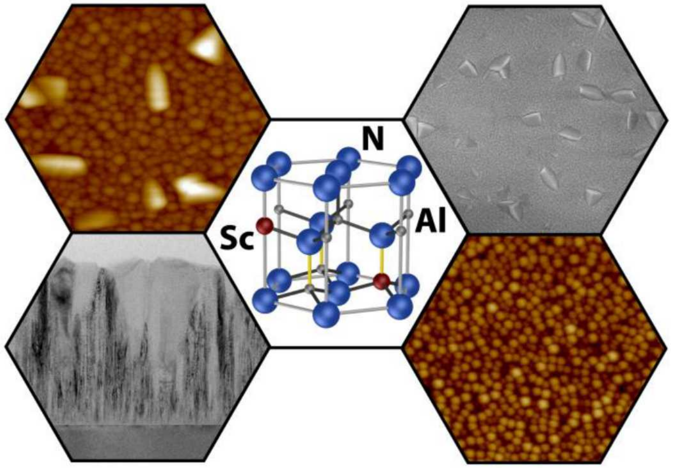
SAND2020-9582PE

Ultra-Wide Bandgap Materials: Enabling Technologies from Power Electronics to MEMS



PRESENTED BY

Erica A. Douglas

with B. Klein, A. G. Baca, A. A. Allerman, A. M. Armstrong, R. J. Kaplar, G. Esteves, M. D. Henry, and B. Griffin

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Outline

Power Electronics

Motivation for Ultra-Wide Bandgap Semiconductors

- Material Comparison
- Figure of Merits

Lateral Device Performance

- Depletion Mode
- Temperature Stability (Univ. of Florida Collaboration)
- Enhancement Mode

MEMS

Motivation for AlN and alloying with Sc

- Material Challenges
- Device Performance

High Temperature Operation

- High Temperature Performance
- High Temperature Stability

Motivation

Lateral GaN

SiC

Ultra WBG

Si

Vertical GaN

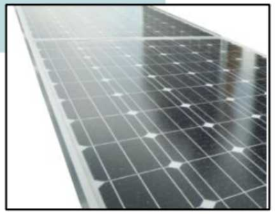
Operating Voltage — 600 V — 1200 V — 10s of kV — MV

600 V: Motor drives, Electric vehicles, Airplanes

- Reduce or eliminate passive components (capacitors, inductors)
- Spectral purity extends motor lifetime
- Operate at higher temperatures without liquid cooling

1200 V: PV inverters

- Higher voltages, lower resistive losses



10s of kV: Electric grid, Electric rail, Grid-level energy storage

- AC subsystems to 13.8 kV

MV: HV-DC transmission and fault protection

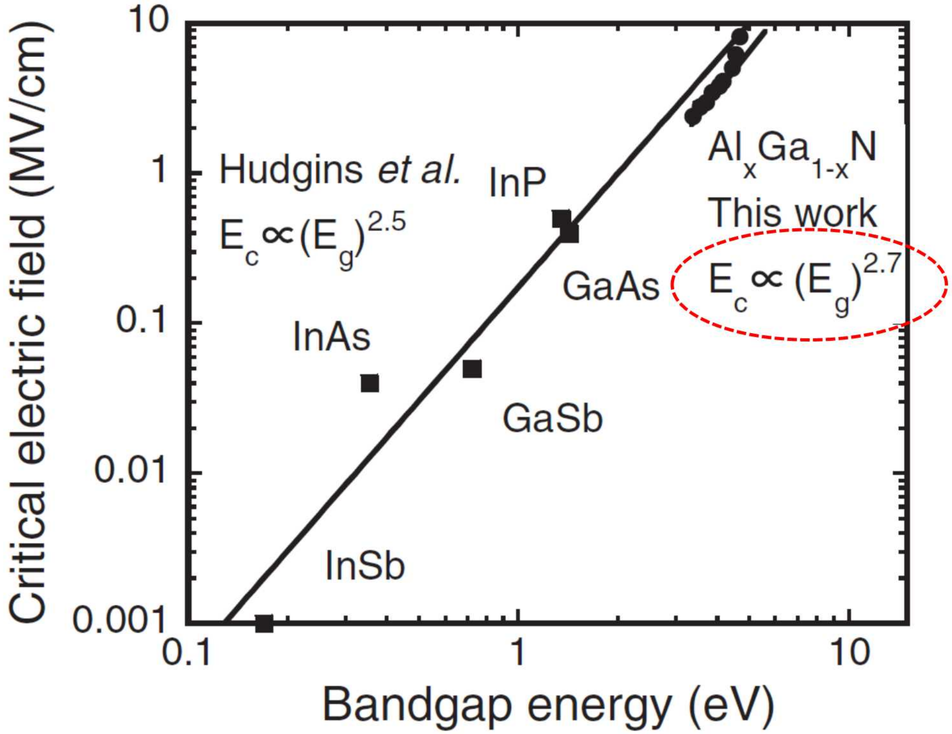
- Increase grid resiliency
- Less resistive energy loss
- Replace expensive IGBT / Thyristor stacks

Material Comparison

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

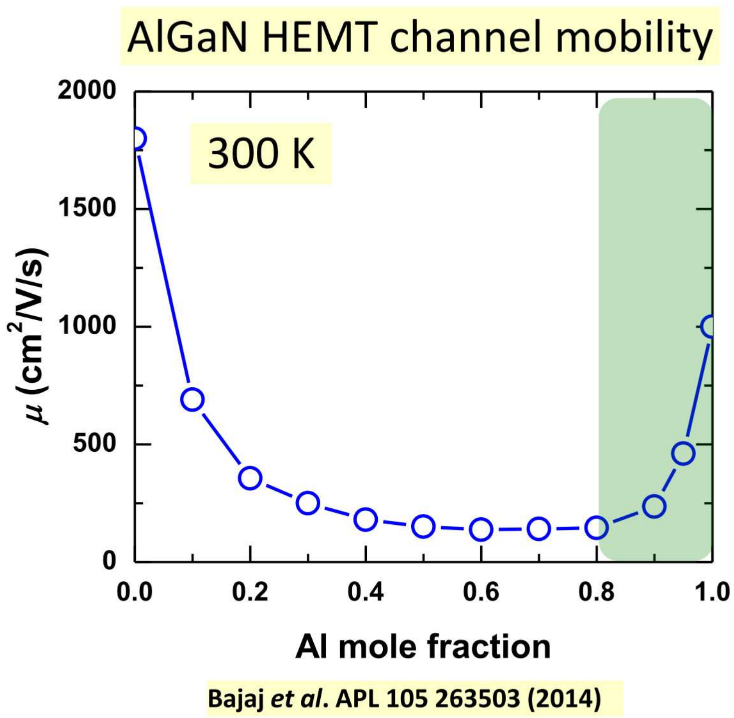
$$R_{on,sp} = \frac{V_{br}^2}{q\mu n_s E_{crit}^2}$$

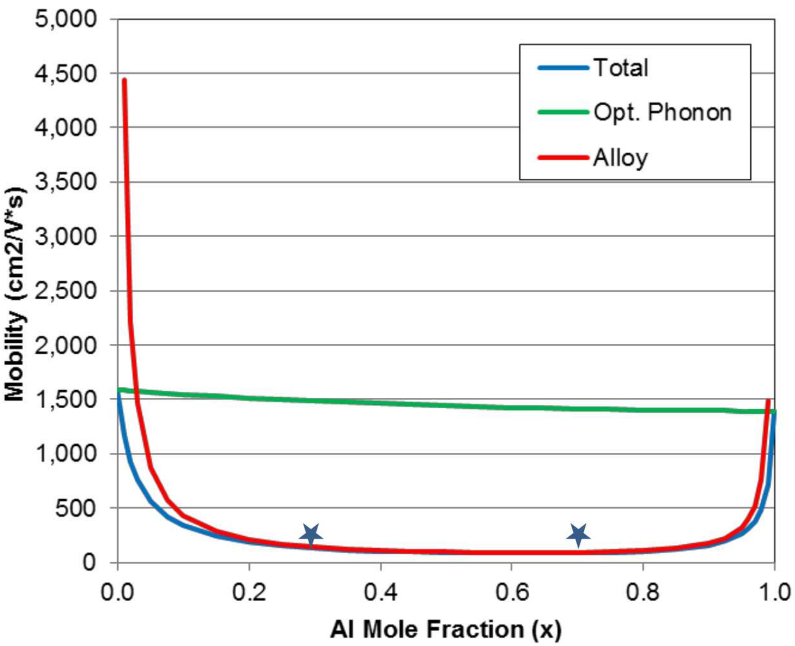
Material	E_{crit} (MV/cm)
Si	0.3
SiC	3.4
GaN	4.0
$Al_{0.3}Ga_{0.7}N$	7.3
β-Ga_2O_3	8
$Al_{0.7}Ga_{0.3}N$	12.7
AlN	17



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

AlGaN Alloy Mobilities are Smaller than Binary Alloys



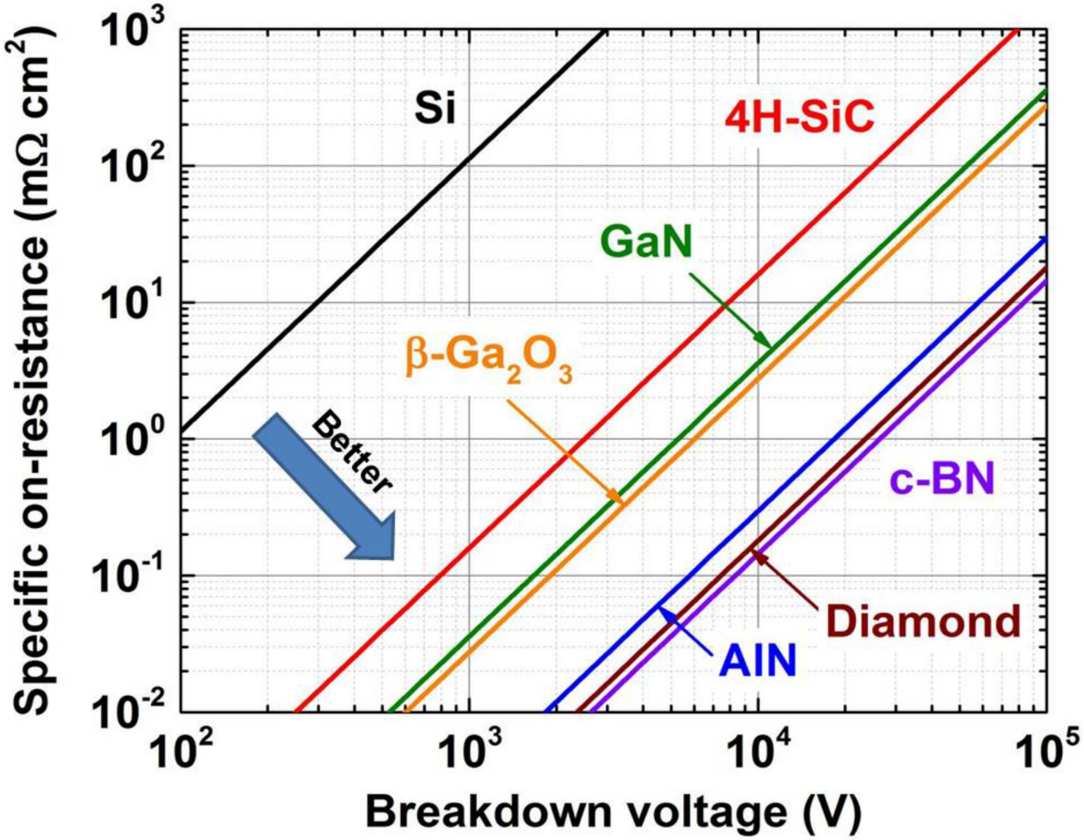


$Al_xGa_{1-x}N$ mobility increases markedly at x > 0.9

Binary alloy mobility drops markedly with (extreme) temperature

Unipolar Figure of Merit Based on Best-Known Parameters

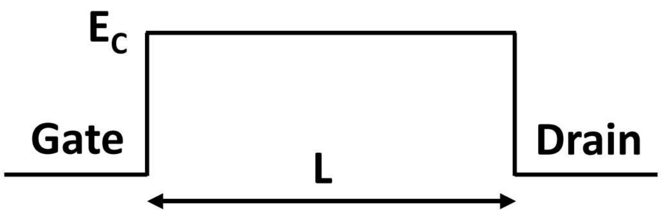
Utilizes refreshed parameters for WBGs and best-known parameters for UWBGs

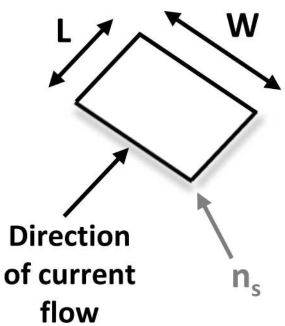


- **Diamond, c-BN, and AlN lead the pack**
  - **c-BN the least mature (difficult to grow in cubic form)**
- **Caveats:**
  - **Some material parameters are unknown**
  - **Some material parameters are not constants**
  - **Assumes full ionization of dopants**
  - **Unipolar only**

Lateral Power Device Figure of Merit

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



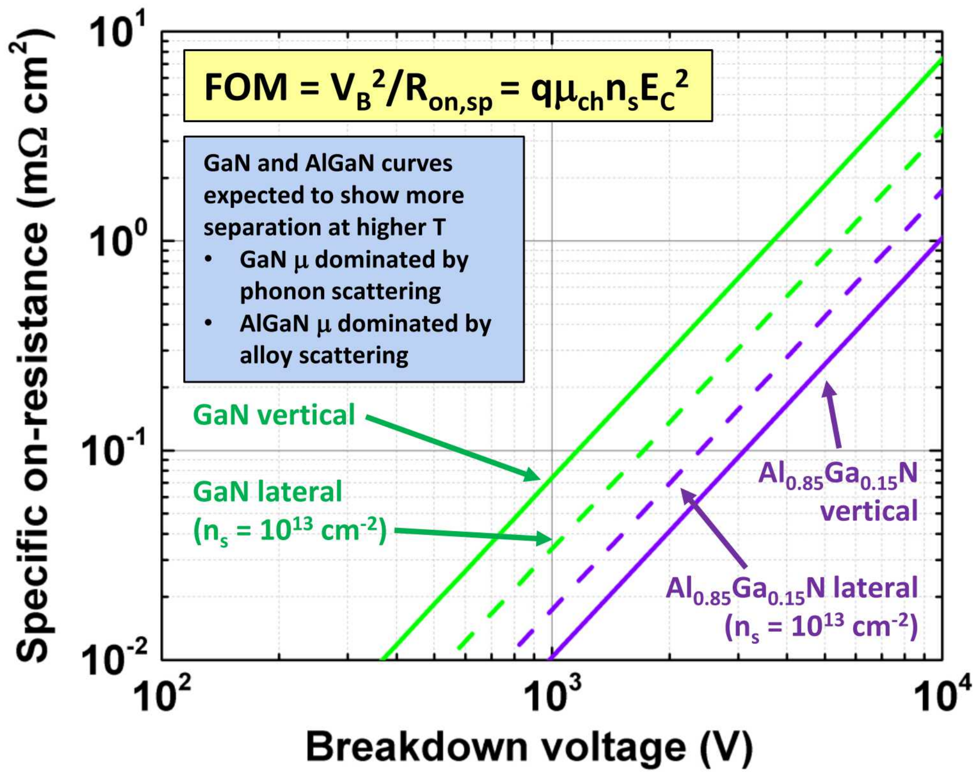


$$V_B = E_C L$$

$$R_{on} = \frac{L}{W q \mu_{ch} n_s}$$

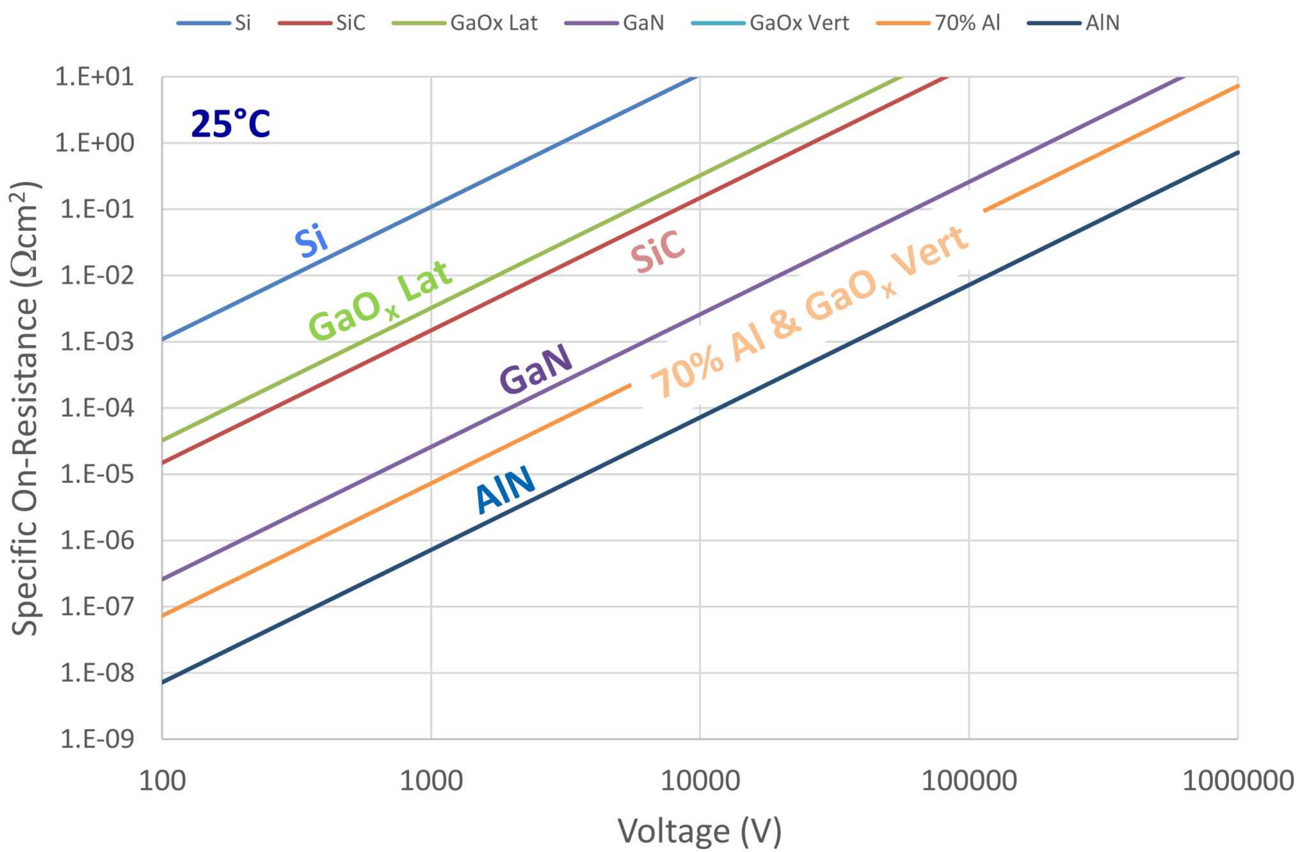
$$R_{on,sp} = R_{on} W L = \frac{L^2}{q \mu_{ch} n_s}$$

$$FOM = \frac{V_B^2}{R_{on,sp}} = q \mu_{ch} n_s E_C^2$$



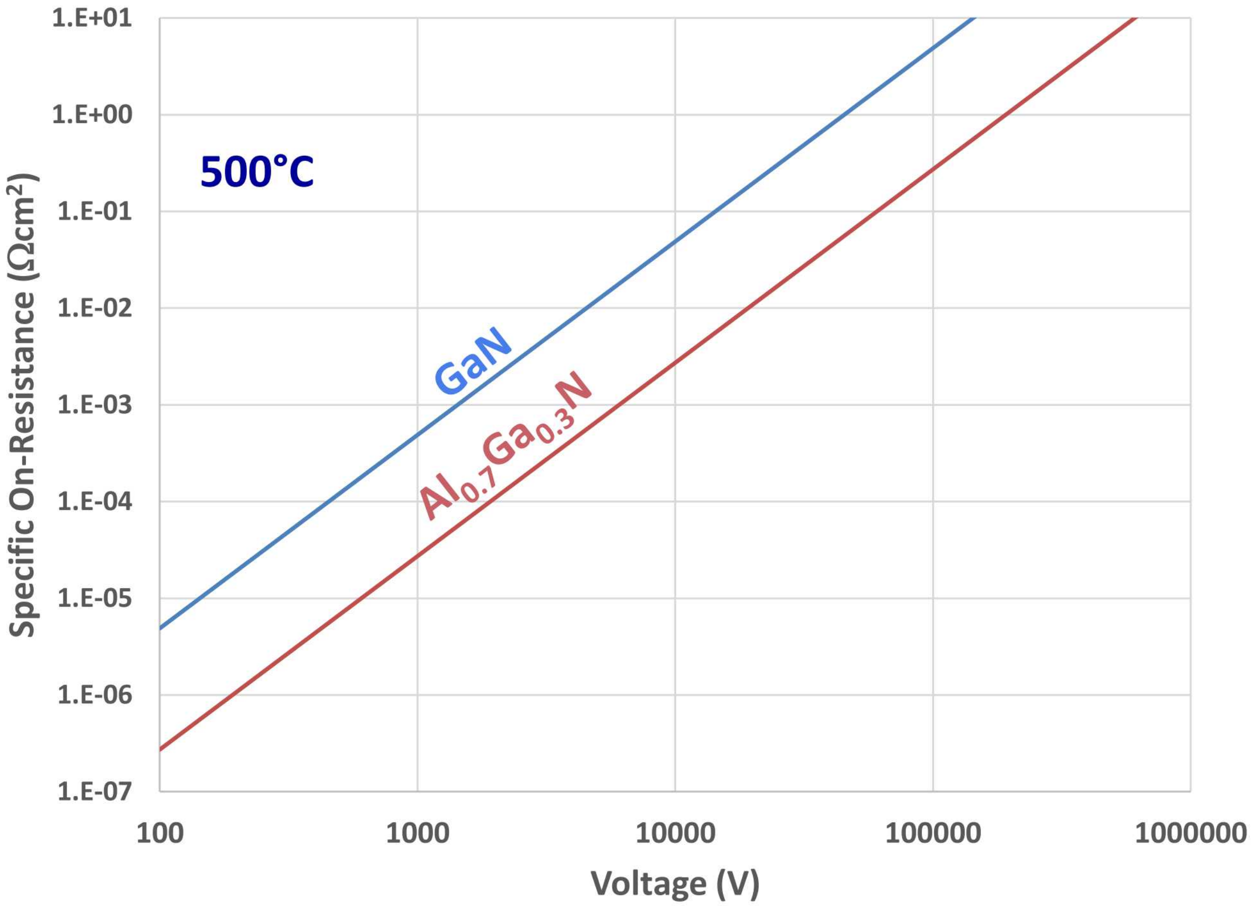
- **Proportional to E_C^2 rather than E_C^3, but high n_s can result in high FOM**

Room Temperature Figure of Merit Lateral Comparison



- **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**

High Temperature FoM Lateral Performance

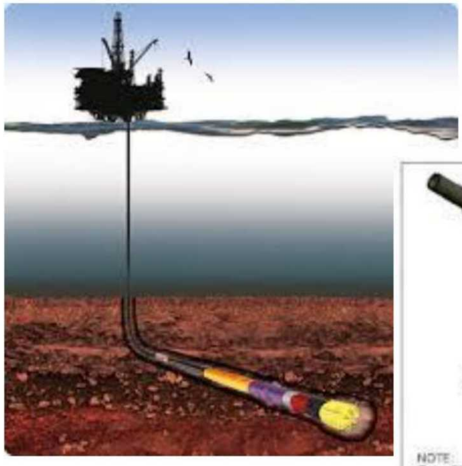


FOM for $Al_{0.7}Ga_{0.3}N$ HEMT is 16x superior to that for GaN at extreme temperature

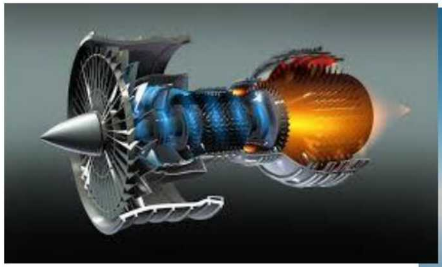
Extreme Environment Applications

Relevant extreme environments for power electronics:

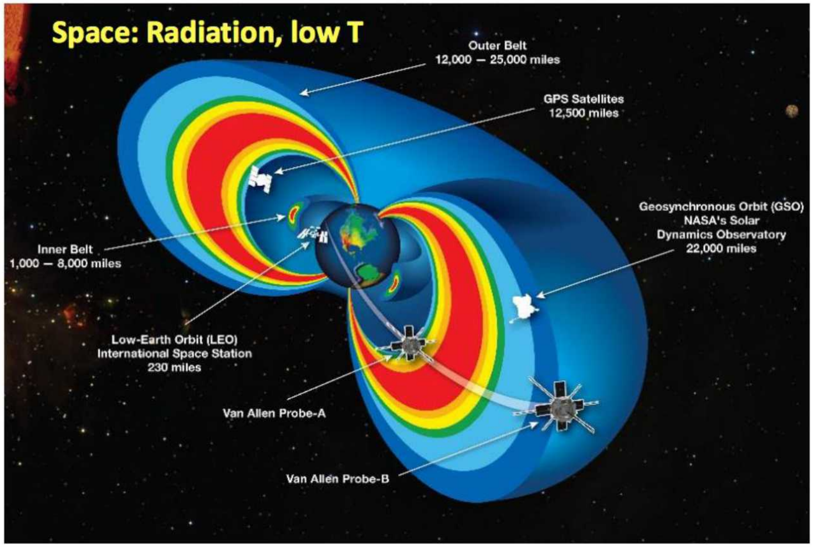
- **Temperature extremes**
- **Vibration**
- **Radiation**



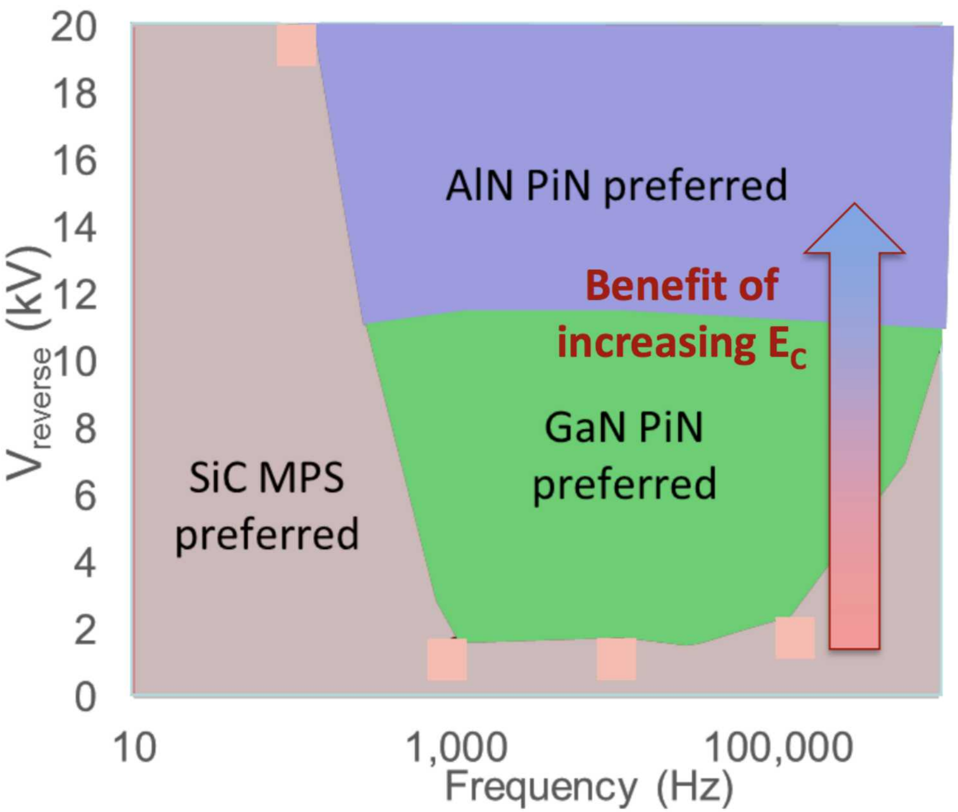
Down-hole: High T, vibration



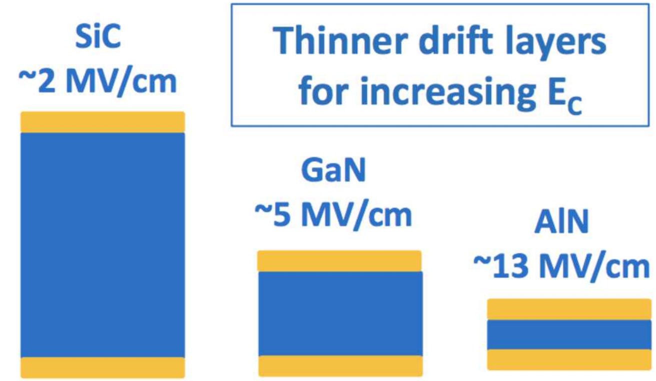
Aviation: High T, vibration



Avalanche ruggedness is important for numerous power conversion circuits



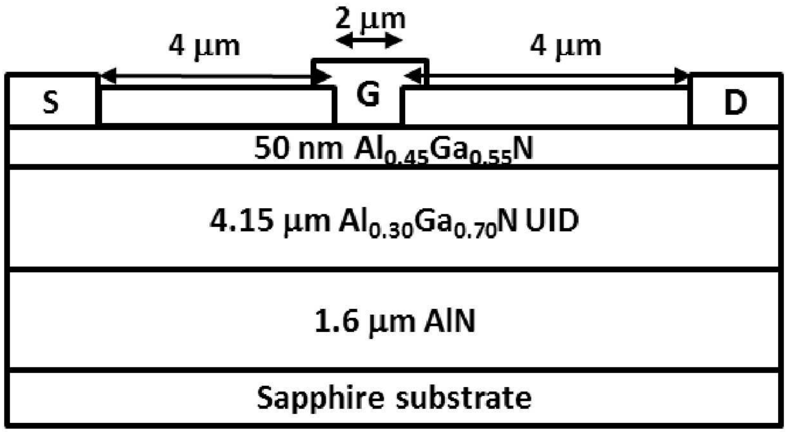
300 K, 50% duty cycle, 500 A/cm^2

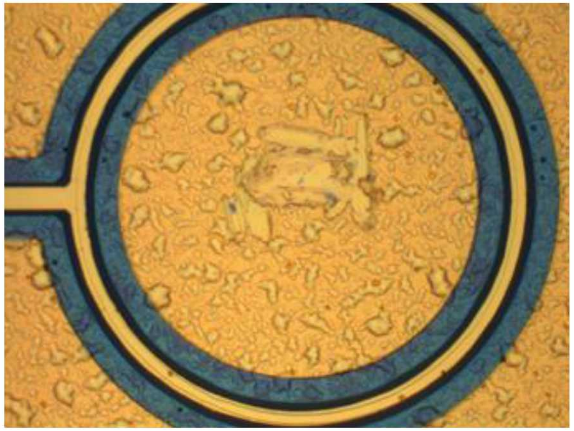


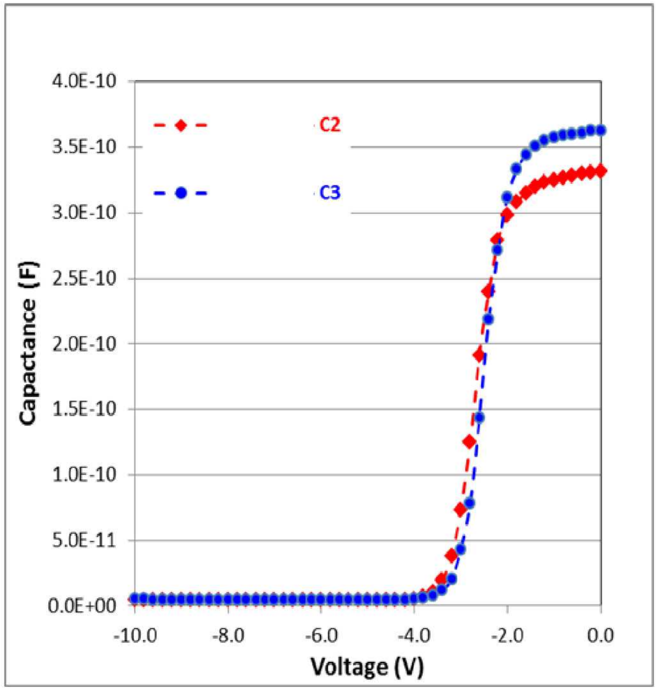
- **GaN and AlN preferred at high voltages over mid-frequency range**
  - **Benefit of higher E_C**
  - **Not as beneficial at low and high frequency (low conductivity modulation and increasing reverse recovery)**
- **Examined PiN diodes since peak field is buried below surface**
  - **Part of more advanced devices**
  - **Also must consider Schottky**

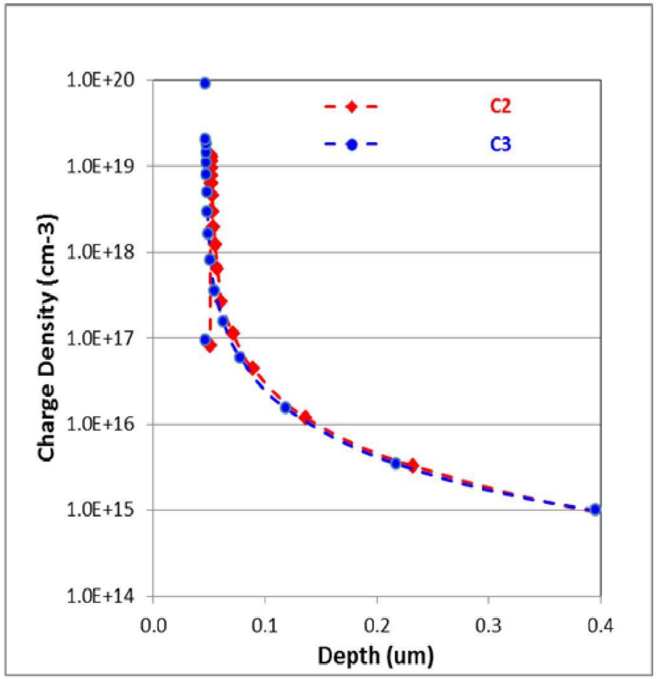
J. Flicker et al., WiPDA 2017
Analysis based on method in Morisette and Cooper, TED 49(9), 1657 (2002)

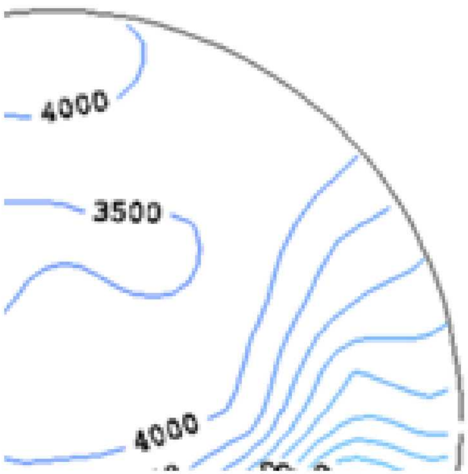
D-mode $Al_{0.45}Ga_{0.55}N$/ $Al_{0.3}Ga_{0.7}N$ HEMT



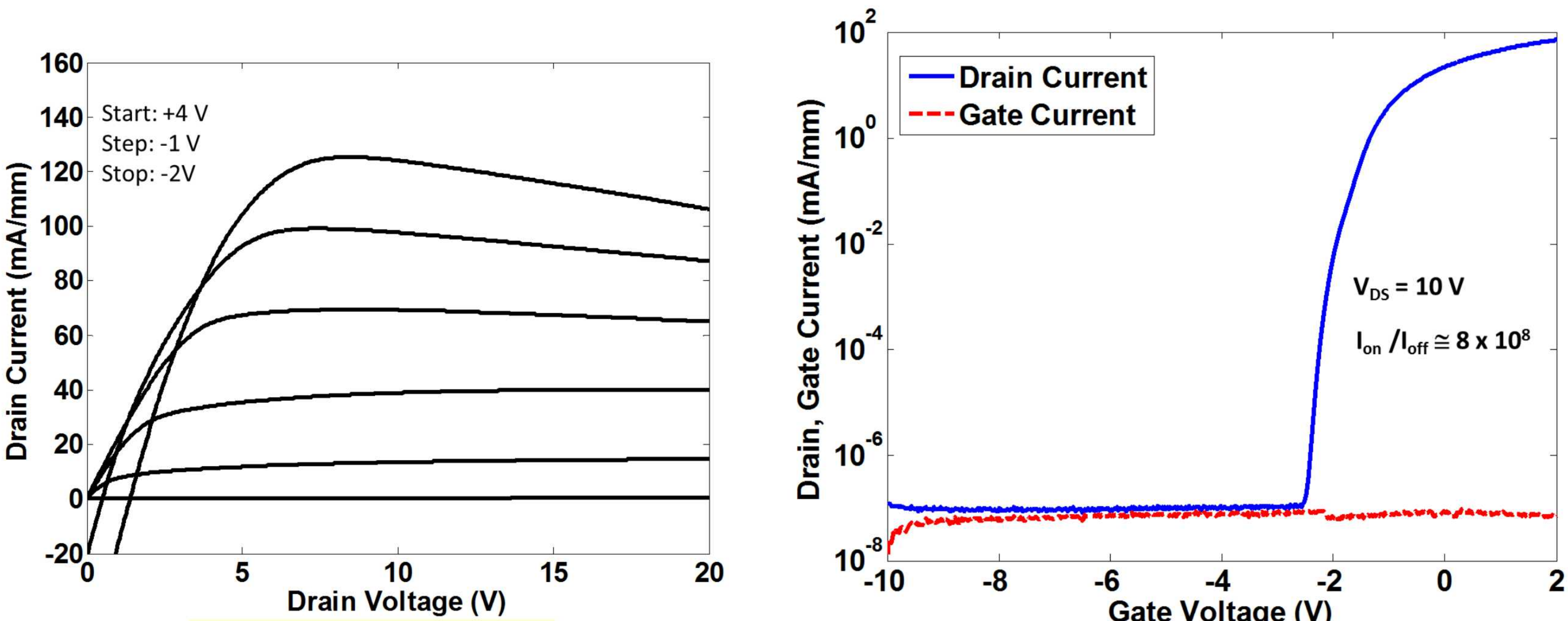








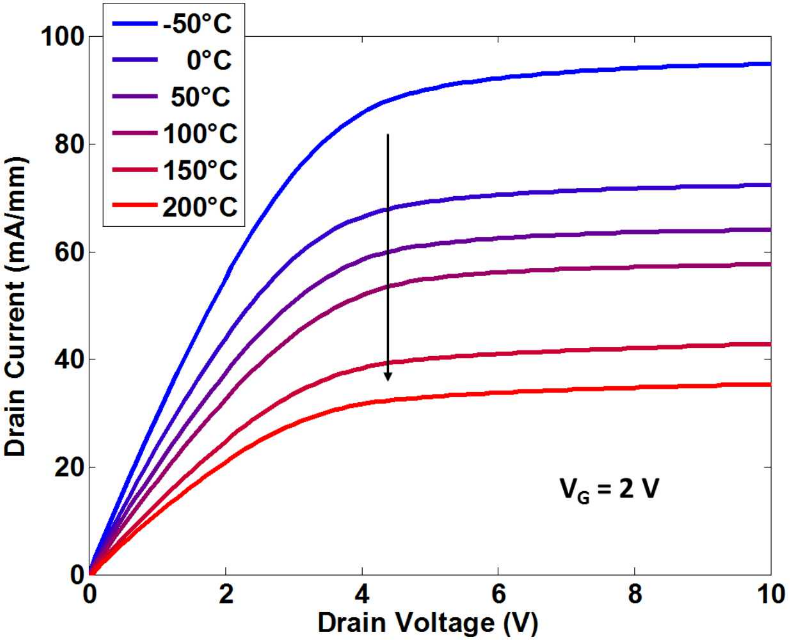
25°C Transfer and Output Characteristics for “45/30” HEMT



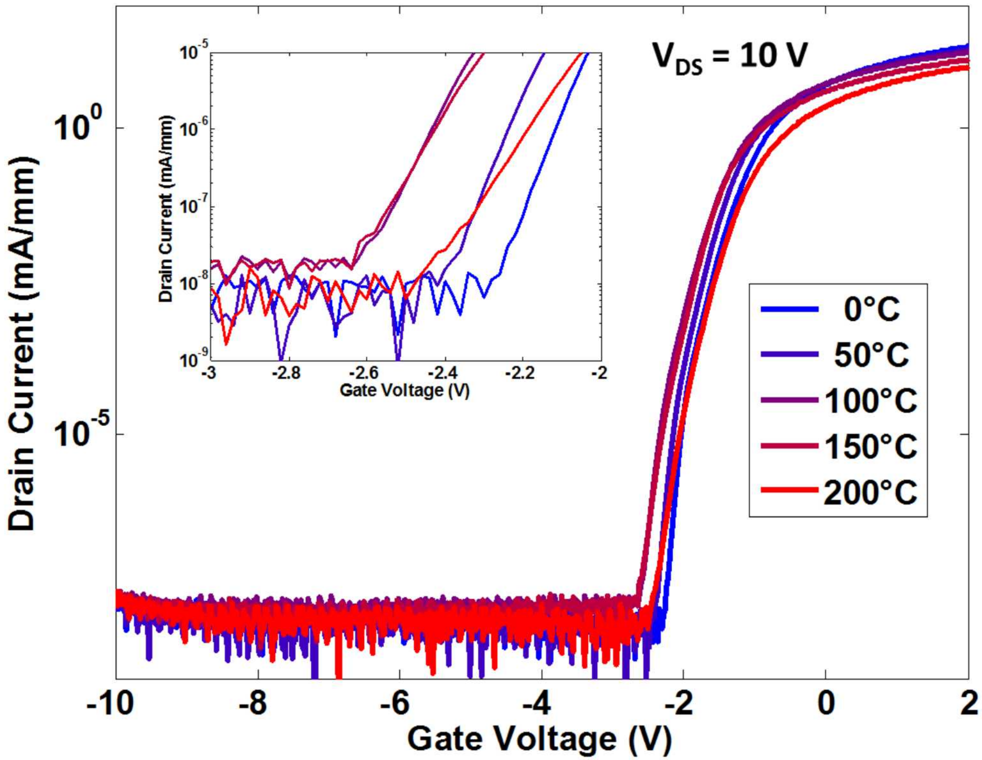
Baca *et al*. JSSST 6, S3010 (2017).

- **Linear through the origin I-V due to ~2.5 x 10^{-5} Ω-cm² 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

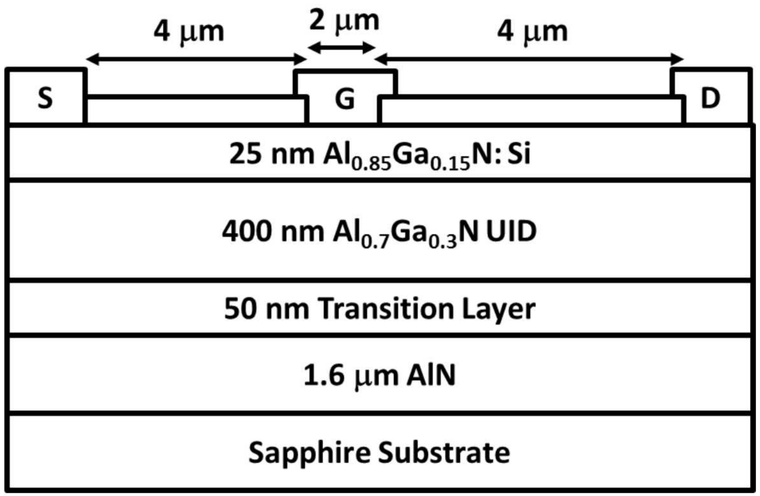


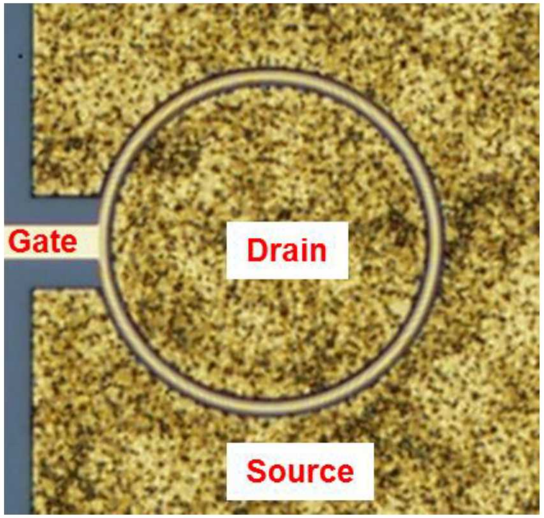
Baca *et al*. JSSST 6, S3010 (2017).

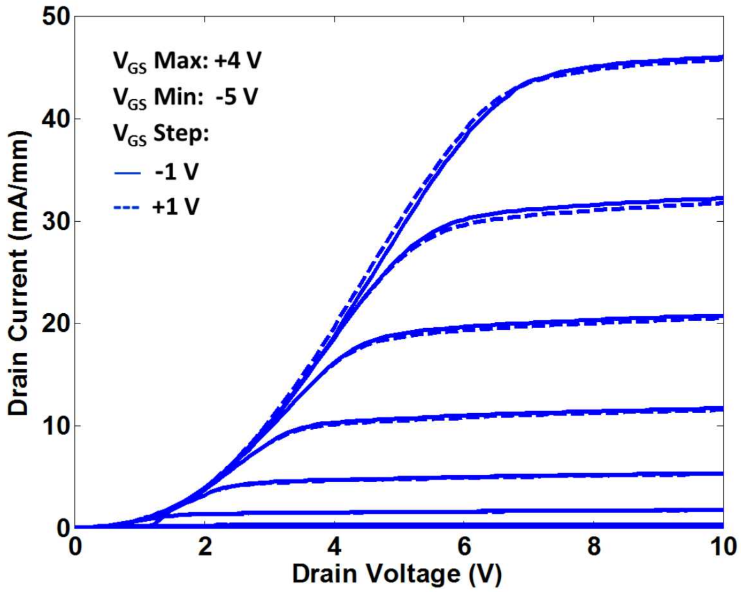


- **Drain current decreases monotonically with temperature**
- **Exceptionally low leakage current is invariant with temperature**
- **Subthreshold slope varies slightly with temperature**

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



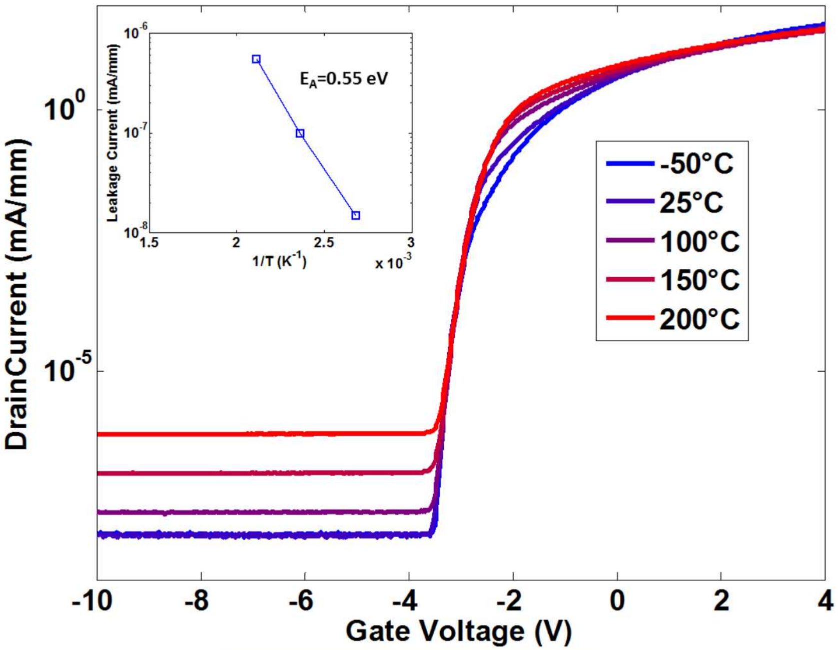




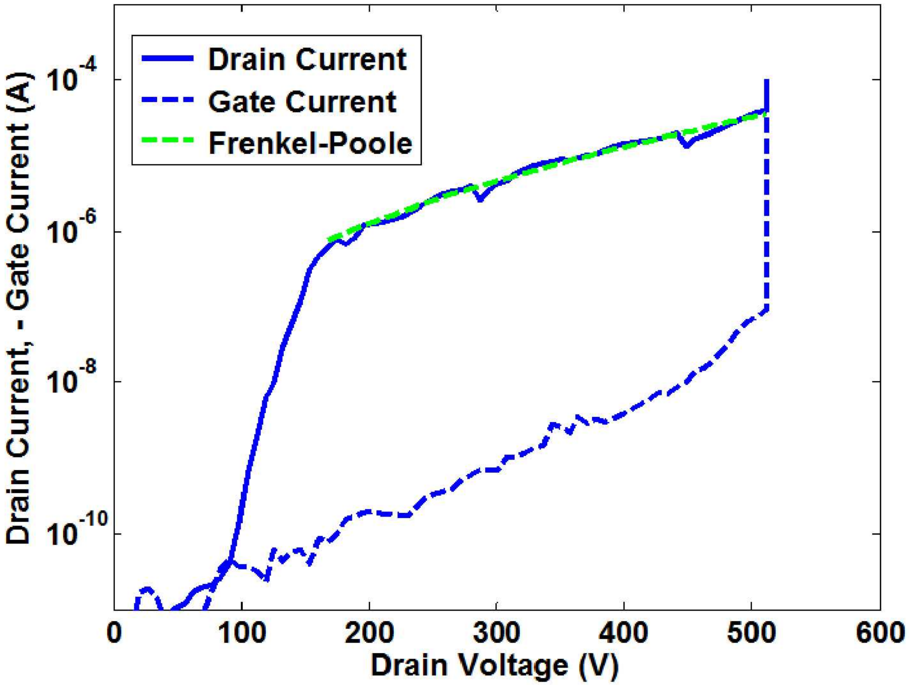
Baca *et al*. JSSST 6, Q161 (2017).

- **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

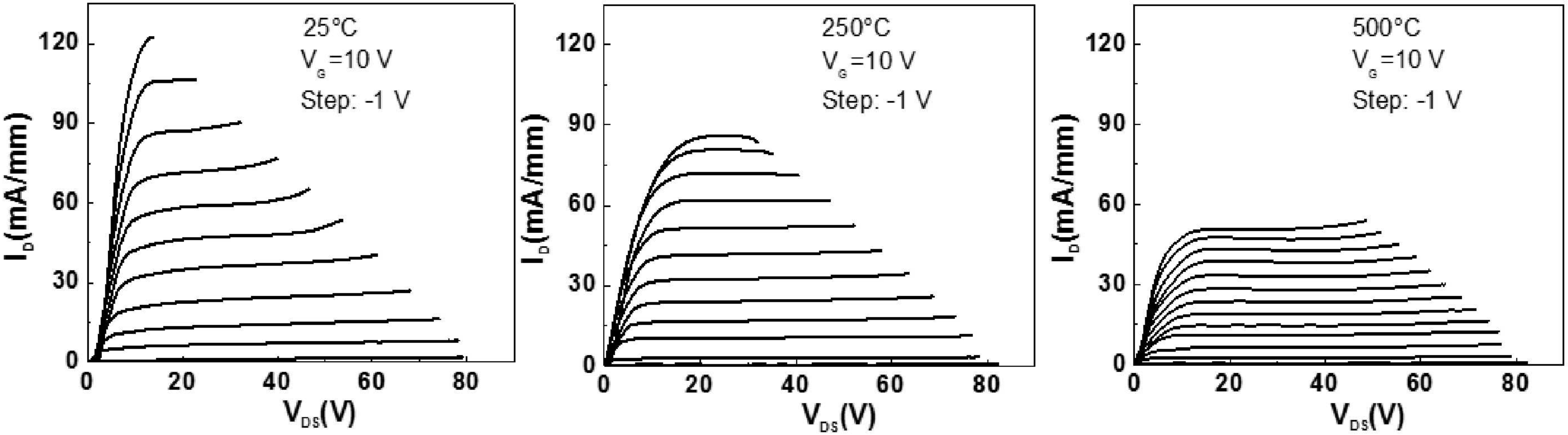


Baca *et al*. JSSST 6, Q161 (2017).



- **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**

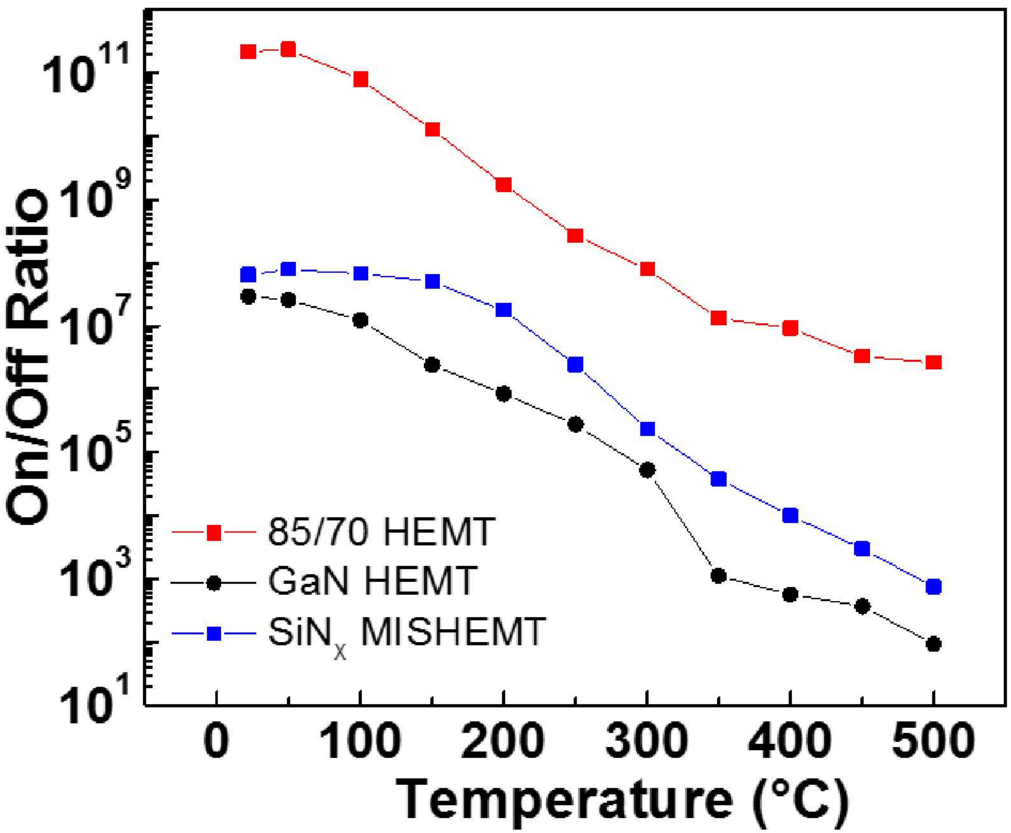
Extreme Temperature Operation of D-mode “85/70” HEMT



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**

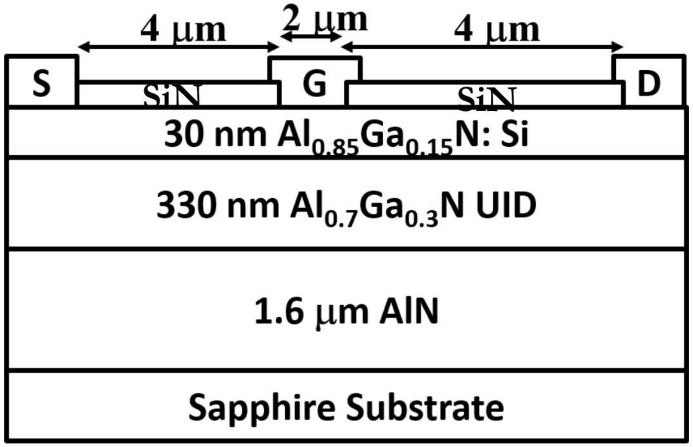
On/Off Ratio of D-mode “85/70” HEMT is Favorable at High Temperature Operation



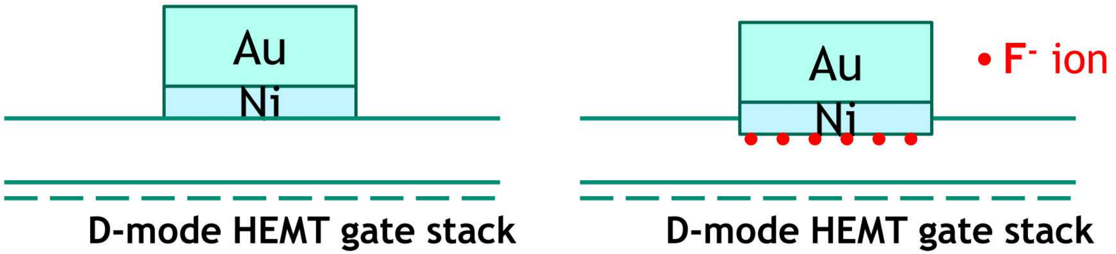
Carey *et al*. submitted to IEEE Trans. El. Dev.

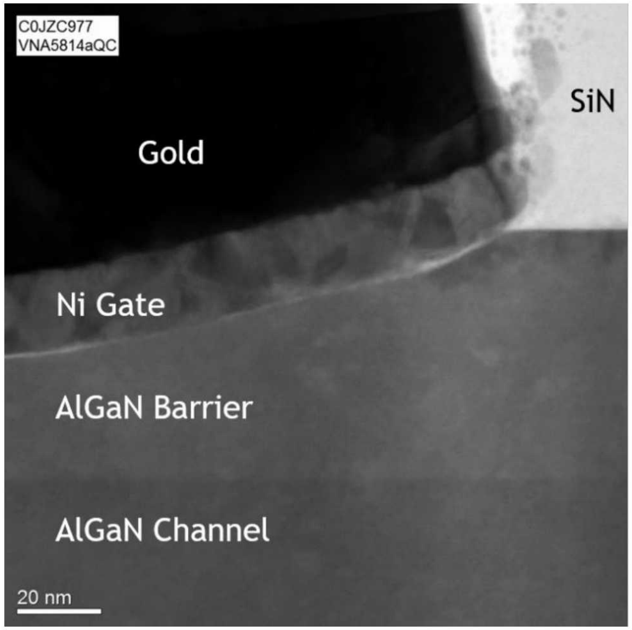
- **Al-rich HEMT maintains excellent On/Off ratio at 500°C and GaN doesn’t**
- **On/Off ratio is fairly flat from 200-500°C**

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



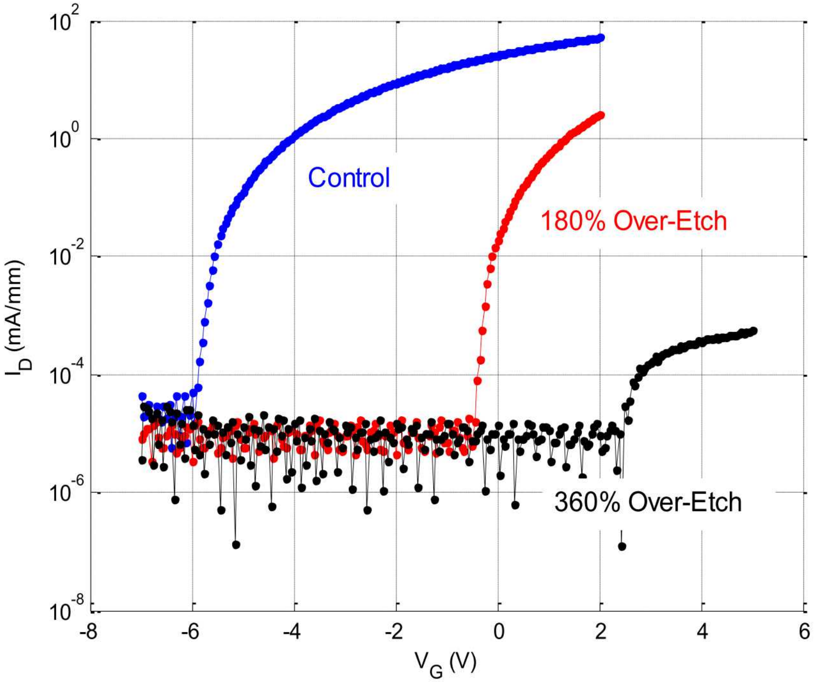
Motivated by Cai *et al.*, IEEE Trans. El. Dev. 53, 2223 (2006)



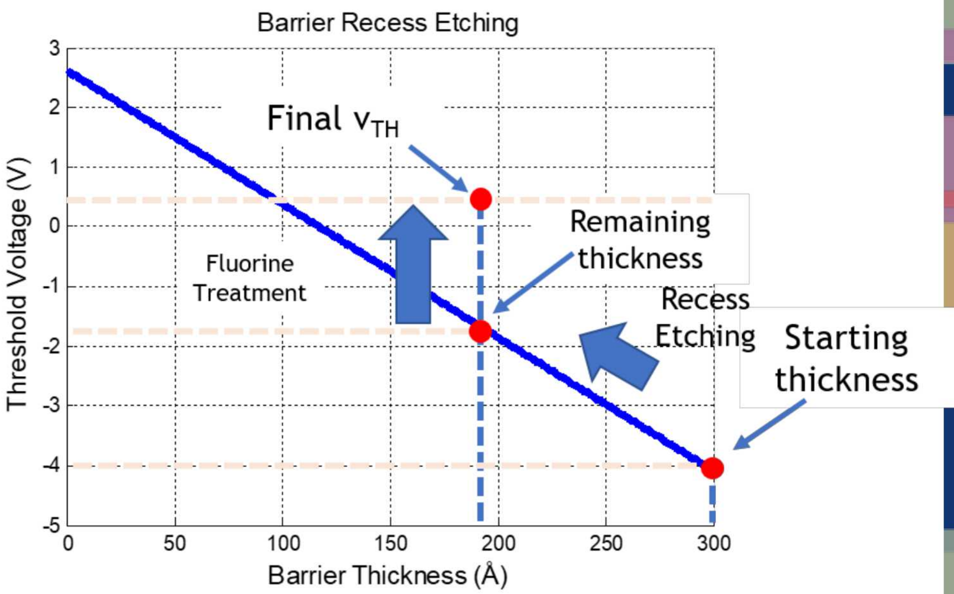


F-plasma **from reactive ion etch (through SiN): combination of AlGaN etch and incorporation of *F*$^-$ ions near the surface**

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



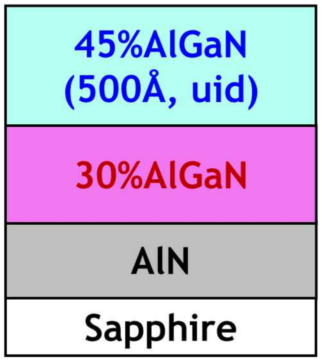
$$v_{TH} = \varphi_b - \frac{q\sigma_p t_{barrier}}{\varepsilon_r \varepsilon_0} - \Delta E_c$$

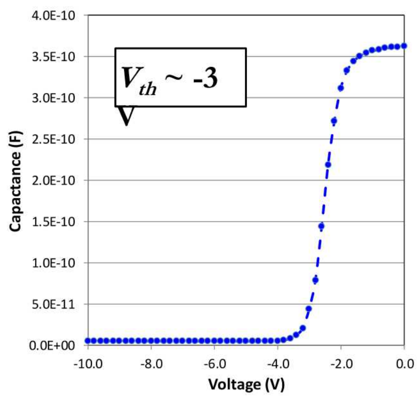


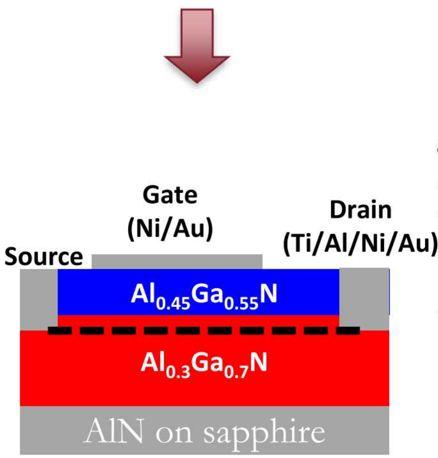
***F-plasma* from reactive ion etch (through SiN, then into AlGaN): combination of AlGaN etch and incorporation of *F^-* ions near the surface**

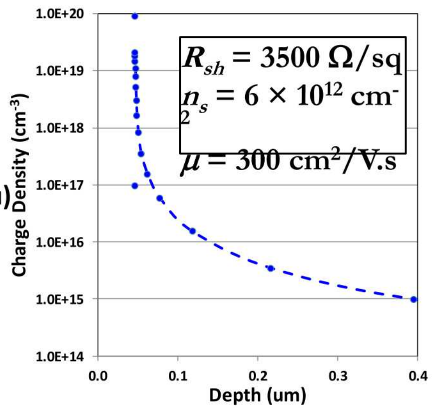
2nd Approach to E-mode AlGaN using *p*-type gate

D-mode 45/30 HEMT

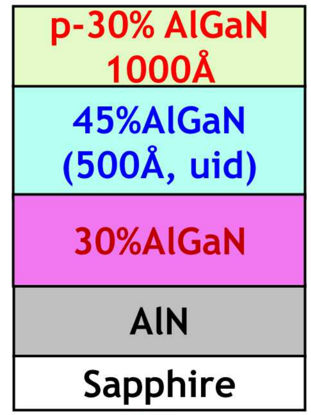


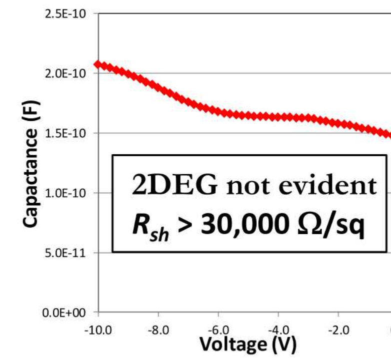


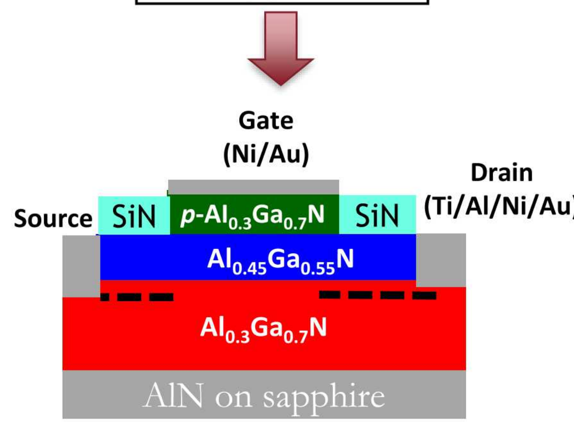




E-mode *p*-30/45/30 HEMT



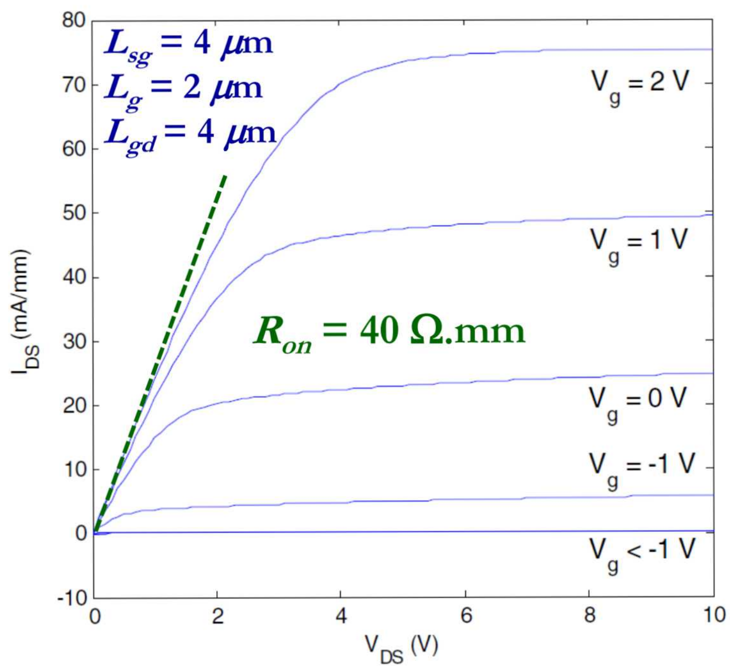




- MOVPE-grown UID $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ **(45/30)** on $Al_{0.3}Ga_{0.7}N$-on AlN-on saphhire
- *p*-$Al_{0.3}Ga_{0.7}N/Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ **(*p*-30/45/30)** heterostructures very resistive
- *p*-AlGaN gate defined by ICP etching and passivated with SiN

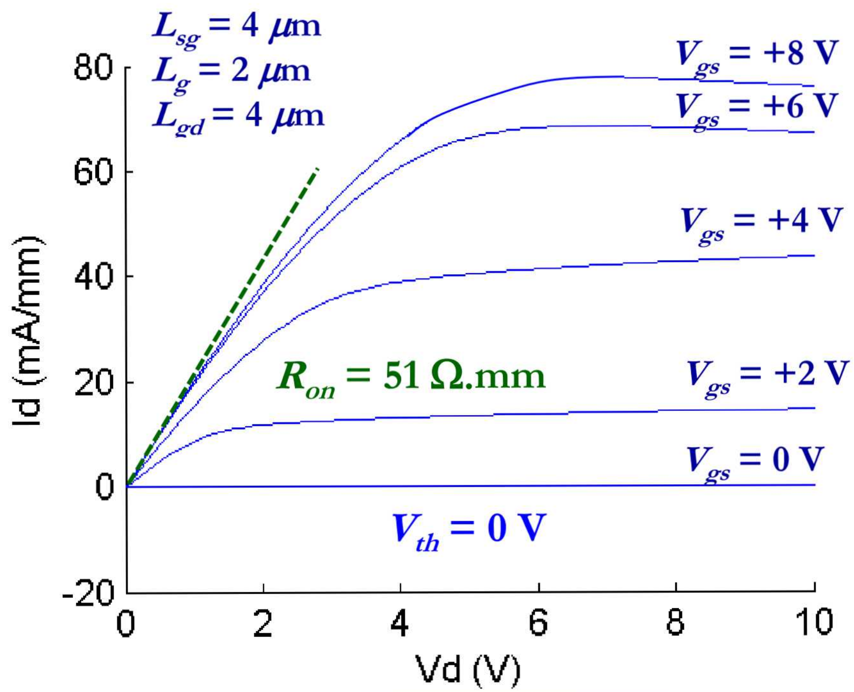
E-mode *p*-30/45/30 with high current density

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



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

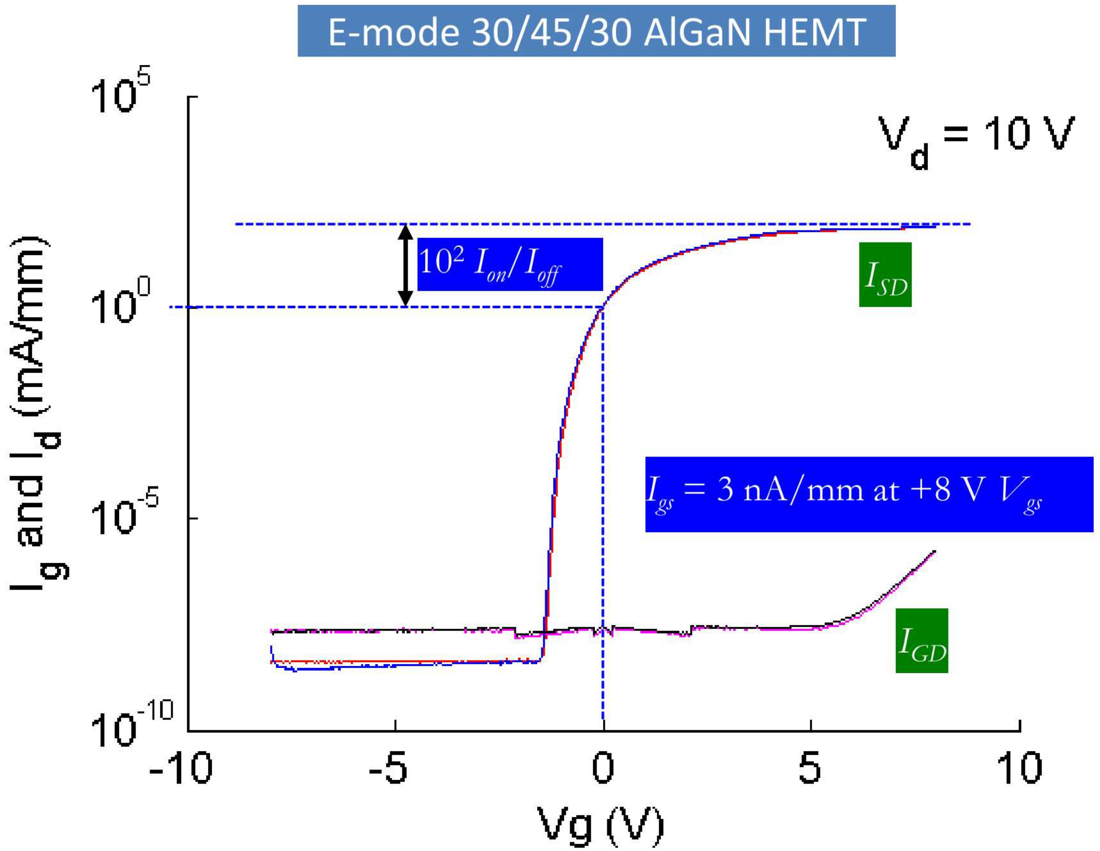
I-V of E-mode 30/45/30 AlGaN HEMT



Douglas, *et al.*, 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

UWBG Development to Enable MEMS

Piezoelectric Aluminum Nitride

Piezoelectric

Material can couple electrical and mechanical energy
- Direct effect
- Converse effect

Magnitude characterized by piezoelectric constant (d_{im})

Efficiency characterized by electromechanical coupling coefficient (k_t)

Direct Effect	Converse Effect
Electrically polarize in response to an applied stress	Mechanically strain in response to an applied electric field
$P_i = d_{im} \cdot \sigma_m$	$\varepsilon_m = d_{im} \cdot E_i$

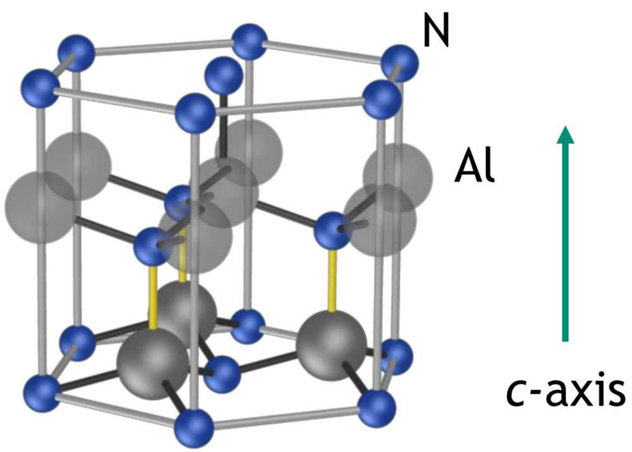
Aluminum Nitride (AlN)

Piezoelectric film
- d_{33}= 5.5 pC/N
- d_{31}= -2.5 pC/N

Reactive sputter deposition

Low temperature deposition ~350˚C

CMOS compatible



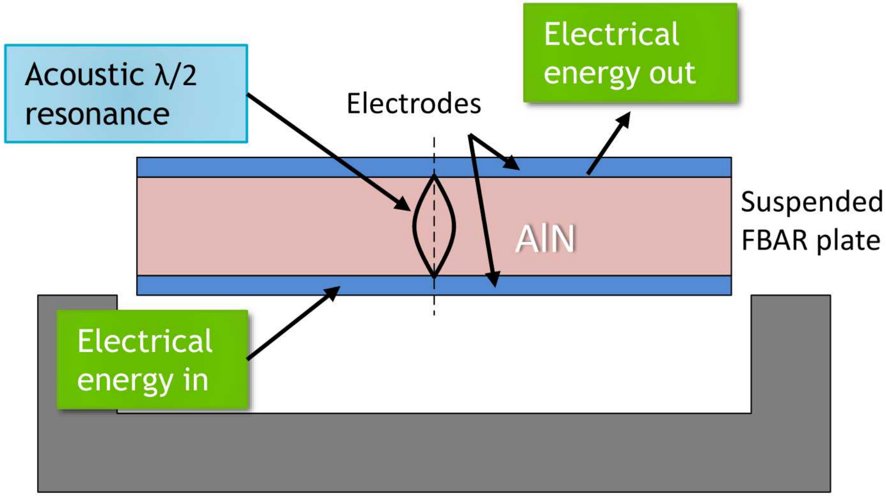
Hexagonal Wurtzite
a= 3.144 Å
c= 5.046 Å

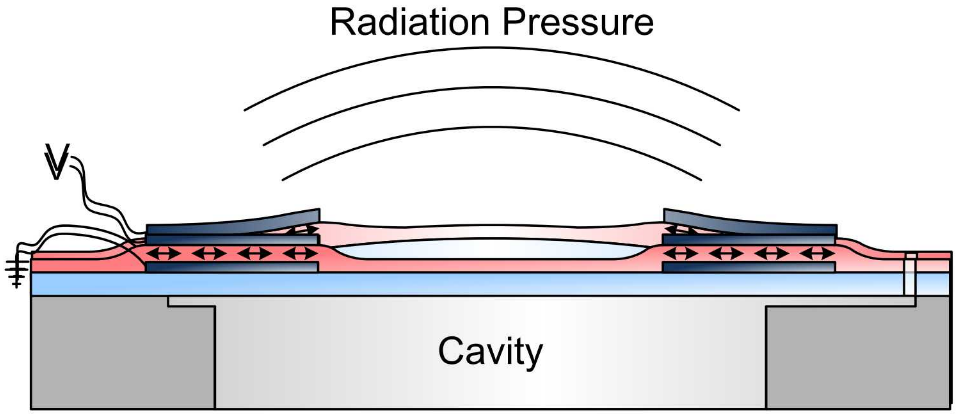
AlN Commercial Success

Film Bulk Acoustic Resonator (FBAR) Filters

- Half-wavelength, thickness mode resonators
- Filter frequency is set by film thickness
- Commercial success for AlN MEMS
  - >1 billion units produced per year from Avago Technologies
- More than 40 discrete filter die in the modern smartphone

- Piezoelectric Micromachined Ultrasonic Transducer (PMUT) Applications
  - Proximity sensing
  - Short range communication
  - Extreme high sound pressure level microphones
  - Imaging





Schematics courtesy of Ben Griffin

Influence of Sc Alloying in AlN

Piezoelectricity

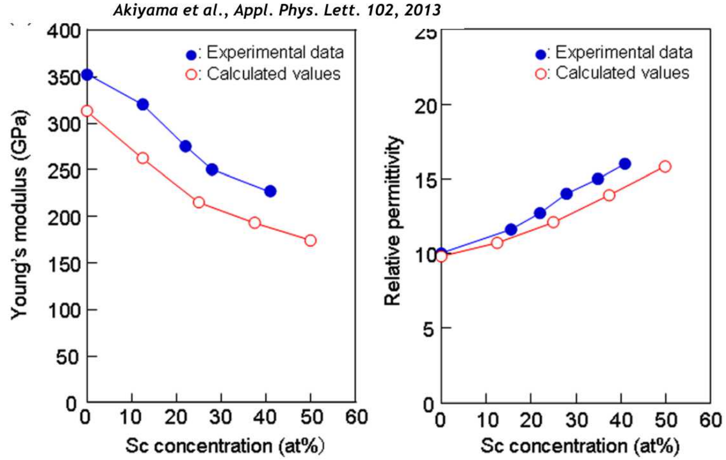
- Material can couple electrical and mechanical energy

ScAlN has the potential to replace current AlN technologies

Alloying Sc into AlN increase piezoelectric response

Challenges in depositing high Sc content films arise and has created a hurdle in current LDRD

Akiyama et al., Appl. Phys. Lett. 102, 2013

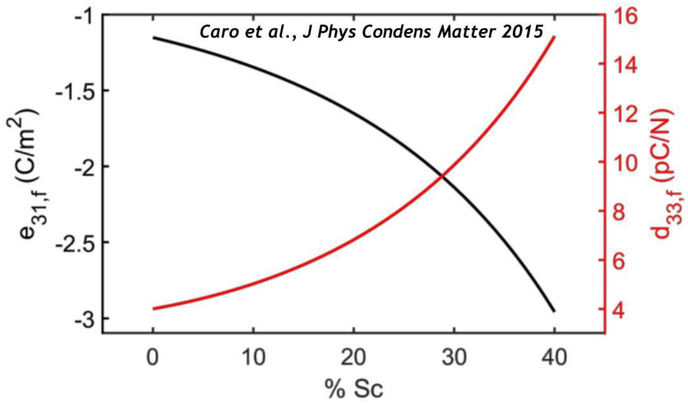


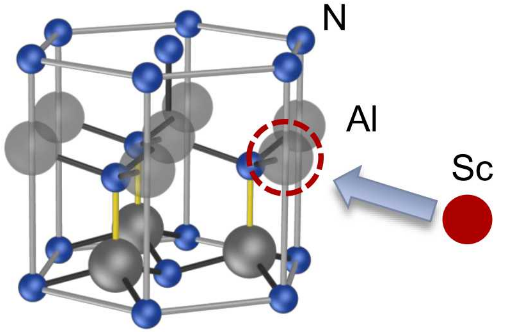
Device Performance Based on Properties

Resonators $$k_t^2 = \frac{e_{31}^2}{E_p \varepsilon_{33}}$$

Energy harvesting $$FOM = \frac{(e_{31,f})^2}{\varepsilon_{33,f}}$$

Sensors $$\frac{S}{N} = \frac{e_{31,f}}{\sqrt{\varepsilon_0 \varepsilon_{33,f} tan\delta}}$$





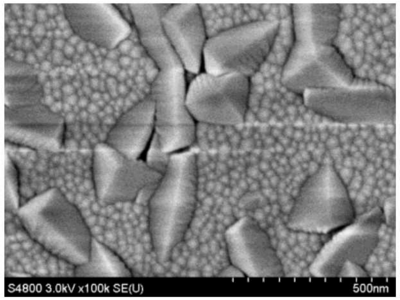
Challenges with Increasing % Sc and Recent Advances

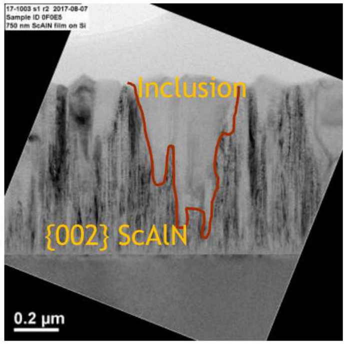
Secondary grain growth (inclusions) in ScAlN
- Increase with Sc concentrations
- Density controlled by processing parameters

Inclusions have a diffuse {100} orientation
- Fichtner *et. al., 2017*

Compressive stress suppresses inclusions
- Henry *et. al.,* 2018
- *Compressive stress not optimal for released MEMS*

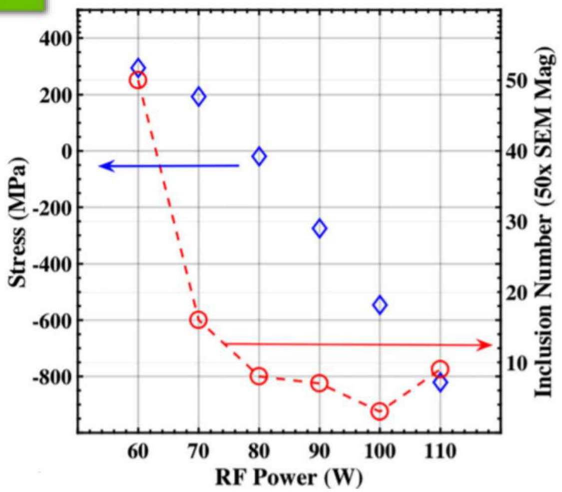
Platinum as a bottom electrode on 8” wafers
- Mertin *et al.,* 2018
- Full suppression of inclusions up to Sc 31%
- *Pt is not CMOS compatible and presents integration challenge*

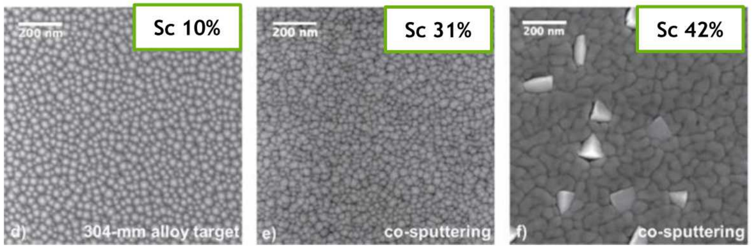




This work

M. D. Henry et al., J. Vac. Sci. Technol. B 36 (2018)





S. Mertin et al., Surf. Coat. Technol. (2018)

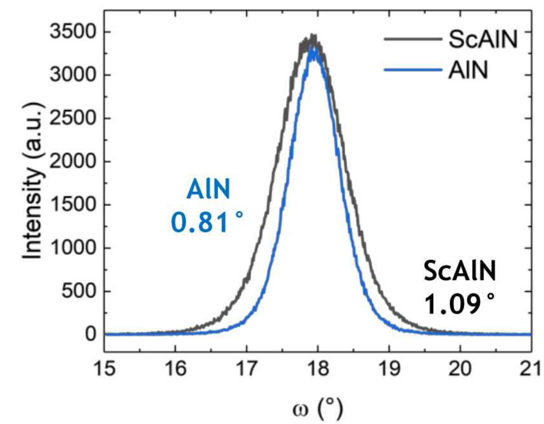
Results: AlN and ScAlN on AlCu

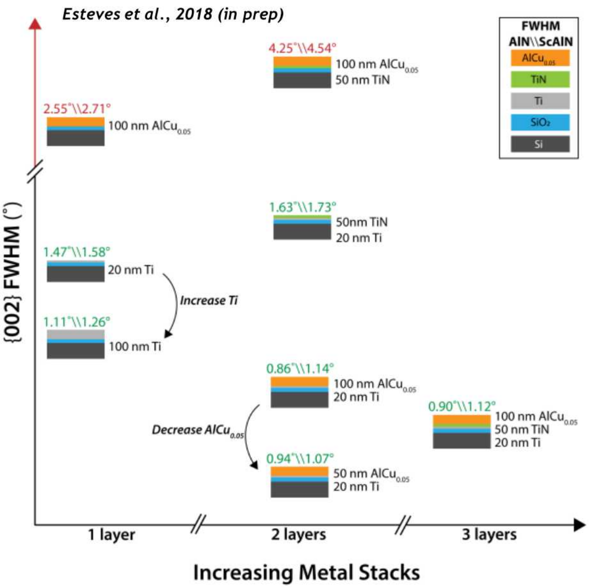
High-quality ScAlN has been deposited on various CMOS compatible metal stacks

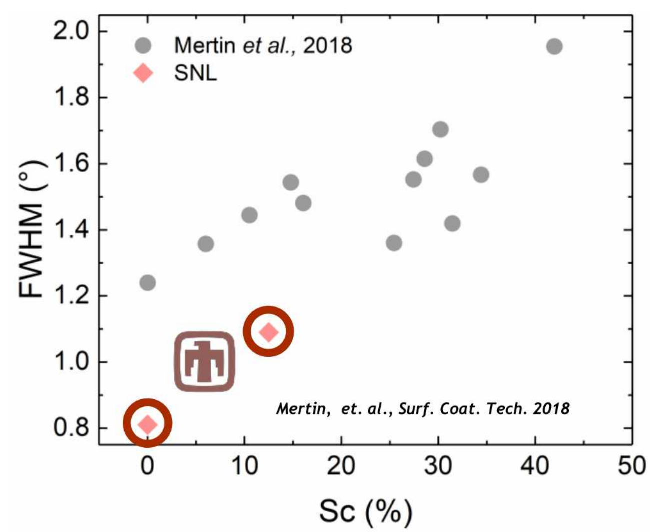
- Depositing ScAlN on CMOS metal is **extremely** valuable to industrial sector
- Attractive to industry leaders and has sparked collaboration

Optimal ScAlN film quality found in Ti, Ti/$AlCu_{0.05}$, and Ti/TiN/$AlCu_{0.05}$ metal stack

Present results are ***state-of-the-art*** for their given thickness and Sc composition







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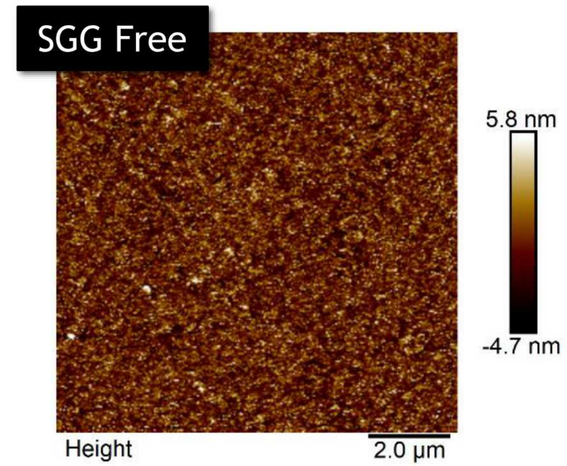
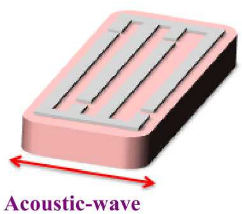


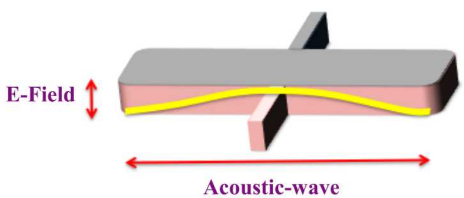
$Sc_{12.5}Al_{87.5}N$ on Ti/TiN/$AlCu_{0.05}$

Contour-Mode Resonators

High-quality ScAlN has been deposited on various CMOS compatible metal stacks

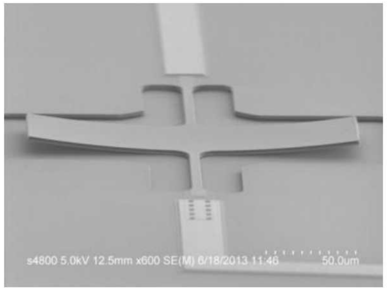
- Electric field in z-axis creates an acoustic wave in x-axis via piezoelectric effect
- Device architecture was chosen to show increases in electromechanical coupling with addition of Sc.

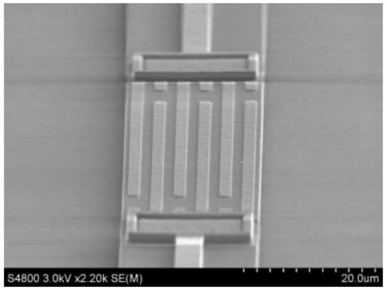


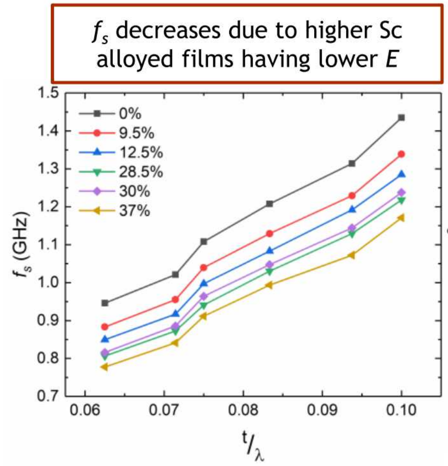


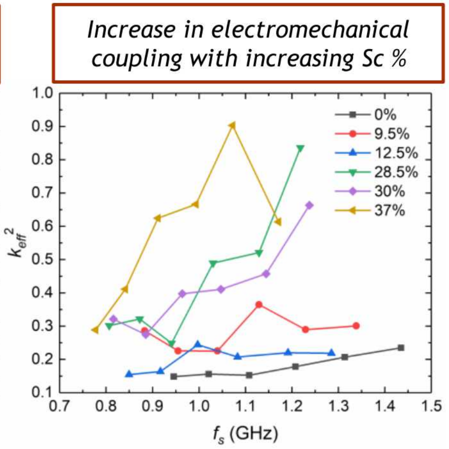
$$w = \frac{n l}{2}$$

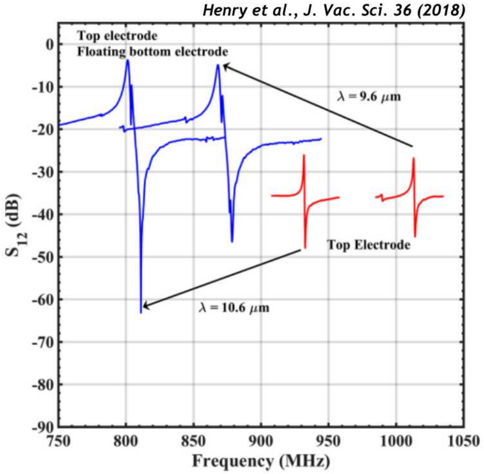
$$f = \frac{n}{l} = \frac{1}{2w} * \sqrt{\frac{\mathring{a} E * t}{\mathring{a} r * t}}$$







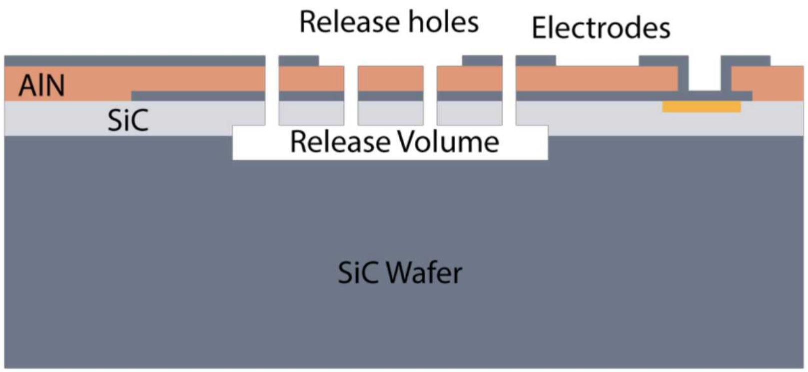




Henry et al., J. Vac. Sci. 36 (2018)

XMEMS Program

XMEMS Process



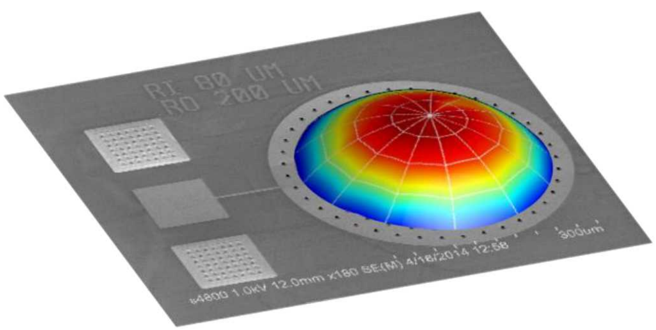
XMEMS process can fabricate devices capable of operating at elevated temperature

- AlN temperature limit >1000°C
- SiC temperature limit > 2000°C

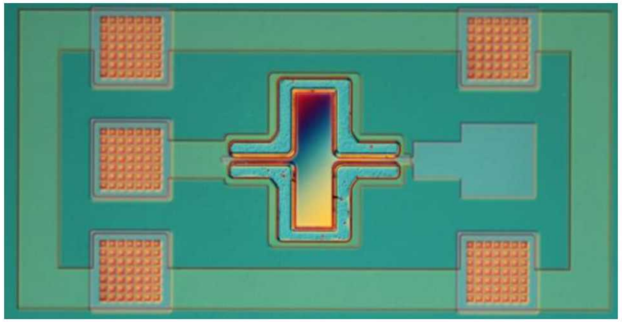
Devices fabricated

- **Ultrasonic transducer**
- **Microresonators**
- Accelerometers
- Phononic crystals
- Tuning forks

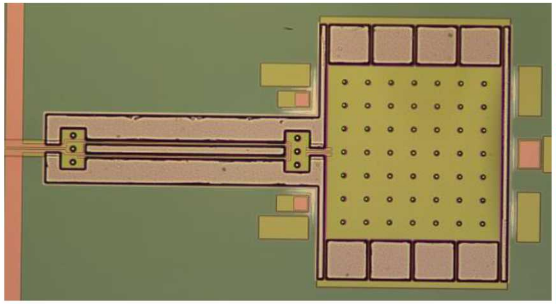
Piezoelectric Micromachined Ultrasonic Transducer (PMUT)



Microresonator



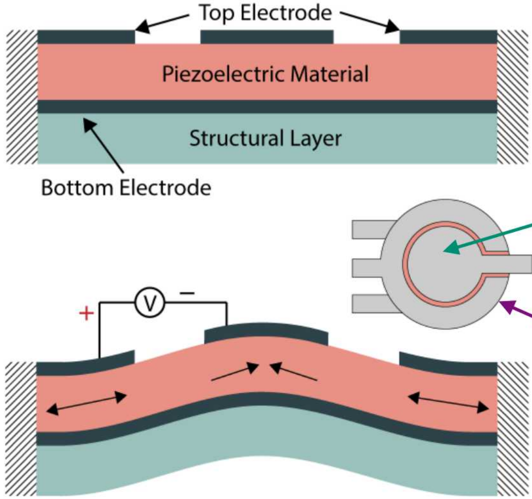
Accelerometer

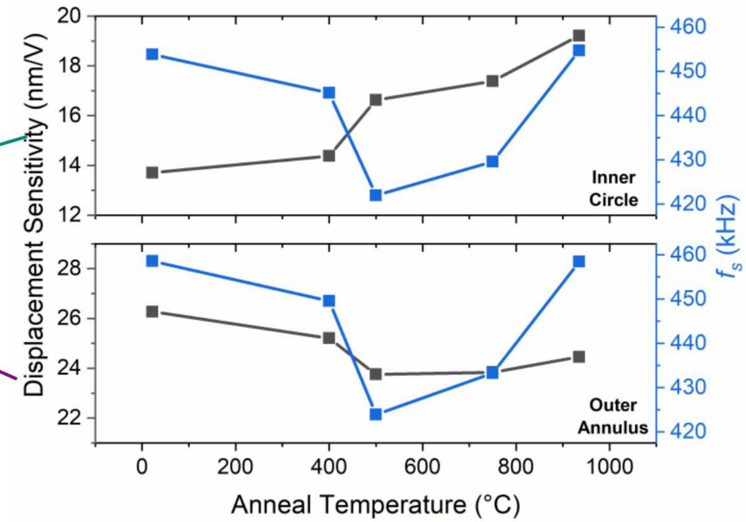


Esteves and Griffin et. al. J Microelectromech Syst (in prep) (2019)

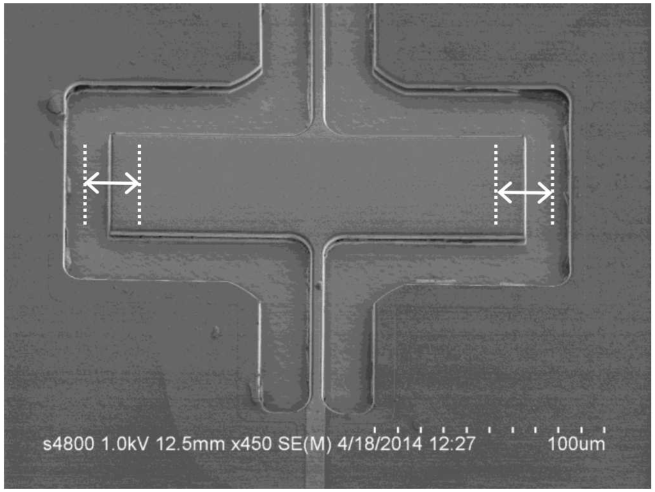
Post-Anneal Test Testing

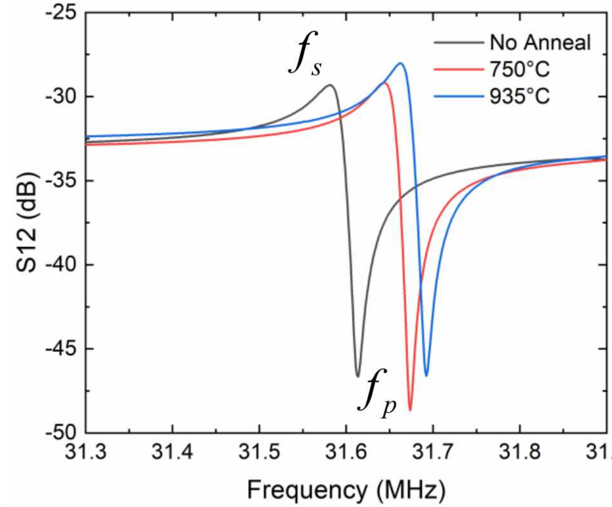
PMUT





Microresonator





Quality Factor

$$Q = \frac{f_s}{\Delta f_{3dB}}$$

Electromechanical Coupling

$$k_{eff}^2 = \frac{f_s^2 - f_p^2}{f_p^2}$$

Esteves and Griffin et. al. J Microelectromech Syst (in prep) (2019)

In situ Testing of Microresonator

Heated chuck from to 500°C in steps of 50°C

Temperature hysteresis loop results in permanent frequency shift in unannealed sample

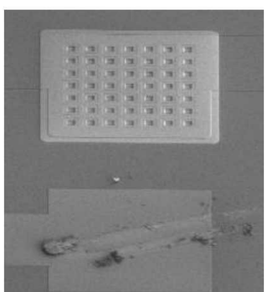
No degradation in piezoelectric performance

Challenges

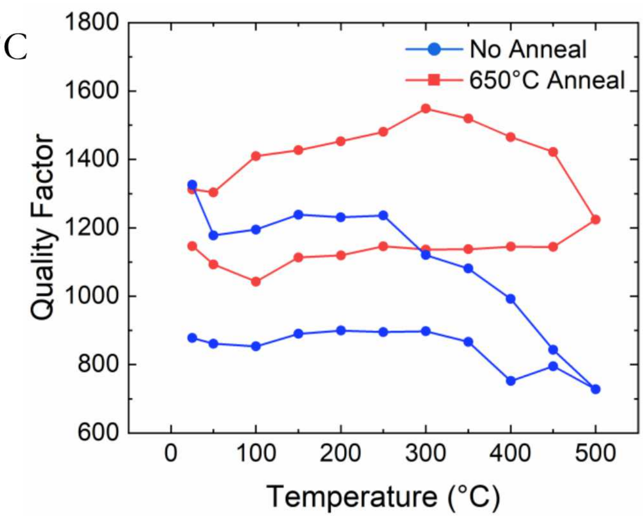
Quality factor degradation observed

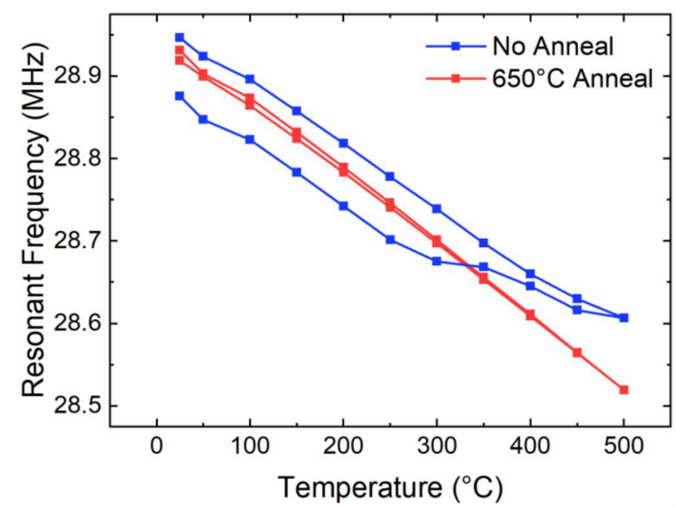
Potential sources
- Probe contact issues
- Carbon contamination
- Via degradation

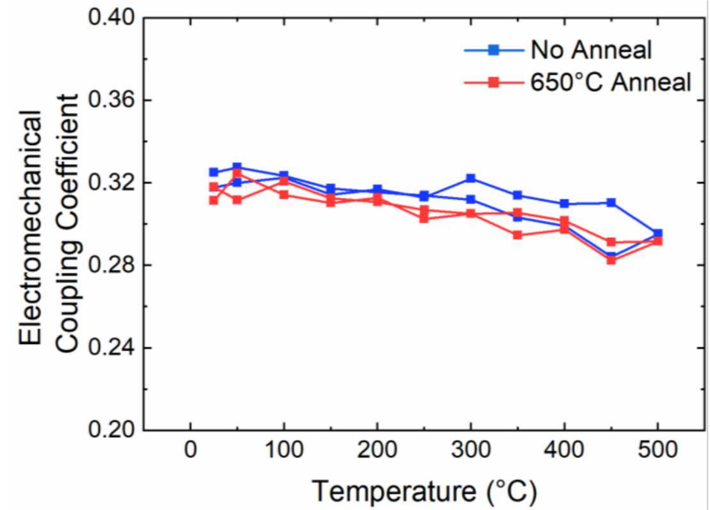
expected to form at 500°C



Probe tip shift from thermal expansion







Esteves and Griffin et. al. J Microelectromech Syst (in prep) (2019)

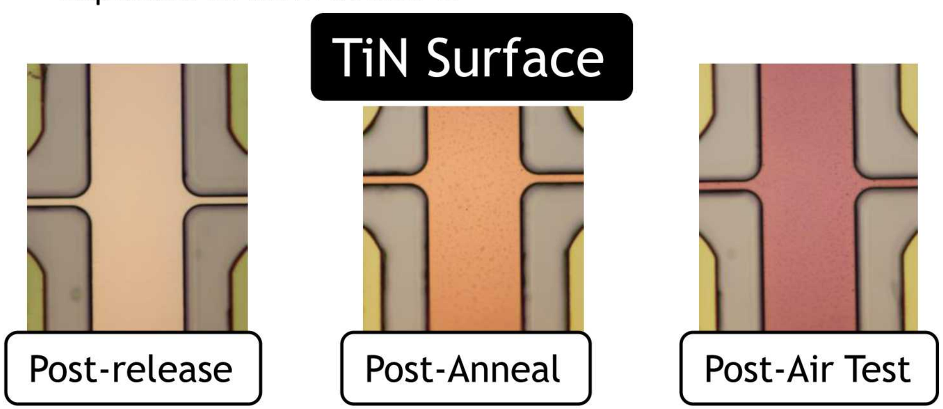
In-situ Testing of Microresonator

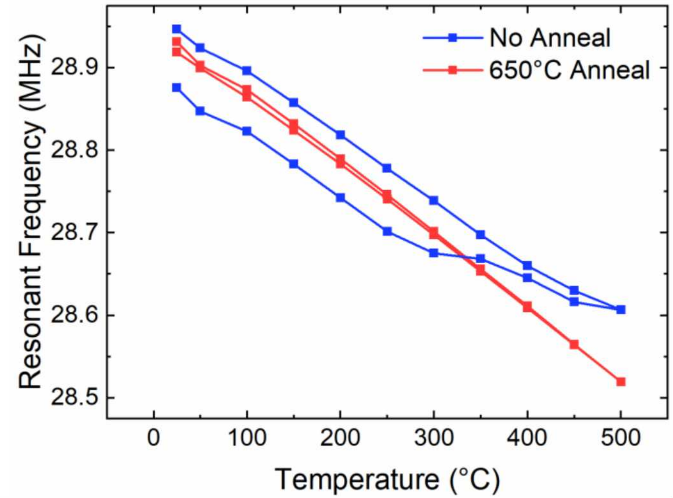
- Heated chuck from to 500˚C in steps of 50˚C
- Temperature hysteresis loop results in permanent frequency shift in unannealed sample
- No degradation in piezoelectric performance

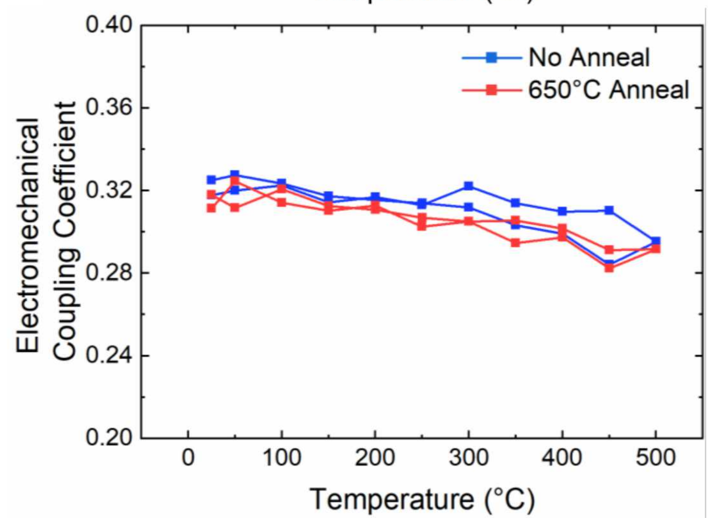
Challenges

- Quality factor degradation observed
- Potential sources
  - Probe contact issues
  - Carbon contamination
  - Via degradation
    - TiO_2 is expected to form at 500 ˚C

expected to form at 500˚C







Esteves and Griffin et. al. J Microelectromech Syst (in prep) (2019)

Conclusion and Acknowledgements

Ti/Ti/$AlCu_{0.05}$ allows for growth of $Sc_{12.5}Al_{87.5}N$ films with a high-quality microstructure and texture

- Inclusion-free ScAlN
- CMOS compatible metal and allows for commercialization of ScAlN technologies

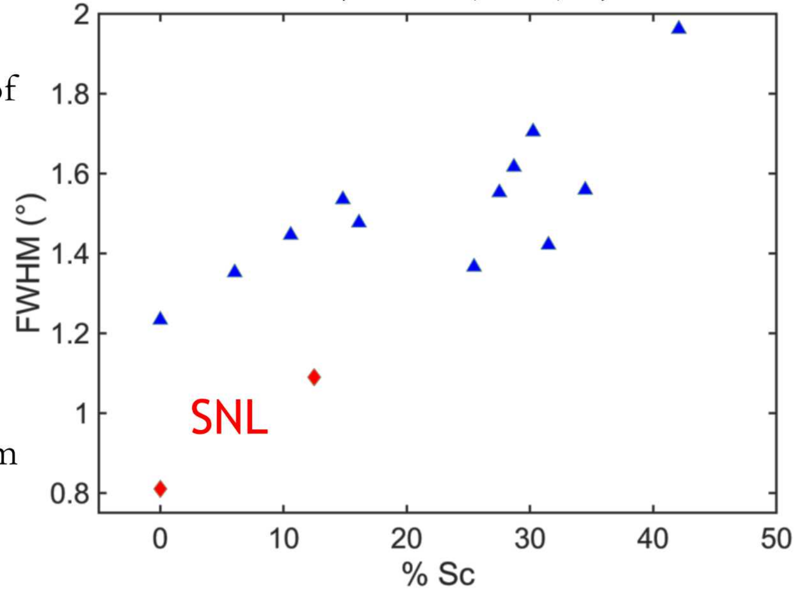
TiN is not needed to grow highly oriented AlN

- Can have significant impacts on device design

Increasing the thickness of Ti produces a well oriented AlN film

- Potential bottom metal for high temperature AlN technologies

Recreated from: Mertin, et. al., Surf. Coat. Tech. 2018



Acknowledgements

- The authors acknowledge and thank the staff of Sandia's MESA fabrication facility for their help in depositing the metal stacks used in this study
- This project was supported by the LDRD program at Sandia National Laboratories