k}{q} ln10\right)\left(1 + \frac{qD_{it}}{C_i}\right)$$

- *Assume model from Chung et al. DRC 2007, p. 111*
- *Consistent with D_{it} = 1 x 10^{11} cm^{-2} (heterointerface defect density)*

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



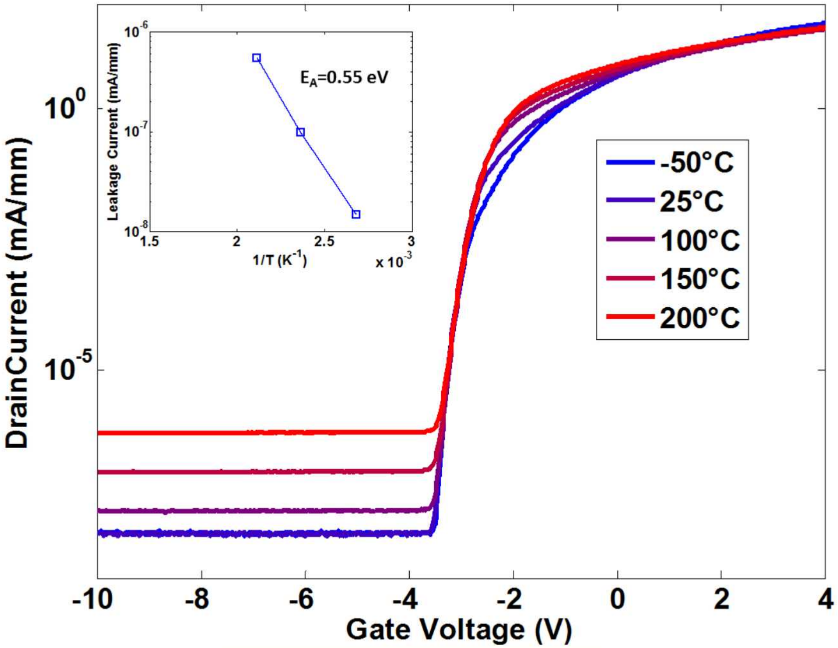




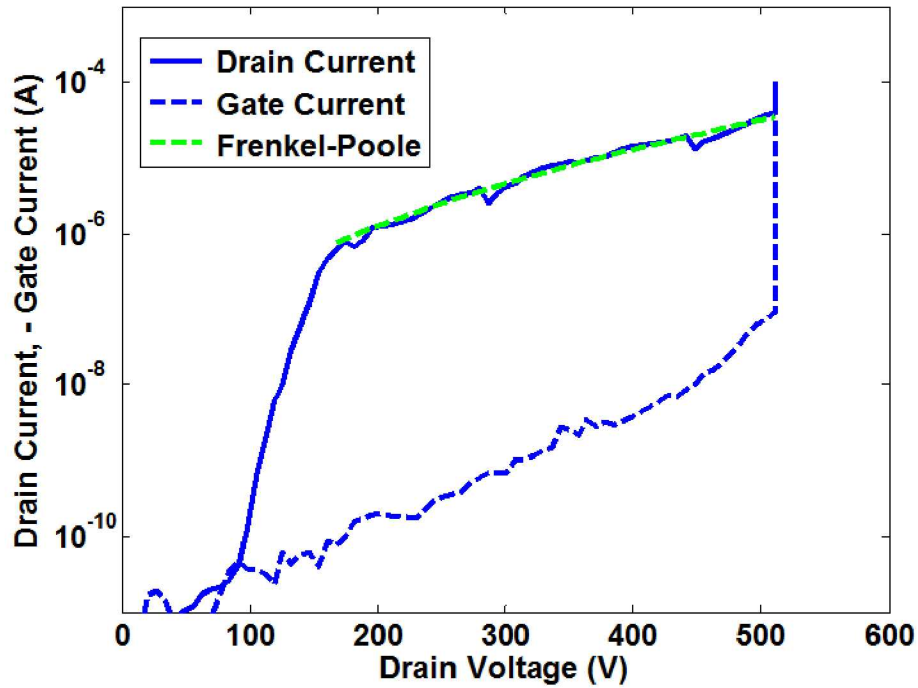
Baca *et al*. JSSST 6, Q161 (2017).

- ***Very little hysteresis***
- ***Greater difficulty in Ohmic contact formation leads to offset voltage and further limitation of drain current potential***

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

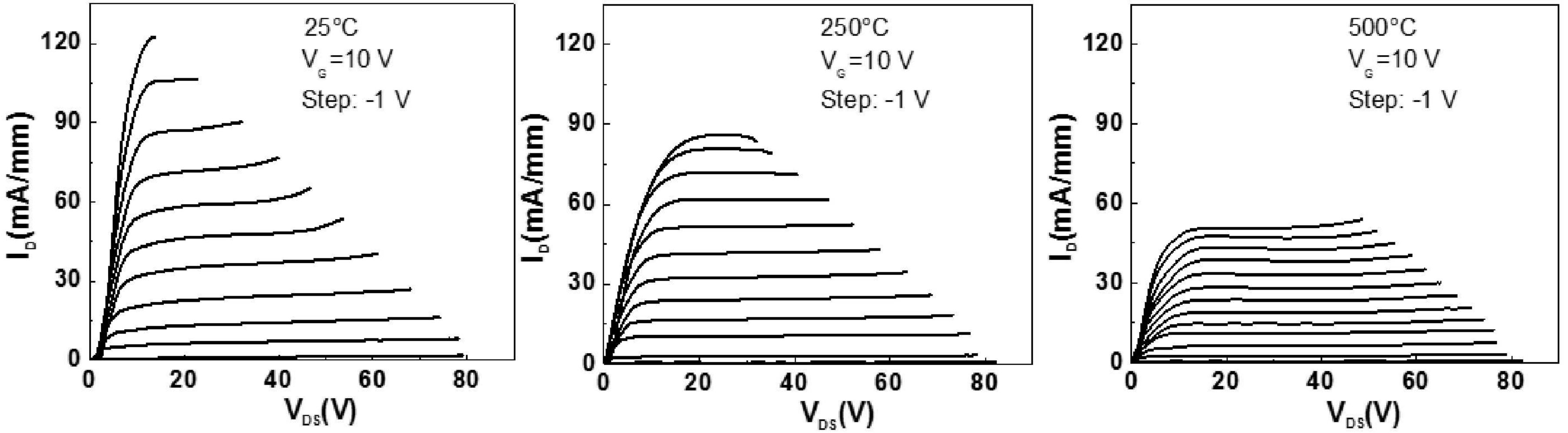


Baca *et al*. JSSST 6, Q161 (2017).



- ***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***

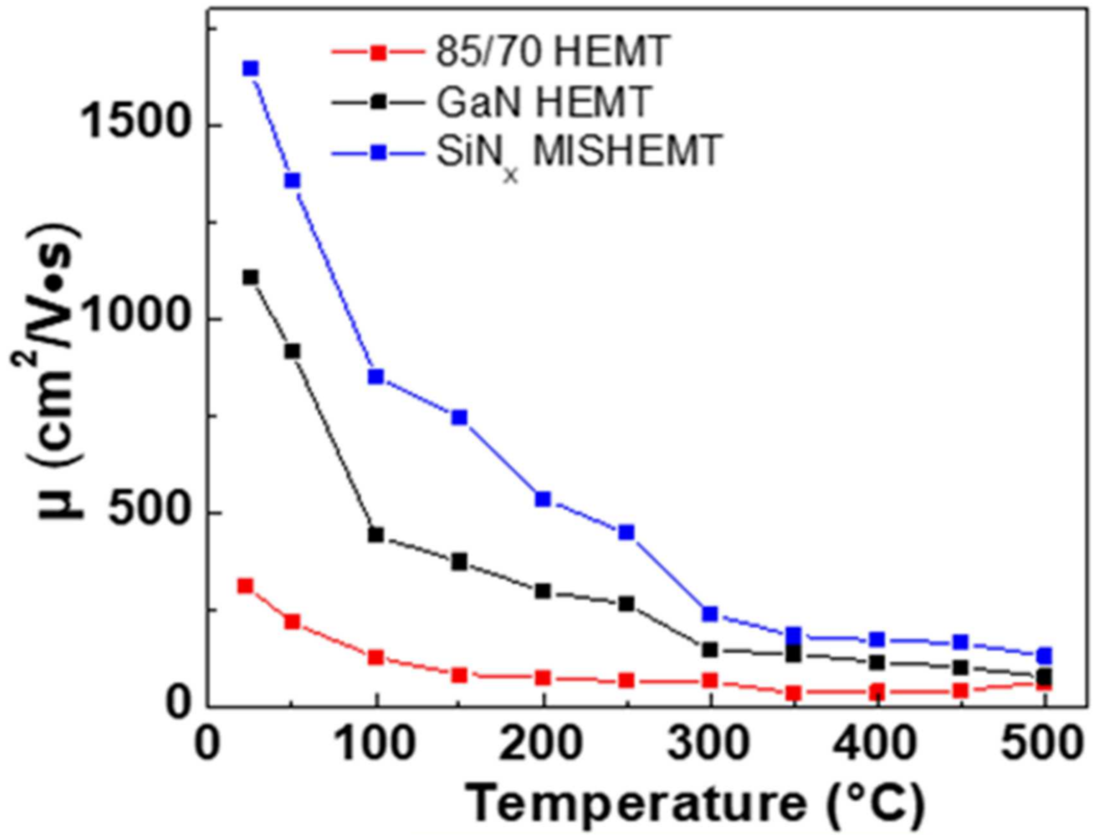
Extreme Temperature Operation of D-mode "85/70" HEMT



Carey *et al*. submitted to IEEE Trans. El. Dev.

- ***Current density exceeds 120 mA/mm from increasing the forward gate bias***
- ***Retain excellent current modulation and over 50 mA/mm current density when operated at 500°C***

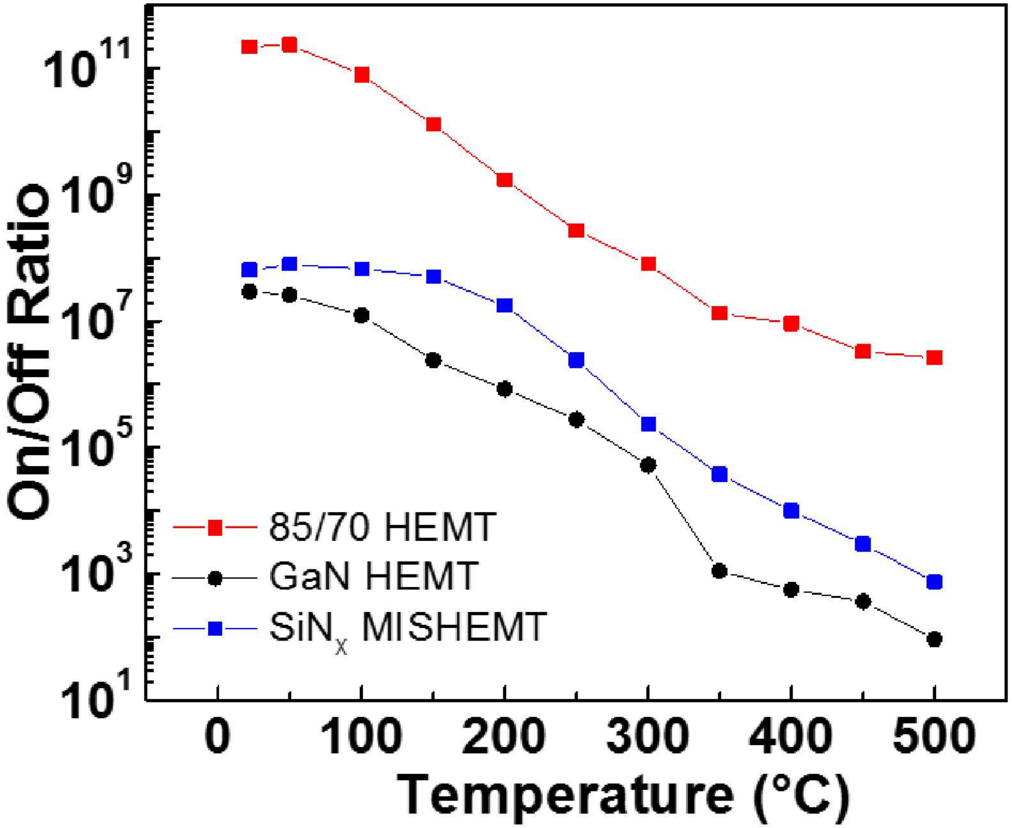
Mobility Trend over wide Temperature Range in (Al)GaN-channel HEMT



Carey *et al*. submitted to IEEE Trans. El. Dev.

- ***Mobility for Al-rich HEMT reaches near parity with GaN HEMT at 500°C and is fairly flat from 200-500°C***
- ***Suggests that you may be able to lessen the cooling requirements for AlGaN electronics***

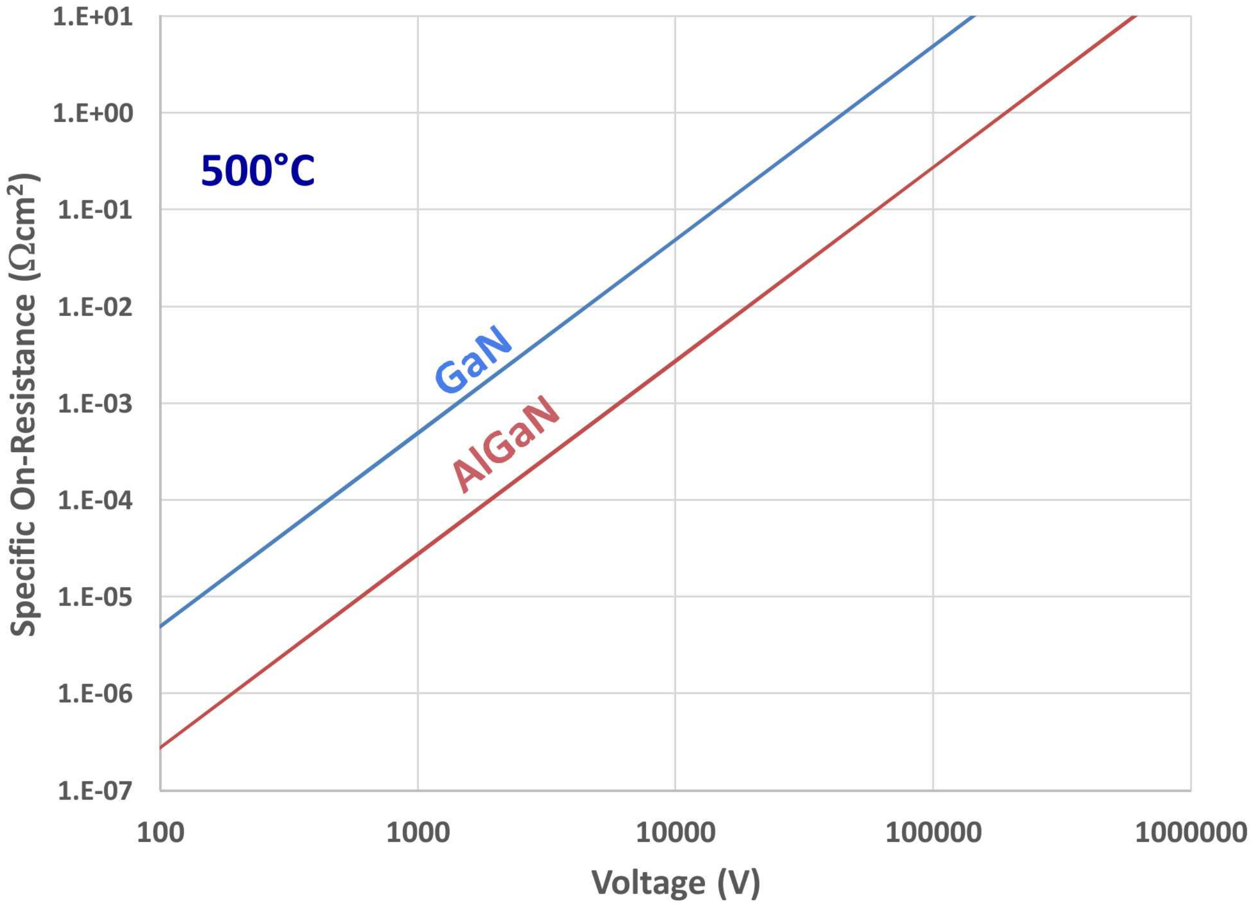
On/Off Ratio of D-mode "85/70" HEMT is Favorable at Extreme Temperature Operation



Carey *et al*. submitted to IEEE Trans. El. Dev.

- ***Al-rich HEMT maintains excellent On/Off ratio at 500°C and GaN doesn't***
- ***On/Off ratio is fairly flat from 200-500°C***

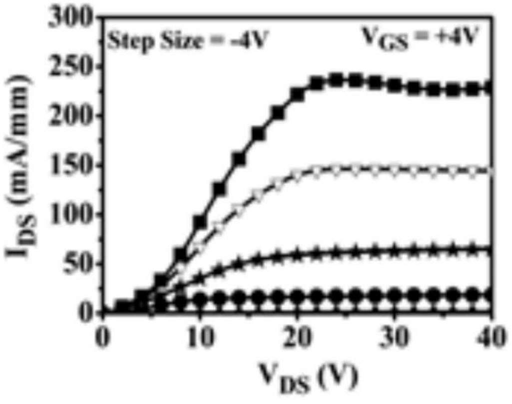
Extreme Temperature Figure of Merit for GaN & 70% AlGaN



FOM for Al-rich HEMT is 16x superior to that for GaN at extreme temperature

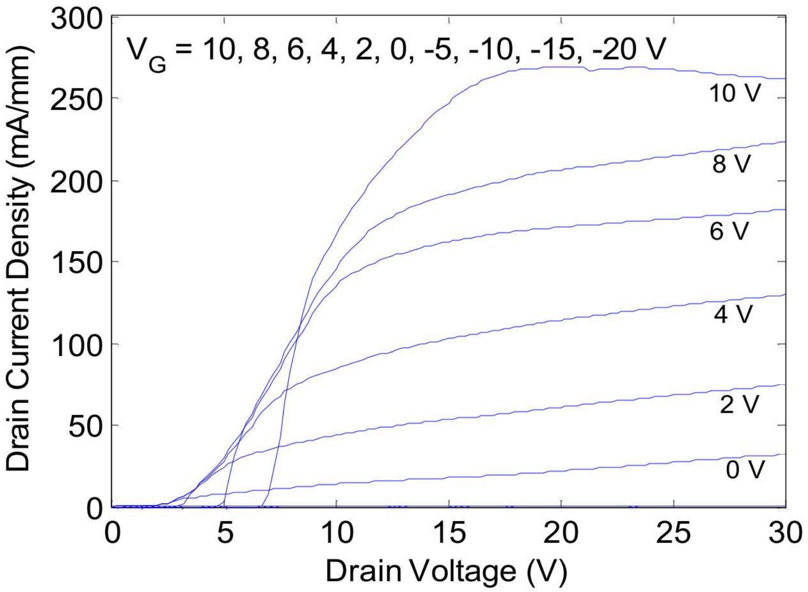
High Current Density D-mode HEMTs

85/65 D-mode HEMT



Muhtadi *et al*. EDL 38, 914 (2017)

85/70 D-mode HEMT, 90 nm gates



Klein *et al*. to be published

Long channel device, d-mode, larger n_s, and 250 mA/mm

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

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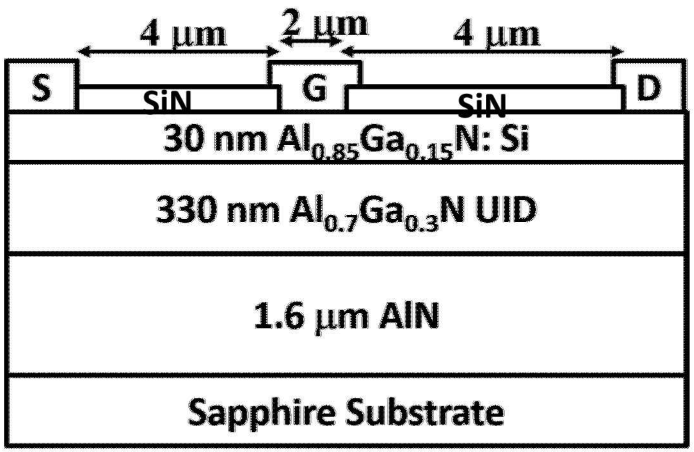
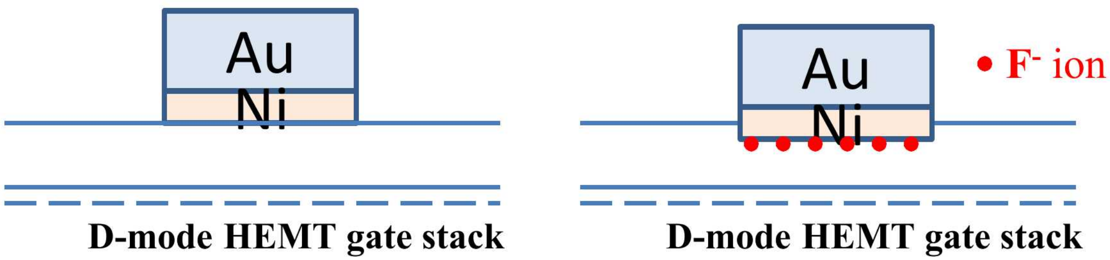
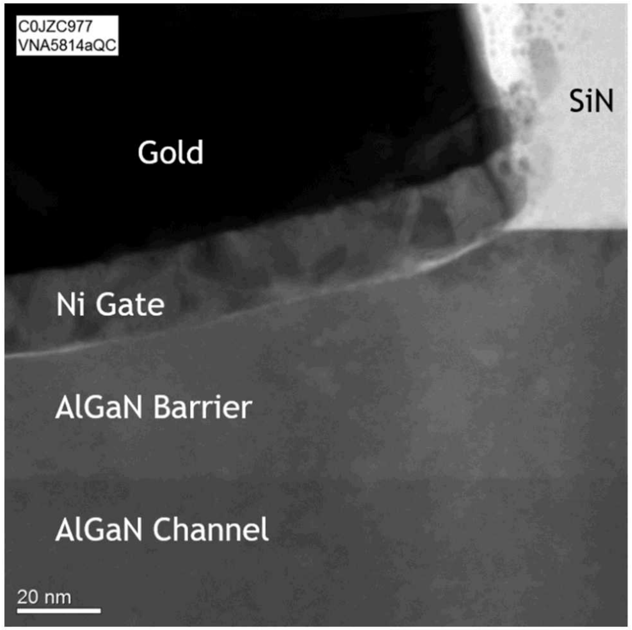
First E-mode $Al_{0.7}Ga_{0.3}N$ using *F-Plasma* Treatment



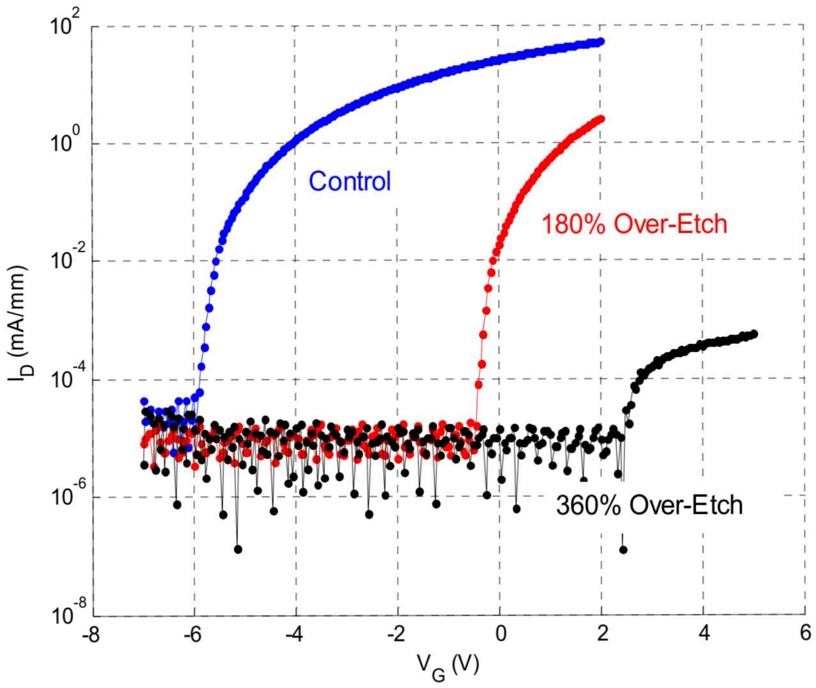
Motivated by Cai *et al*., IEEE Trans. El. Dev. 53, 2223 (2006)



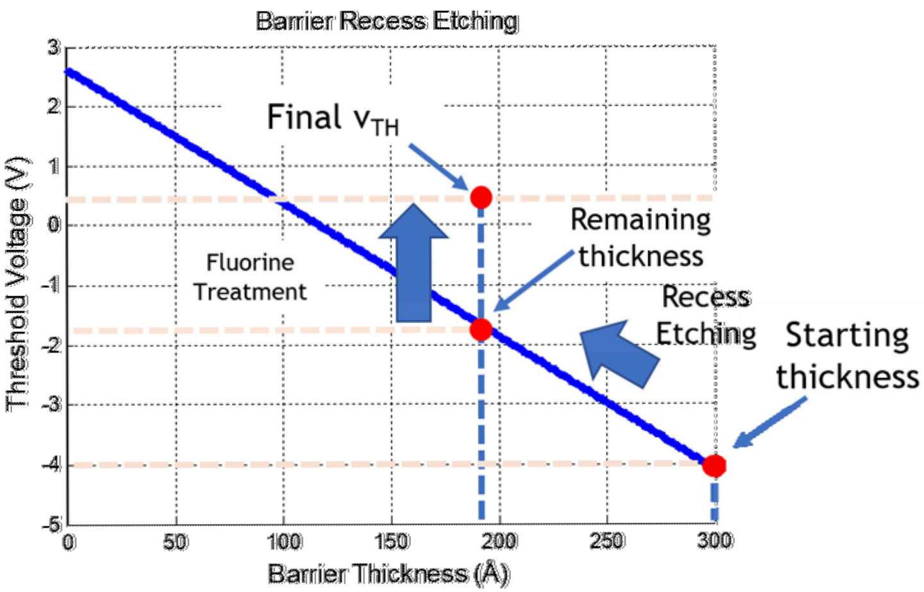


F-plasma from reactive ion etch (through SiN): combination of AlGaN etch and incorporation of F^- ions near the surface

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



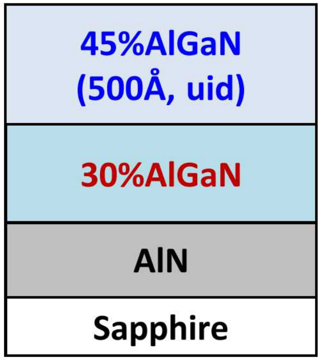
$$v_{TH} = \varphi_b - \frac{q\sigma_p t_{barrier}}{\varepsilon_r \varepsilon_0} - \Delta E_c$$

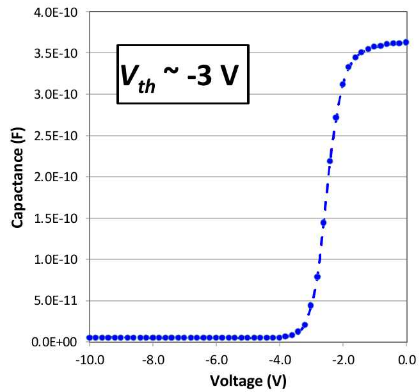


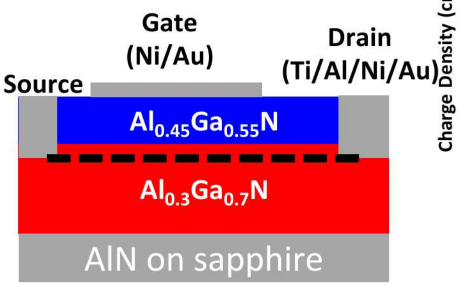
***F-plasma* from reactive ion etch (through SiN, then into AlGaN): V_{th} shift is a combination of AlGaN etch and incorporation of F^- ions near the surface**

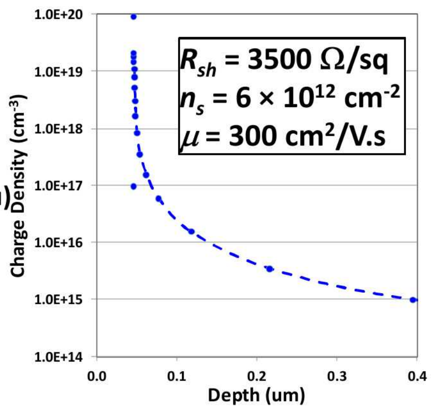
2^{nd} Approach to E-mode AlGaN using *p*-type gate

D-mode 45/30 HEMT

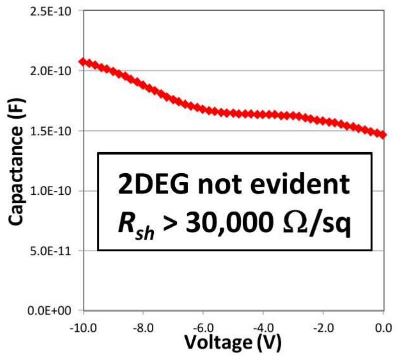


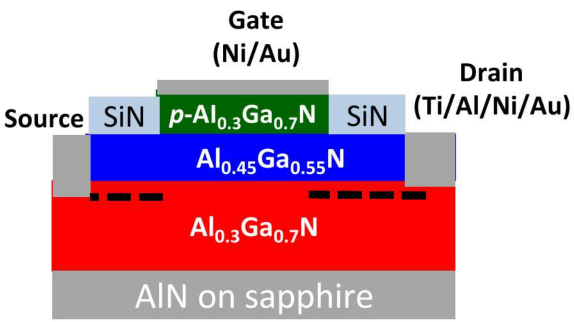






E-mode *p*-30/45/30 HEMT

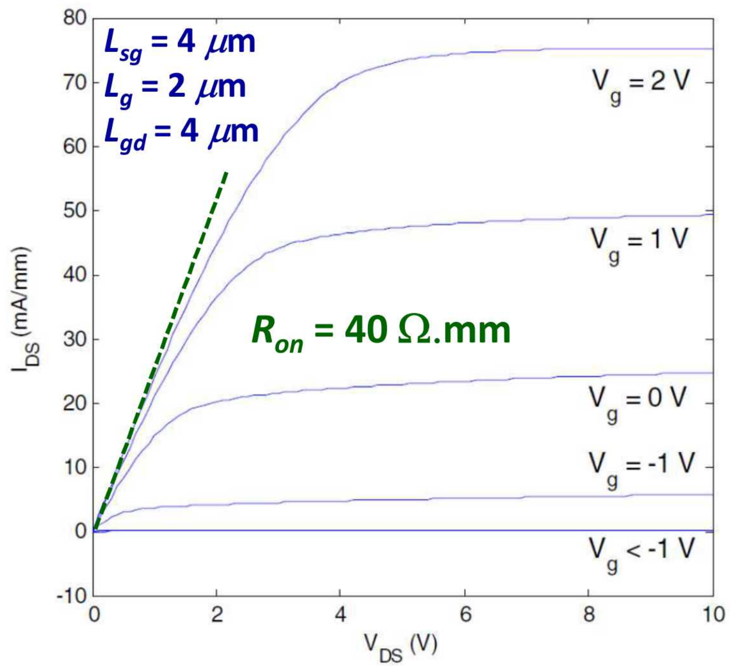




- MOVPE-grown UID $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ **(45/30)** on $Al_{0.3}Ga_{0.7}N$-on AlN-on saphhire
- *p*-$Al_{0.3}Ga_{0.7}N/Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ **(*p*-30/45/30)** heterostructures very resistive
- *p*-AlGaN gate defined by ICP etching and passivated with SiN

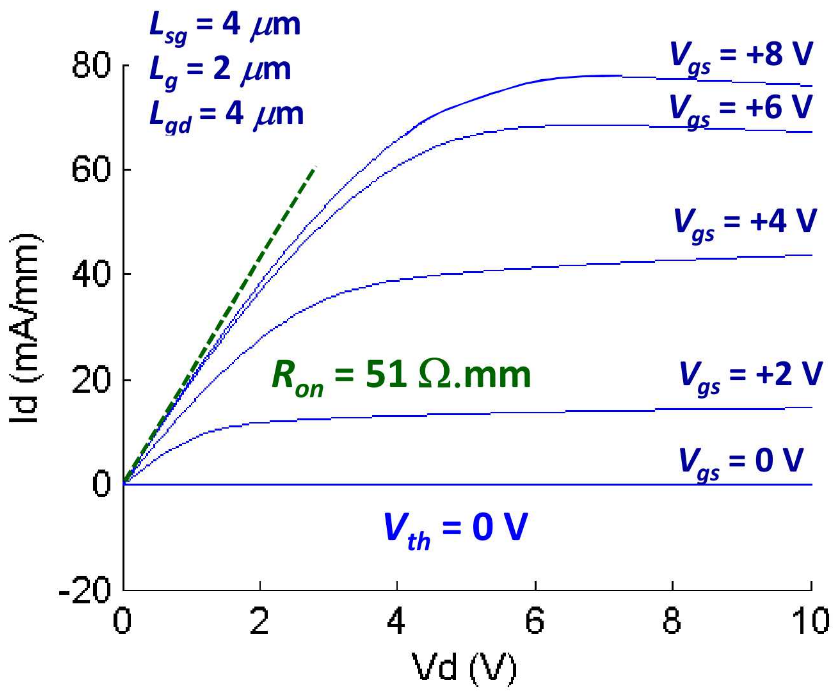
First p+ gate E-mode *p*-30/45/30

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



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

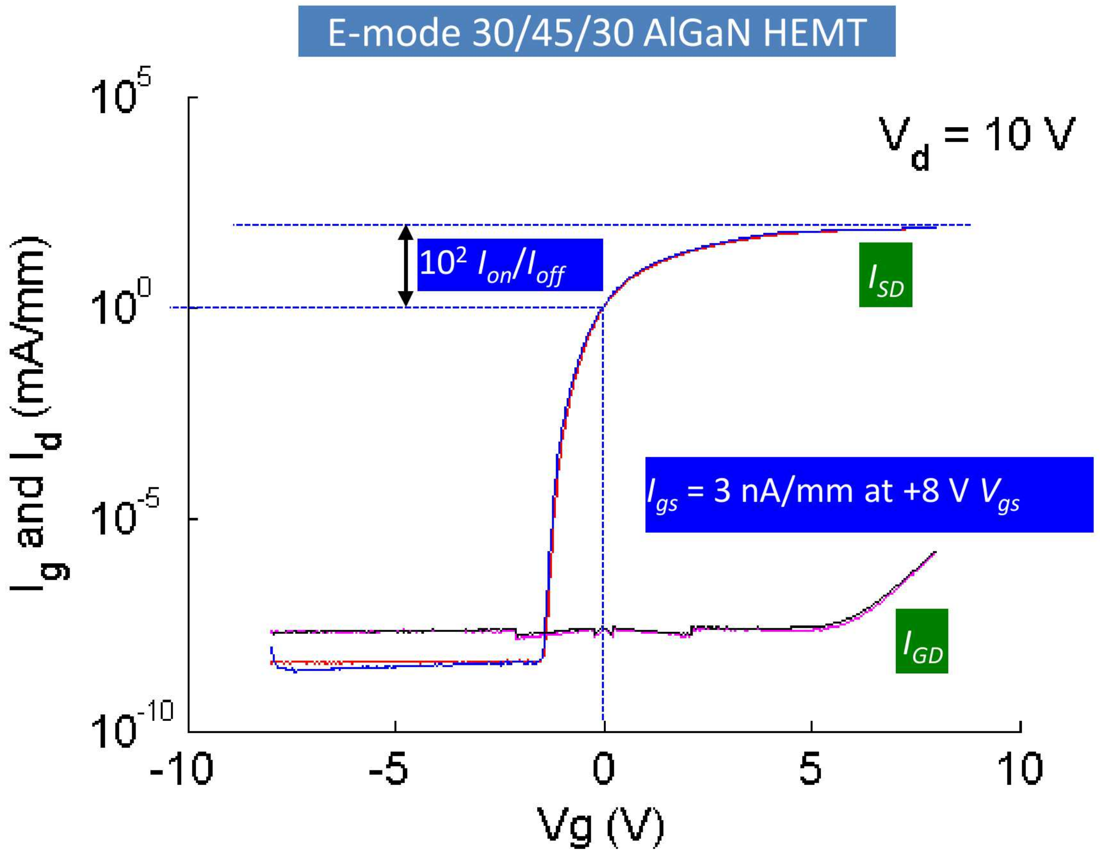
I-V of E-mode 30/45/30 AlGaN HEMT



Douglas, *et al.*, DRC, Santa Barbara, CA, June 25, 2018

- V_{th} = 0 V
- Little to no degradation of I_{max} or R_{on} for E-mode *vs.* D-mode AlGaN HEMT

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

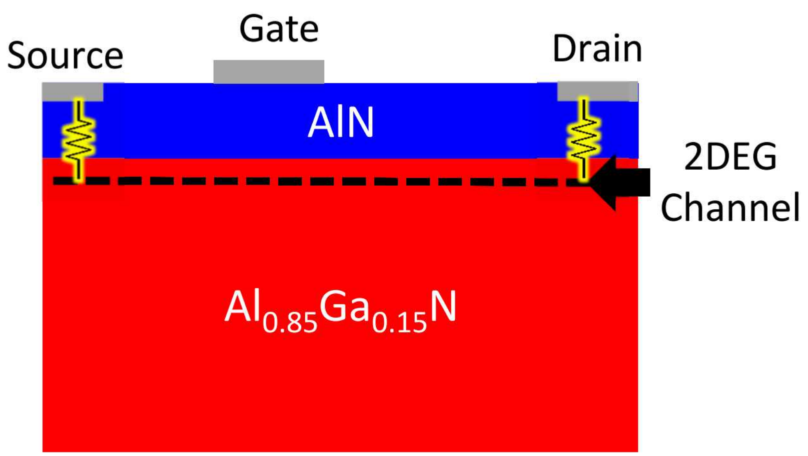


- Small hysteresis (~ 80 mV)
- Vanishingly small gate current

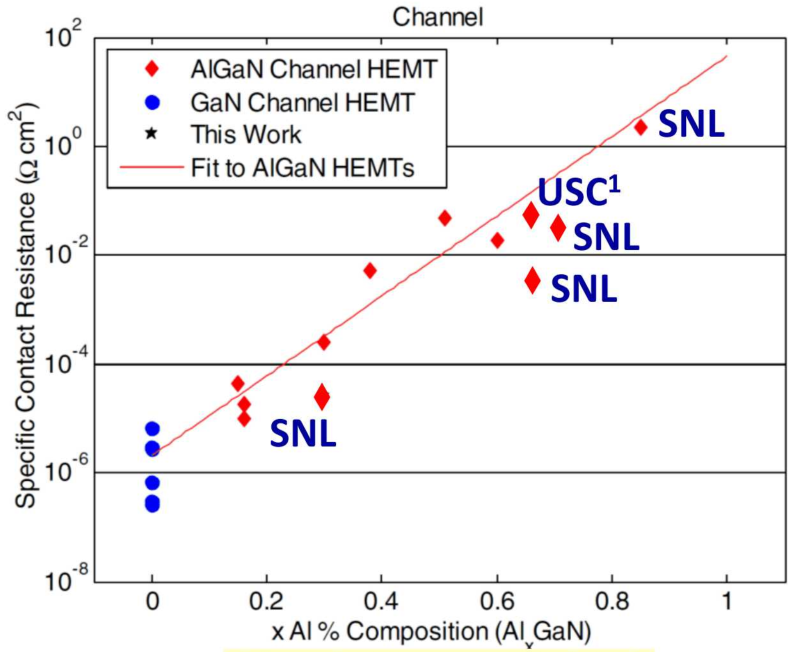
Challenges

- Ohmic contacts
- Substrates
- Dielectrics for high breakdown

Ohmic Contact Resistance increases with Al-composition



HEMT ρ_c *vs.* AlGaN channel Al



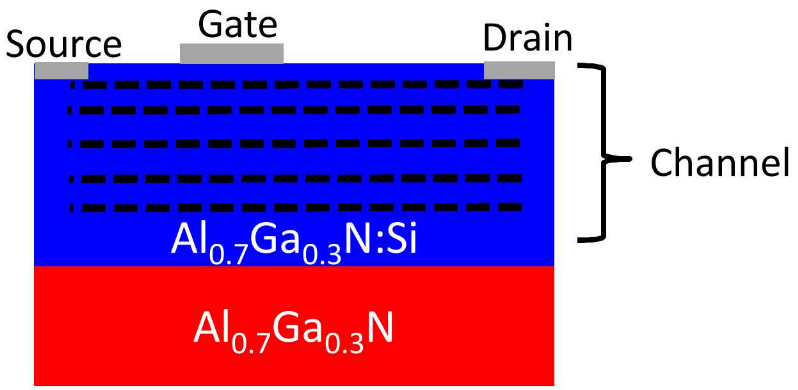
Klein *et al*. ECS JSSST 6 S3067 (2017).

Unlike Ga-rich AlGaN, Ohmic metal does not traverse the Al-rich AlGaN barrier to reach 2DEG

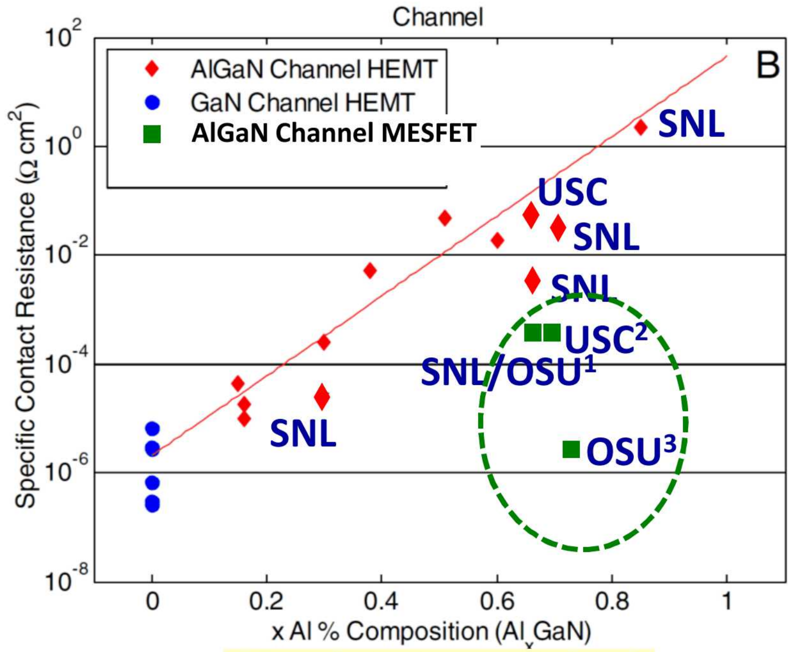
1. Muhtadi *et al*., IEEE EDL 38 914 (2017).

AlGaN MESFETs solve contact problem…

AlGaN MESFET



HEMT ρ_c *vs.* AlGaN channel Al



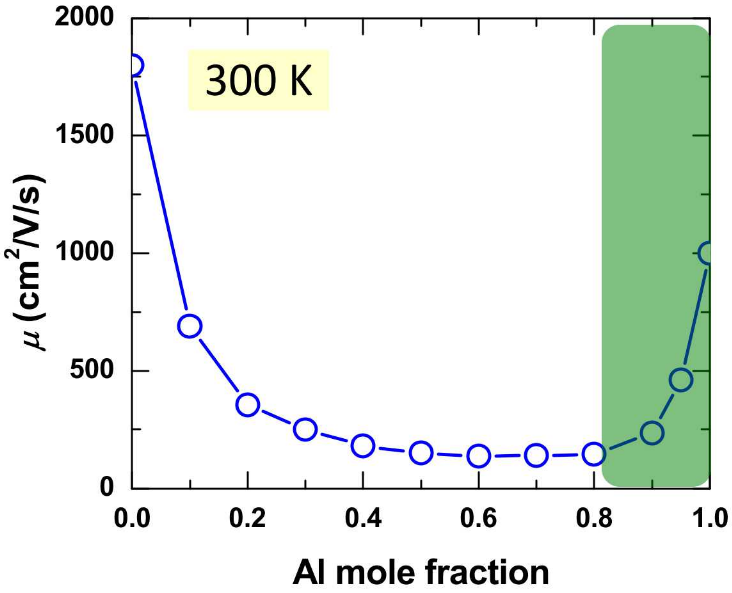
Klein *et al*. ECS JSSST 6 S3067 (2017).

$Al_xGa_{1-x}N$ MESFETs achieve good contacts up to x = 0.75 using impurity doping

1. Bajaj *et al*. IEEE EDL 39 256 (2018).
2. Muhtadi *et al*., APL 110 193501 (2017).
3. Bajaj *et al*., APL 109 133508 (2016).

…but AlGaN MESFETs are fundamentally limited

AlGaN HEMT channel mobility



Bajaj *et al*. APL 105 263503 (2014)

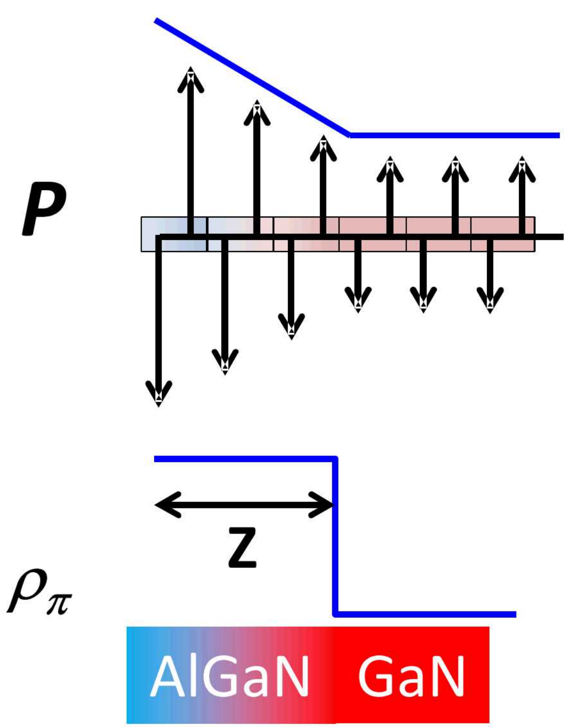
Impurity-doped AlGaN:Si resistivity

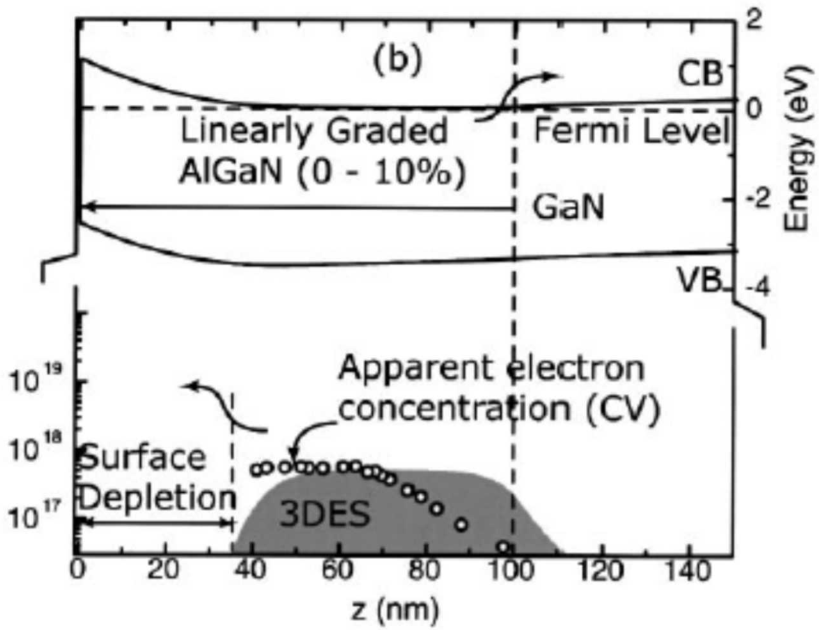
Mehnke *et al*. APL 103 212109 (2013)

AlGaN MESFET $\mu < 100$ cm^2/Vs because impurity doping is inefficacious for $x > 0.8$

Polarization-induced three-dimensional doping solves μ-ρ_c problem

$$\rho_\pi = \nabla \cdot \boldsymbol{P} = \Delta \boldsymbol{P}/\boldsymbol{z}$$

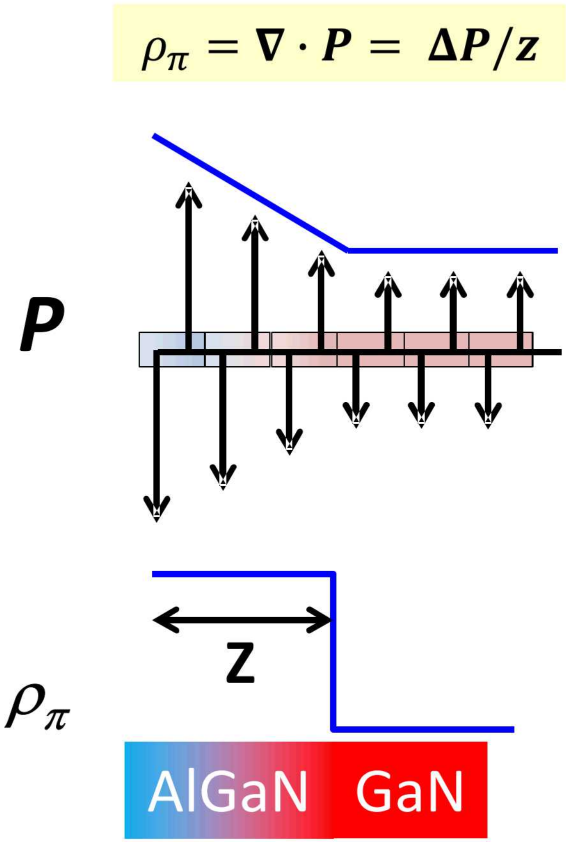


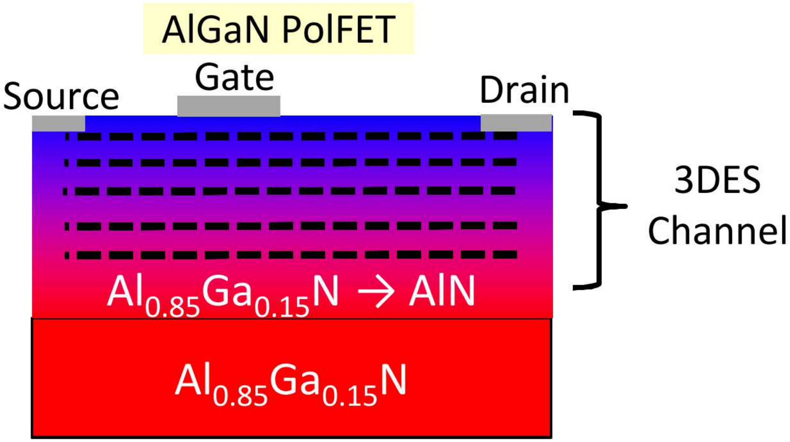


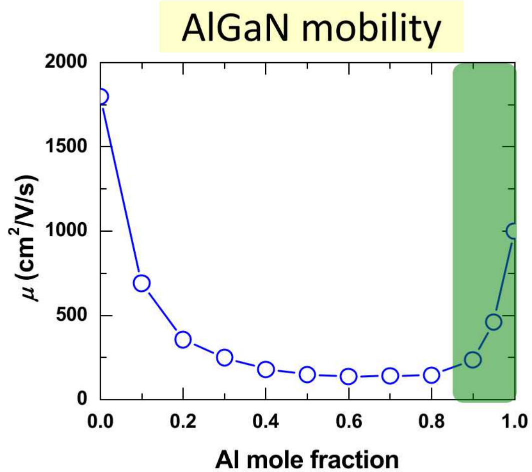
Jena *et al*. APL 81 4395 (2002).

- Linearly graded Al composition leaves a uniform volume of space-charge ρ_π
- Forms a three-dimensional electron slab, i.e. bulk doping

Polarization-induced 3-dimensional Doping Solves μ-ρ_c Problem



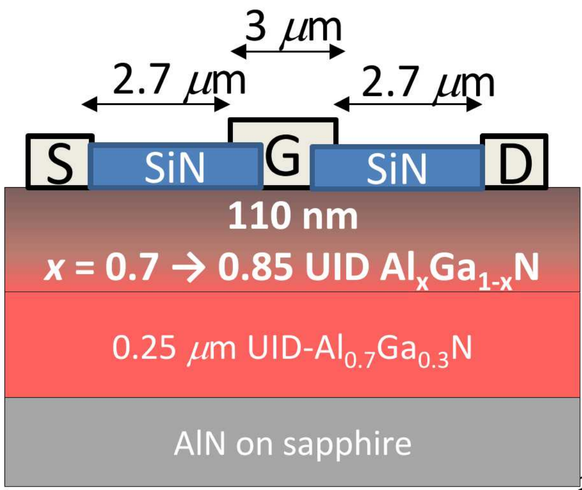


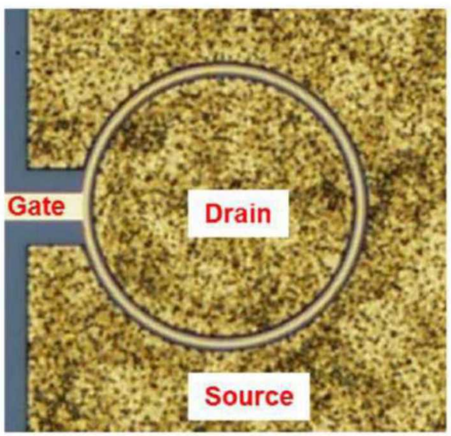


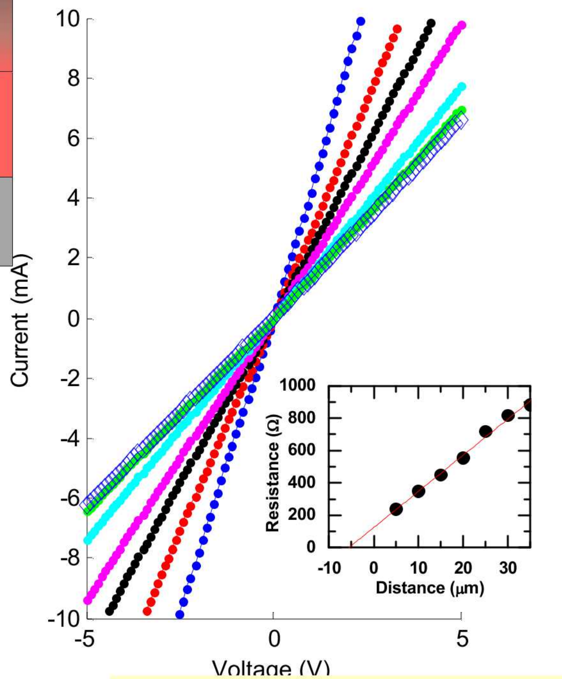
Bajaj *et al.* APL 105 263503 (2014)

- Polarization-doped field effect transistor[1] (PolFET) could achieve good ρ_c
- Higher μ than MESFET

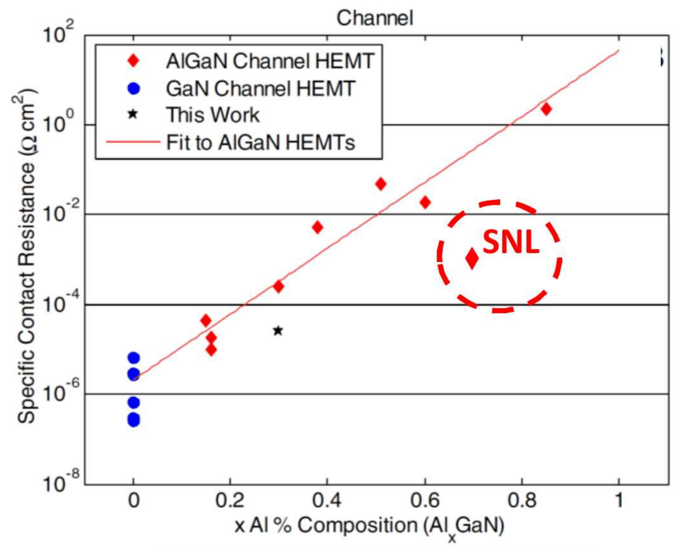
First Al-rich AlGaN PolFET Ohmic Contact Characterization







Armstrong *et al*. JJAP 57 074103 (2018).

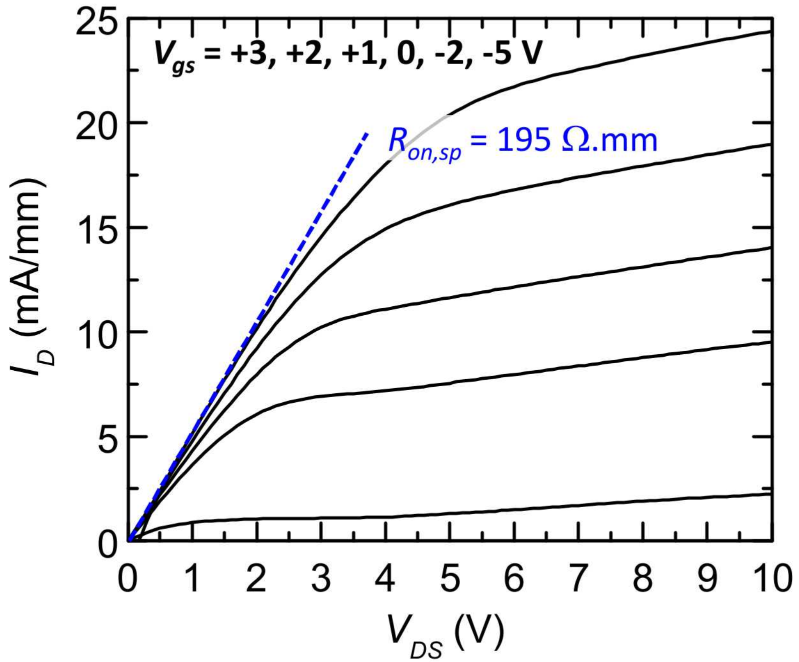


Klein *et al*. ECS JSSST 6 S3067 (2017).

- Circular gate PolFETs with Ni/Au gate and Zr/Al/Mo/Au ohmics (1000 °C anneal)
- ρ_c = 1.1 × 10^{-3} Ω-cm^2 from circular TLM analysis confirms linear ohmic behavior

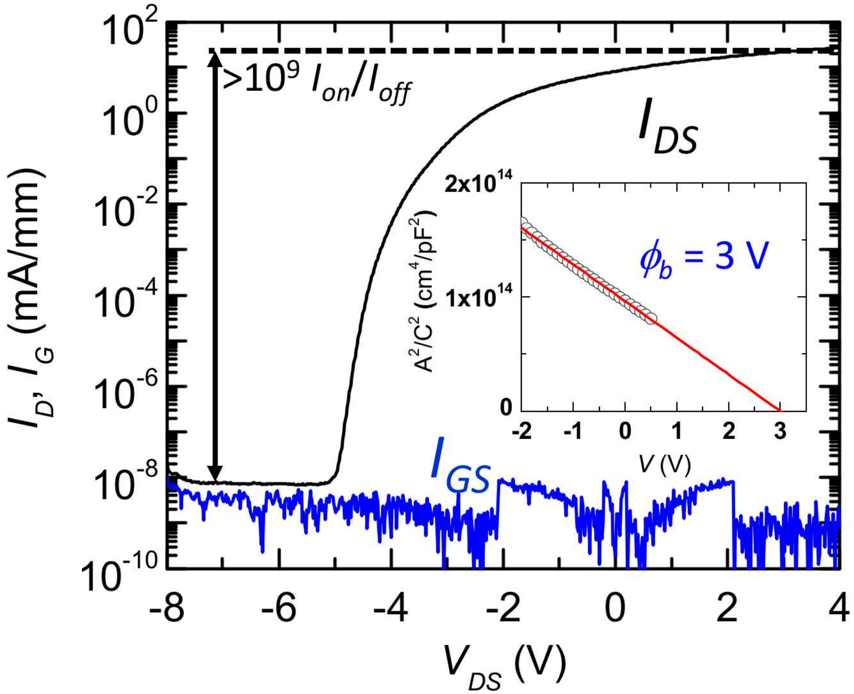
First Al-rich AlGaN PolFET Characteristics

0.70→0.85 PolFET *I-V*



Armstrong *et al*. JJAP 57 074103 (2018).

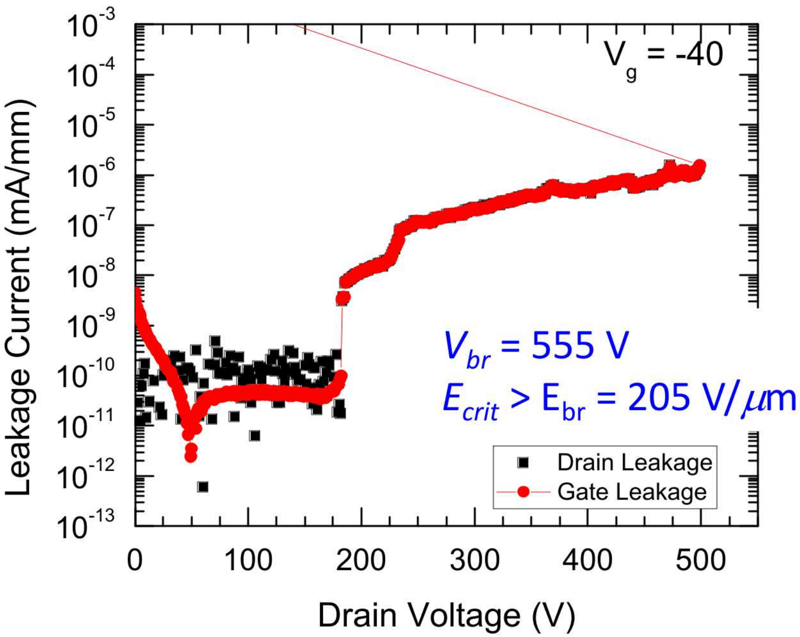
0.70→0.85 PolFET transfer characteristics



- First Al-rich AlGaN FET with $\mu > 200$ $cm^2/V/s$ and linear ohmic contacts
- Excellent off-state behavior with vanishingly small gate leakage

AlGaN PolFET Breakdown

0.70→0.85 PolFET breakdown



Armstrong *et al*. JJAP 57 074103 (2018).

AlGaN PolFET has > 2x larger E_{crit} vs. GaN without device optimization

Summary

- Progress in Ohmic contacts – linear through the origin contacts for 45/30 HEMTs and 70-85 PolFETs
- Current density exceeds 250 mA/mm in slightly depletion-mode transistor with 90 nm gates
- Demonstrated first Al-rich enhancement-mode HEMT with F-plasma treatment
- Demonstrated first AlGaN-channel enhancement-mode HEMT with p^+ gate (45/30) HEMT
- Demonstrated first Al-rich PolFET to alleviate mobility cliff and improve Ohmic contacts
- Demonstrated E_{crit} > 200 V/cm at breakdown in Al-rich PolFET, approximately 2 x E_{crit}(GaN)
- Demonstrated 500°C operation of an 85/70 HEMT with 16x improvement in FOM over GaN