Exceptional service in the national interest

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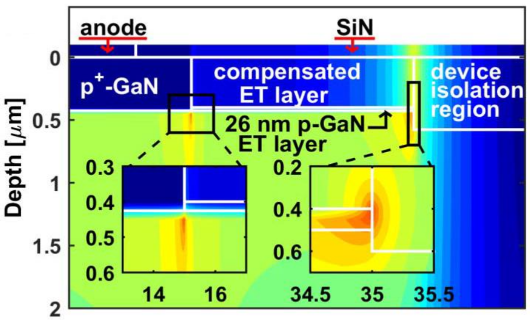

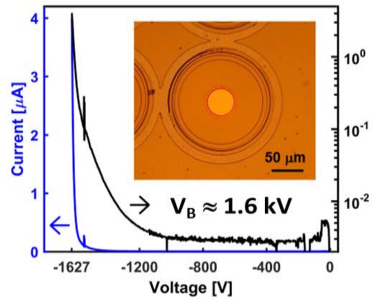

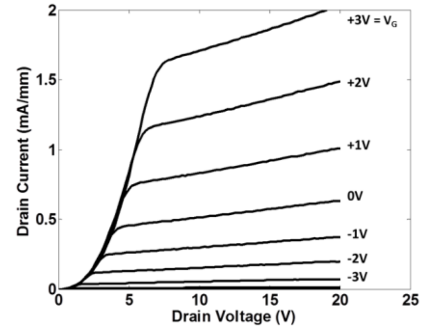

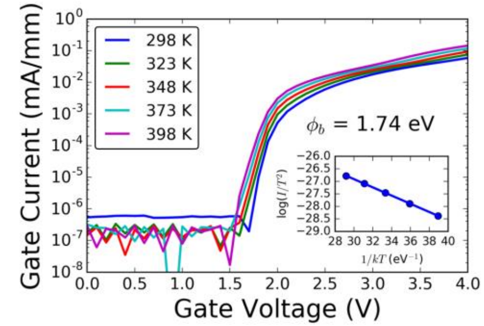

Ultra-Wide-Bandgap Power Electronic Devices based on Aluminum Gallium Nitride

R. J. Kaplar, A. A. Allerman, A. M. Armstrong, M. H. Crawford, A. G. Baca, J. D. Flicker, G. Pickrell, J. R. Dickerson, B. A. Klein, E. A. Douglas, M. A. Miller, F. Leonard, A. A. Talin, K. C. Collins, S. Reza, M. P. King, G. Vizkelethy, and M. E. Coltrin

Sandia National Laboratories
Albuquerque, NM and Livermore, CA USA

Reno, NV
March 23, 2017

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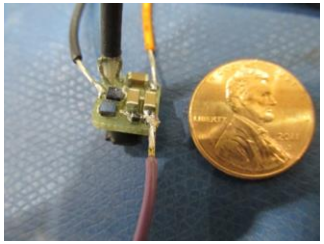
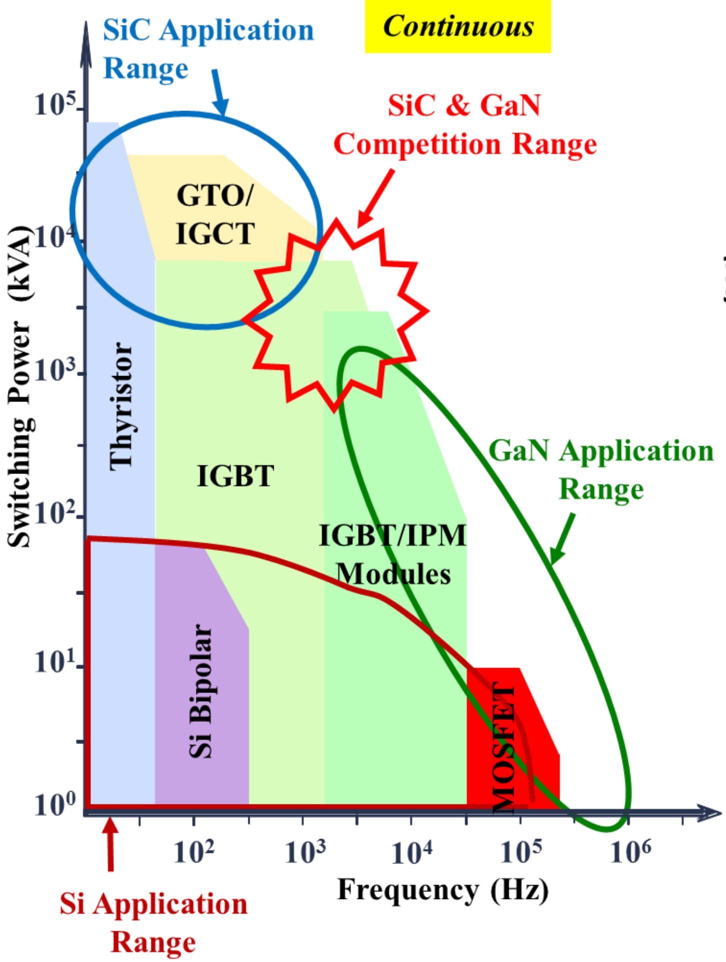
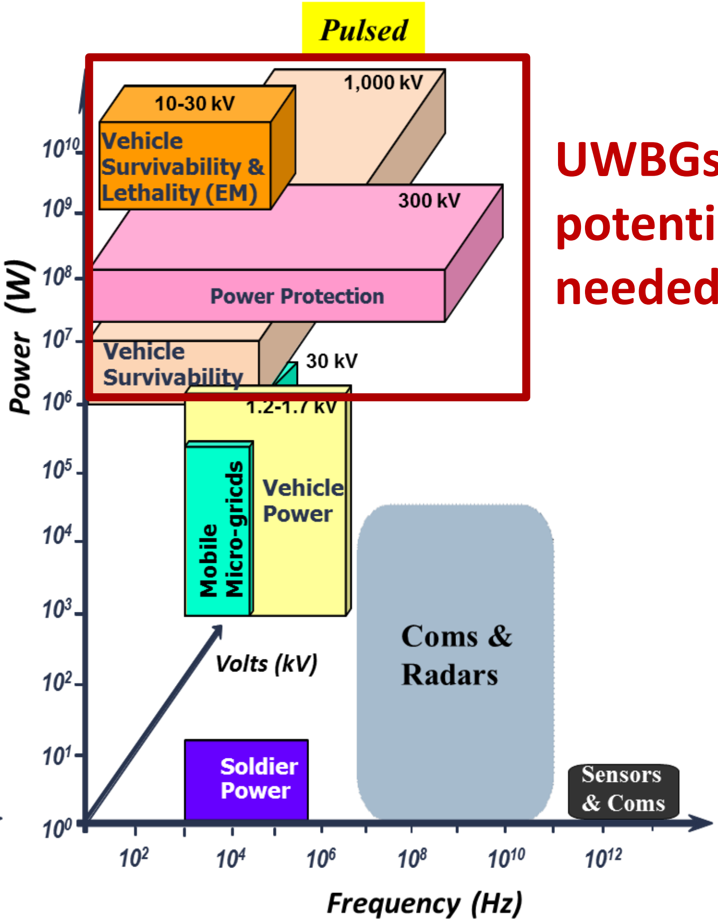
Continuous and Pulsed Power Applications Space

SNL "Coin Converter" 215 W/in^3





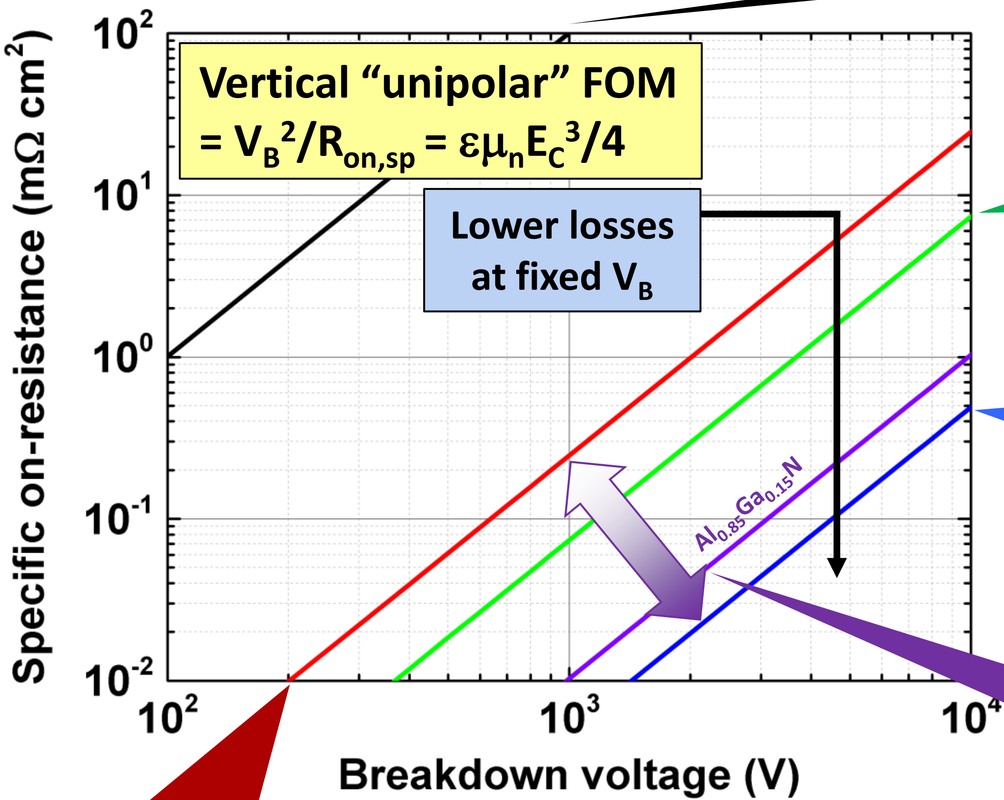


UWBGs potentially needed

Plots courtesy of Dr. Ken Jones, Army Research Lab

AlGaN is a Generation-After-Next Material for Power Electronics

Si (1.1 e V) – Today's standard



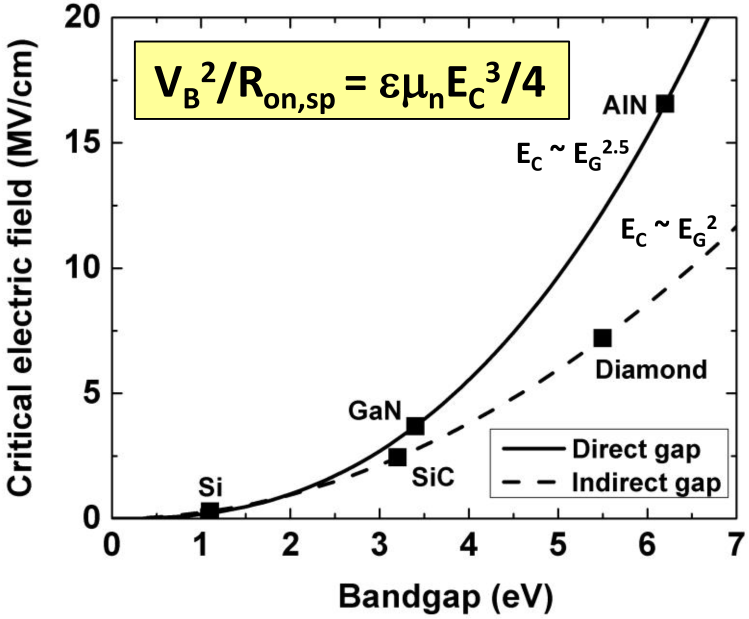
GaN (3.4 eV)
Lateral devices fairly mature
Vertical devices emerging

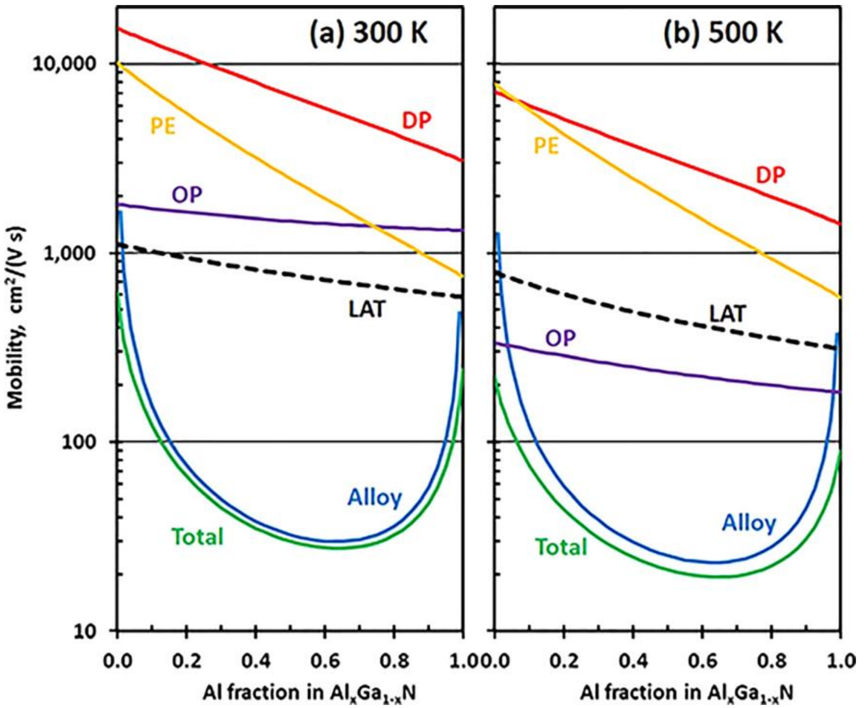
AlN (6.2 eV)
Unexplored space
Unprecedented performance

SiC (3.2 eV)
Many commercial devices now available

AlGaN (3.4 – 6.2 eV)
Unexplored space
Unprecedented performance
Heterostructures are available

Properties of III-N Semiconductors Relevant to Power Switching





Critical electric field postulated to scale as $E_C \sim E_G^{2.5}$ (currently under investigation)

But alloy scattering reduces mobility – *Implies that high Al composition is best target*

Hudgins et al., IEEE Trans. Pwr. Elec. 18, 907 (2003); M. E. Coltrin and R. J. Kaplar, J. Appl. Phys. 121, 055706 (2017)

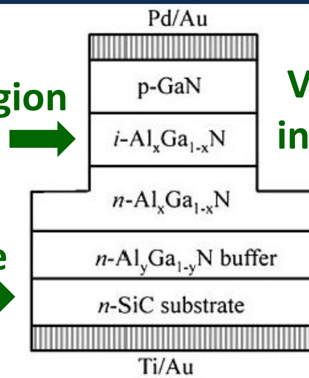
Prior AlGaN PiN Diode Results (Nishikawa et al., 2007)

$Al_xGa_{1-x}N$ *vertical* PiN diode ($0 < x_{Al} < 0.57$)

- **Drift Layer: ~ 0.2 μm, N_o ~ $2x10^{16}$ cm^{-3}**
- **N-SiC substrates, $R_{on,sp}$ = 1.45 mΩ-cm^2 (x_{Al} = 0.22)**

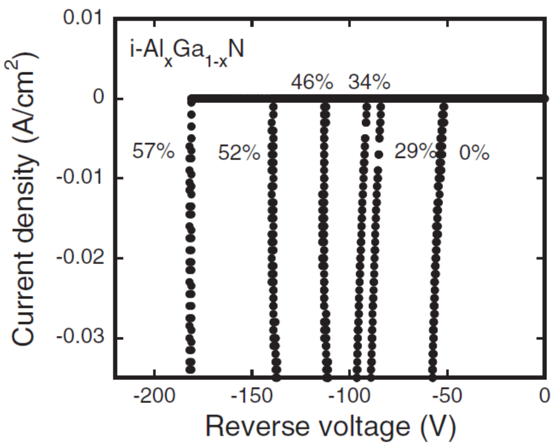
Drift region

Conducting SiC substrate

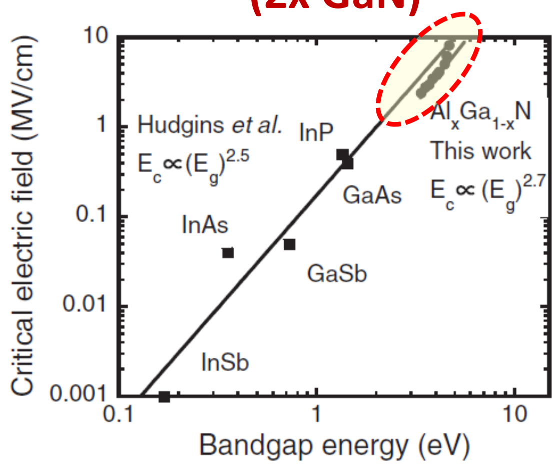


Vertical injection

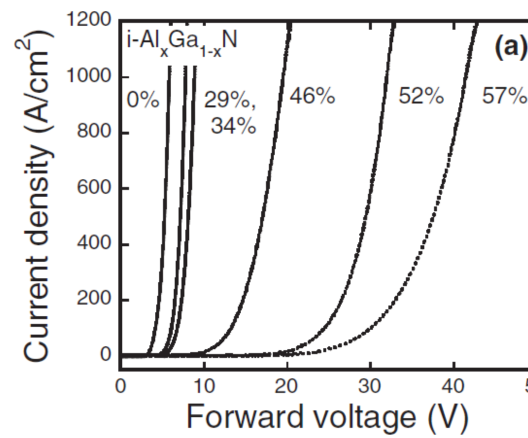
Reverse breakdown < 200 V



E_C ~ 8 MV/cm (2x GaN)



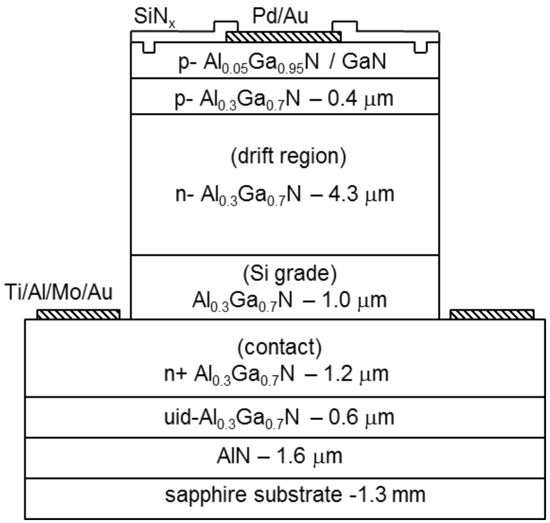
Higher forward turn-on for increasing Al %



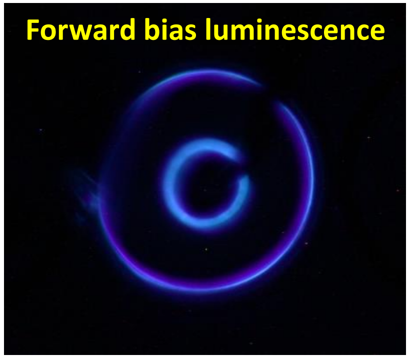
- **Breakdown voltage increases with larger bandgap**
- **Critical electric field scales as $E_G^{2.7}$**

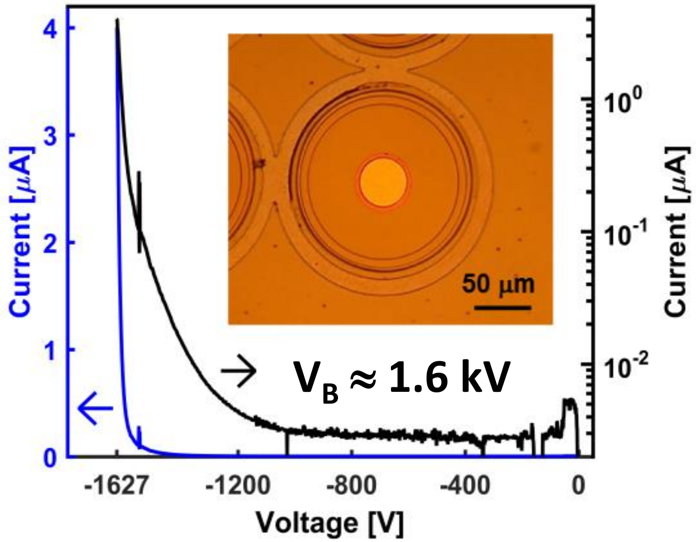
Nishikawa et al., Jap. J. Appl. Phys. 46 (4B), 2316 (2007)

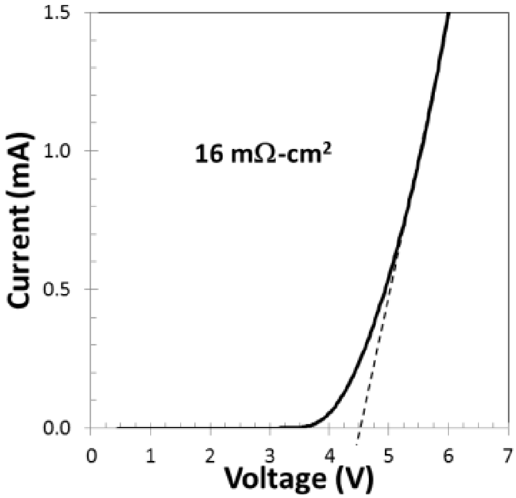
kV-Class Quasi-Vertical $Al_{0.3}Ga_{0.7}N$ PiN Diode



- **Drift region doping mid-10^{16} cm^{-3} *n*-type**
- **Record $V_B^2/R_{on,sp}$ = 150 MW/cm^2, *>20x higher than any previously published result***
- **Drift region thickness = 4.3 μm, likewise >20x greater than previously published results**
- **Current density up to 3.5 kA/cm^2 measured**

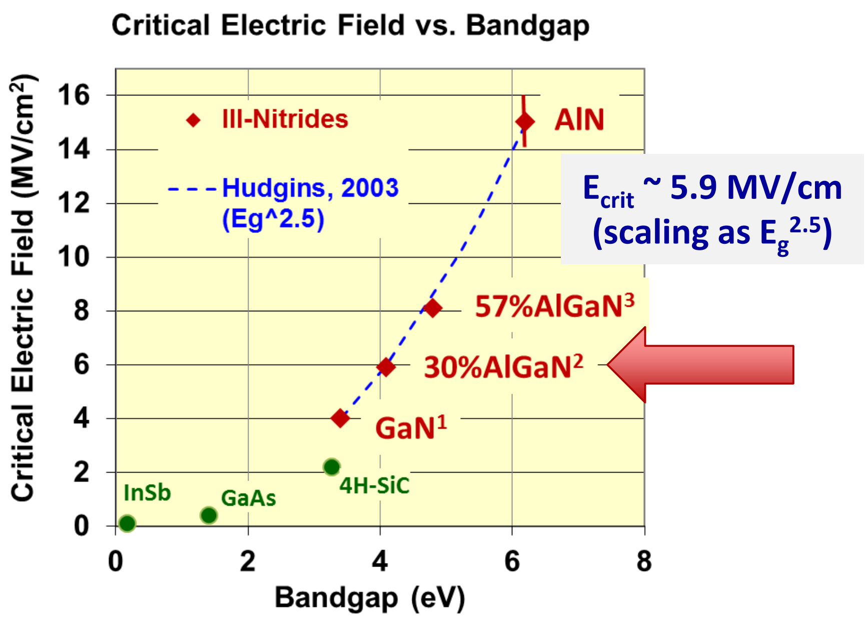






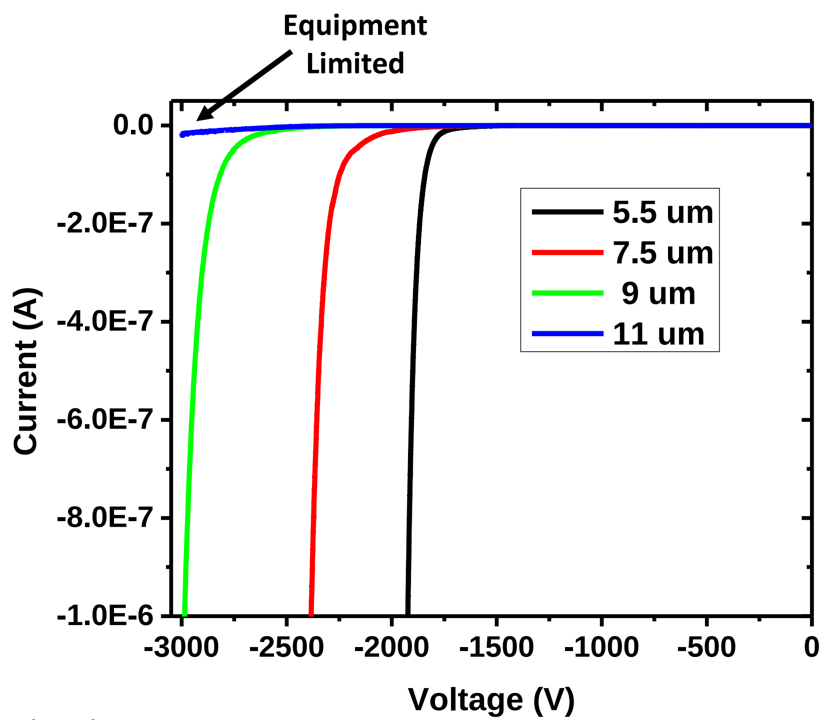
A. Allerman et al., Elec. Lett. 52(15), 1319 (2016)

Critical Electric Field Scaling and Thicker Drift Regions for Higher V_B



More recent devices grown using thicker drift regions show higher breakdown voltage

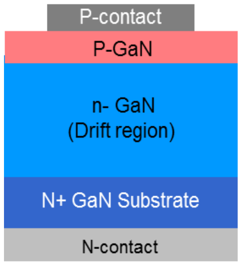
- **4.3 μm $Al_{0.3}Ga_{0.7}N$ drift region is punched-through at breakdown**
- **Punch-through analysis indicates E_C = 5.9 MV/cm, consistent with $E_C \sim E_G^{2.5}$ scaling (avalanche not yet proven)**



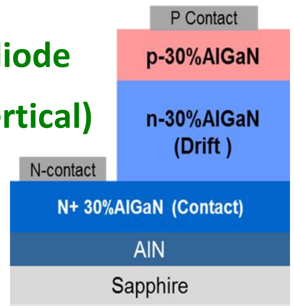
1 – Armstrong EL 2016; 2 – Allerman EL 2016; 3 – Nishikawa et al. JJAP 46 (4B), 2316 (2007)

Comparison of Breakdown Voltages Reported for III-N PiN Diodes

GaN diode (Vertical)



AlGaN diode (Quasi-vertical)



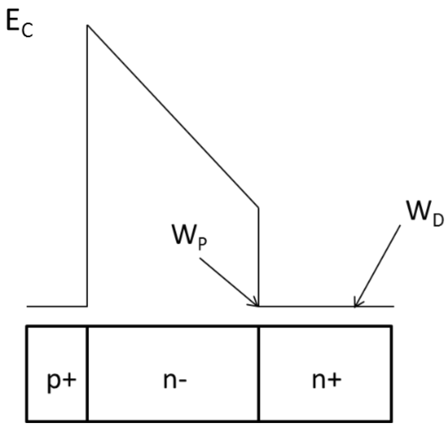
Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7	2/9/16e15	33	GaN	Hosei Univ.	EDL 36 p1180 (2015)
4.0	2-5e15	40	GaN	Avogy	EDL 36 p1073 (2015)
3.9	3e15	30	GaN	Sandia	EL 52 p1170 (2016)
3.7	5e15	>30	GaN	Avogy	EDL 35 p247 (2014)
3.48	1/3/12e15	32	GaN	Hosei Univ.	IEDM15-237 (2015)
>3	0.8-3e16	11	30%-AGaN	Sandia	This work
3.0	0.8-3e16	9	30%-AGaN	Sandia	This work
3.0	1/10e15	20	GaN	Hitachi	Jpn J Appl Phys 52 p028007 (2013)

Advantages of Ultra-Wide-Bandgap AlGaN

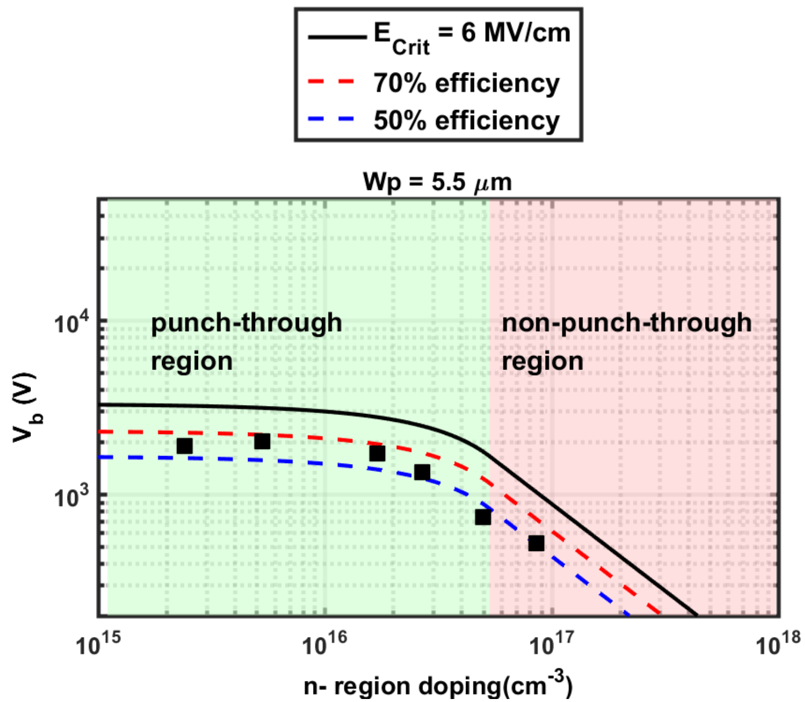
	GaN	$Al_{0.3}Ga_{0.7}N$	
N_o (cm^{-3})	low 10^{15}	low 10^{16}	← Larger E_C & E_G
Drift (μm)	20-30	~10	
TDD (cm^{-2})	≤ 10^6	low 10^9	← Impact?

$Al_{0.3}Ga_{0.7}N$ PiNs: Doping Dependence of Breakdown

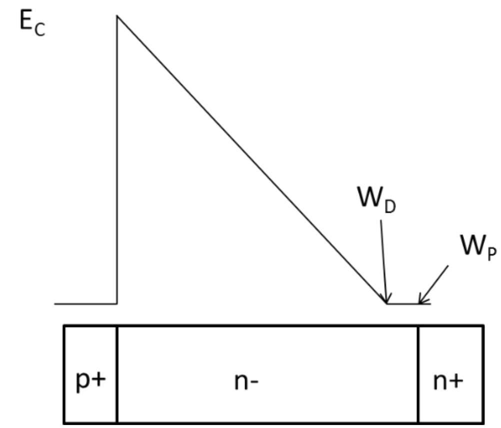
Punch-Through
$W_P < W_D$



$$V_{br} = E_C W_P - \frac{qN_D W_P^2}{2\varepsilon}$$



Non-Punch-Through
$W_P \geq W_D$

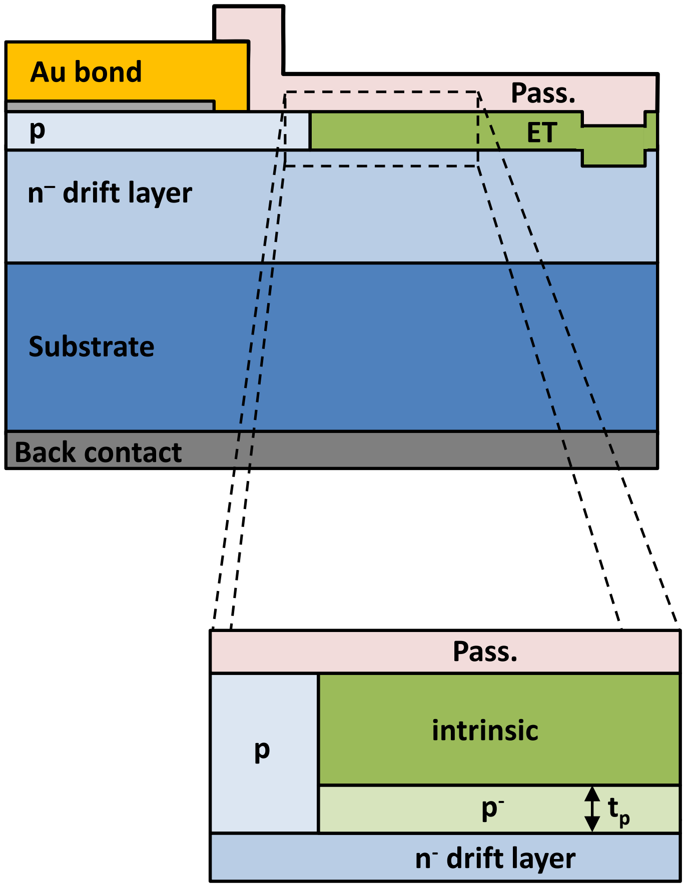


$$V_{br} = \frac{\varepsilon E_C^2}{2qN_D}$$

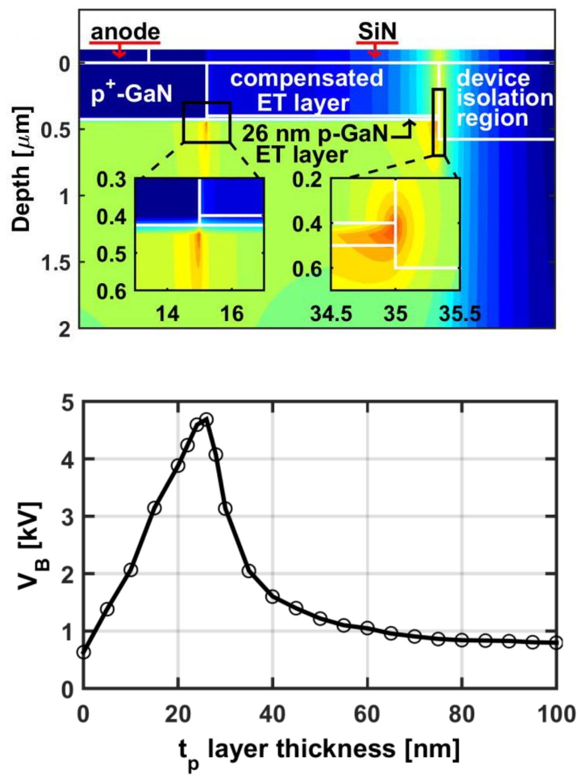
- C-V measurements performed to determine net doping of the drift region (n- layer)
- V_b of highest performing diode for each doping concentration compared with theory
  → JTE layer is as high as 70% efficient assuming critical electric field is 6 MV/cm

Edge Termination for High Breakdown Voltage

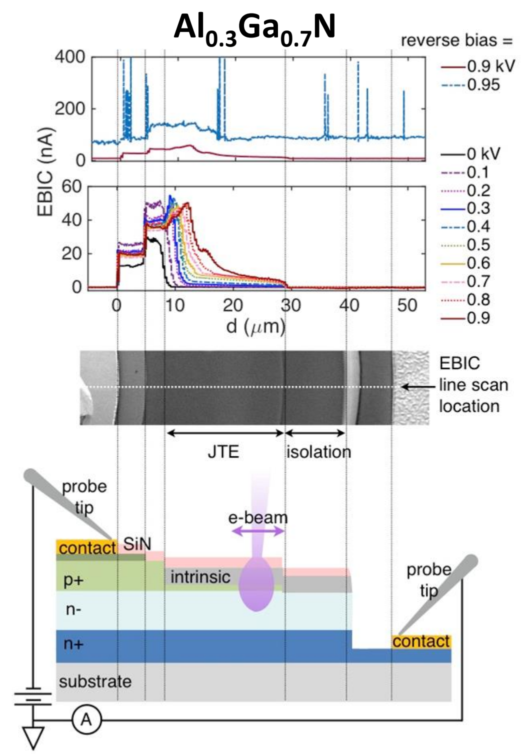
Effective edge termination is required to avoid premature lateral breakdown



Junction Termination Extension (JTE)



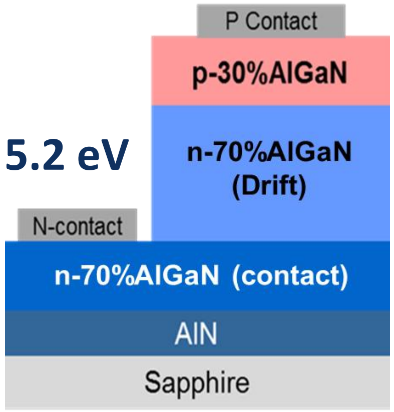
TCAD simulation



EBIC characterization to determine electric field distribution

J. Dickerson et al., IEEE TED 63(1), 419 (2016)

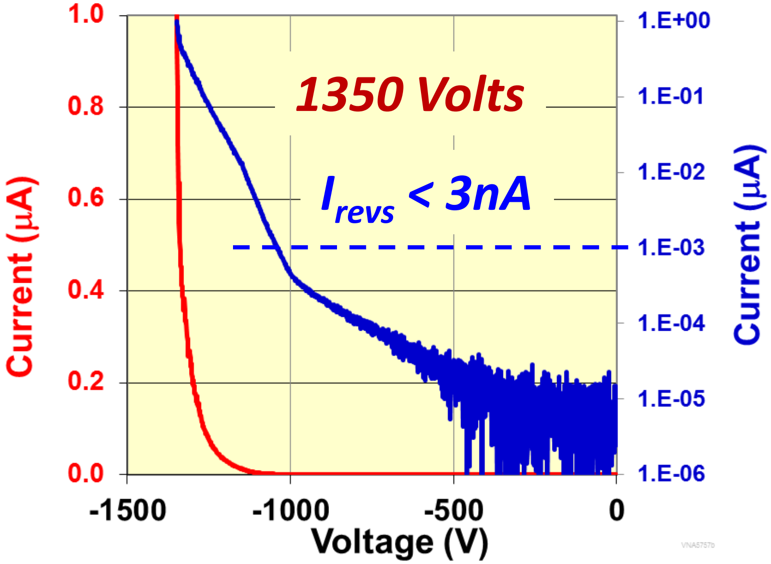
$Al_{0.7}Ga_{0.3}N$ "Quasi-Vertical" PiN Diode on Sapphire



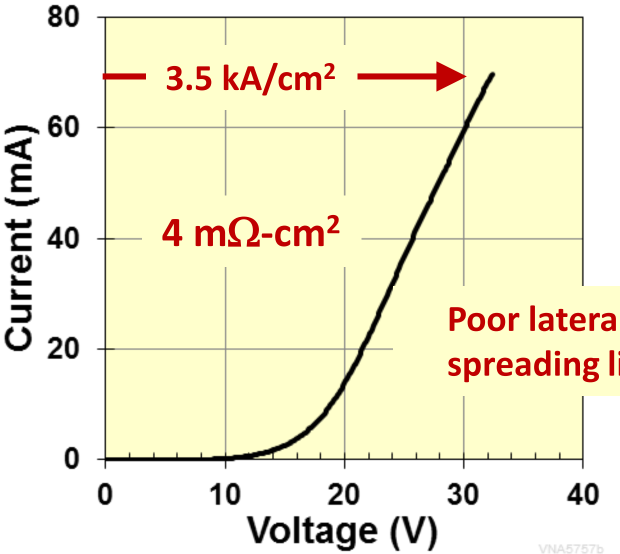
- ***Heterojunction PN diodes (p-30% / n-70%)***
  - **Utilize p-type doping of 30%-AlGaN**
  - **Drift region: 5.3 μm (Total: 10 μm)**
  - **N_o = 2-4 x 10^{16} cm^{-3}**
  - **TDD ~ 1-2 x 10^9 cm^{-2} (Best: $5x10^8$ cm^{-2})**
  - **R_s = 600 Ohm/sqr. (Best: 70 Ohm/sqr.)**

Optical image of diode

Reverse IV Characteristics



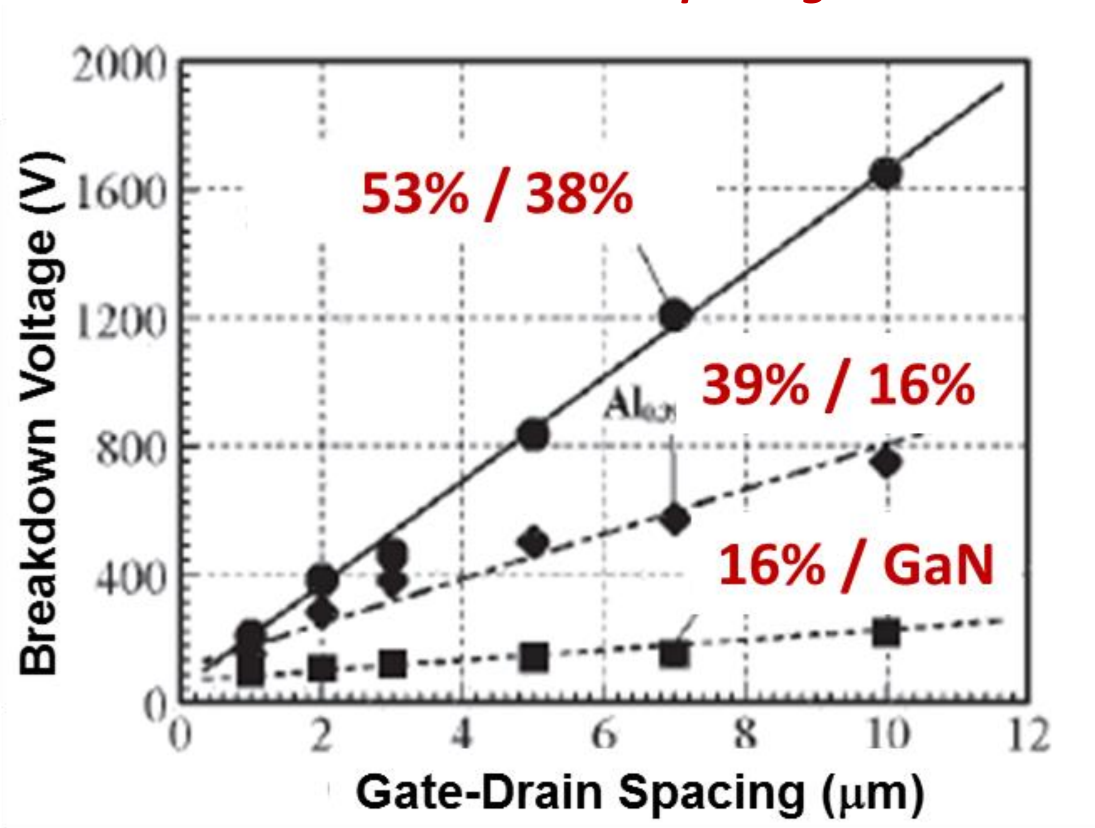
Forward IV Characteristics



Poor lateral current spreading limits R_{on}

Prior Work on AlGaN/AlGaN HEMTs (Nanjo et al., 2008)

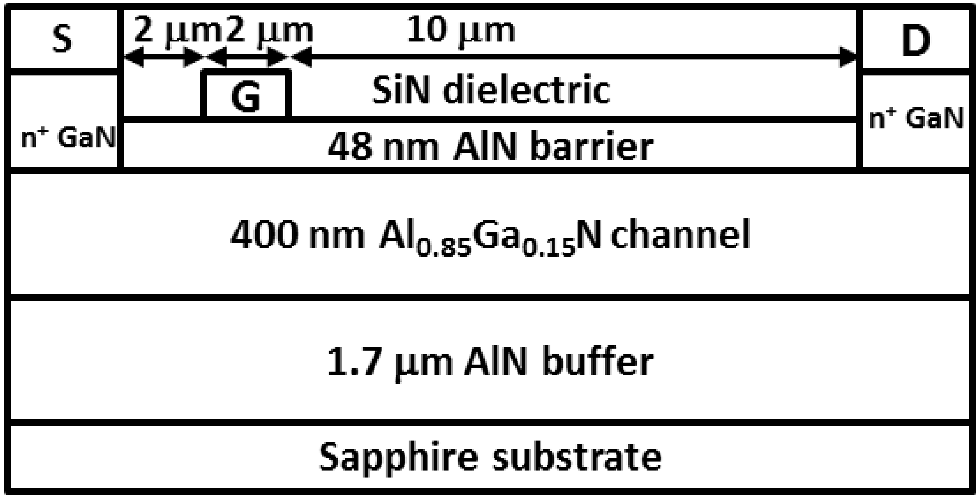
Breakdown voltage of AlGaN HEMTs vs. G-D spacing



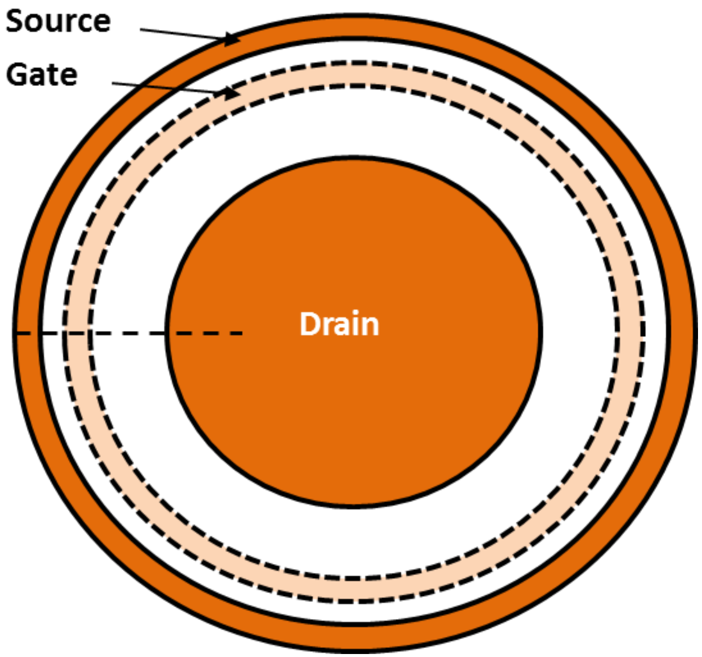
Higher Al composition in the channel and barrier results in higher breakdown voltage for fixed G-D spacing

Nanjo et al, Appl. Phys. Lett. 92, 263502 (2008)

UWBG HEMT Structure and Geometry: AlN Barrier, $Al_{0.85}Ga_{0.15}N$ Channel



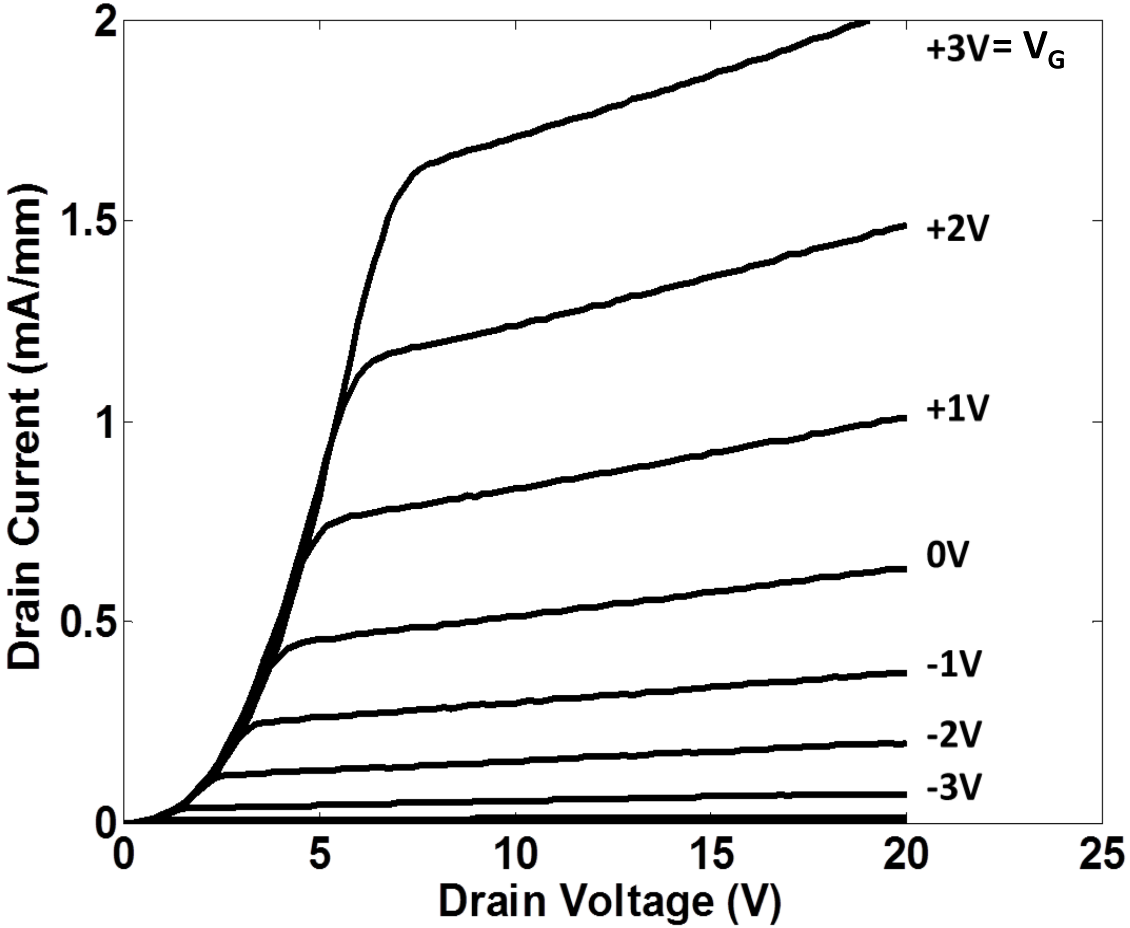
Circular Geometry



Process Steps:

1. SiN deposition, photolithography, SiN etch, AlN etch, PR removal, GaN:Si regrowth, SiN removal
2. Photolithography, ohmic metal deposition, lift-off, RTA
3. Gate photolithography, evaporation, lift-off
4. SiN deposition, photolithography, SiN etch (pads)

AlN/$Al_{0.85}Ga_{0.15}N$ HEMT Shows Transistor Characteristics

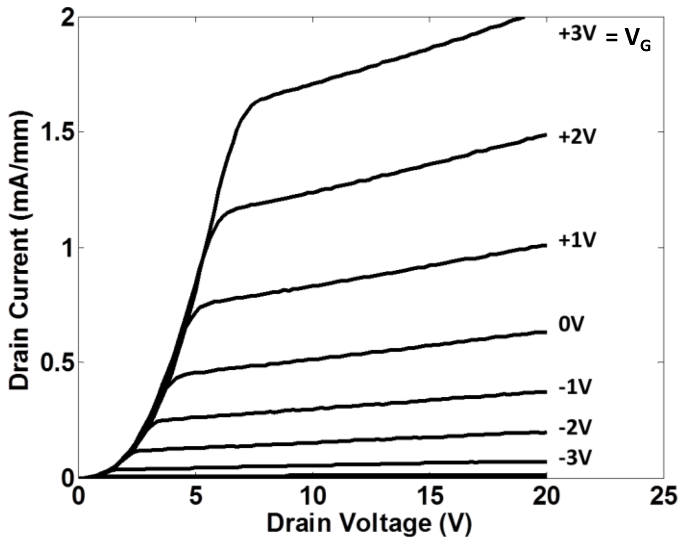


- Operates like a Field-Effect Transistor
  - Good gate control and pinch-off
  - Highest bandgap demonstrated in a transistor (5.7 eV channel)
- Not ideal in some aspects
  - Source and drain contacts are quasi-rectifying
  - As a result, drain current is ~40x lower than expected from sheet resistance

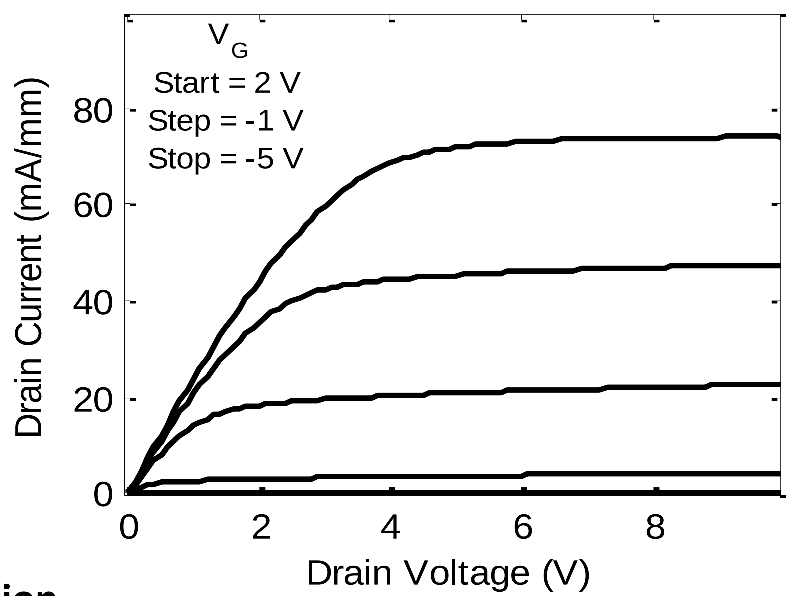
A. G. Baca et al., Appl. Phys. Lett. 109, 033509 (2016)

Good Ohmic Contacts Demonstrated for Lower Al%

$AlN/Al_{0.85}Ga_{0.15}N$ HEMT (previous slide)

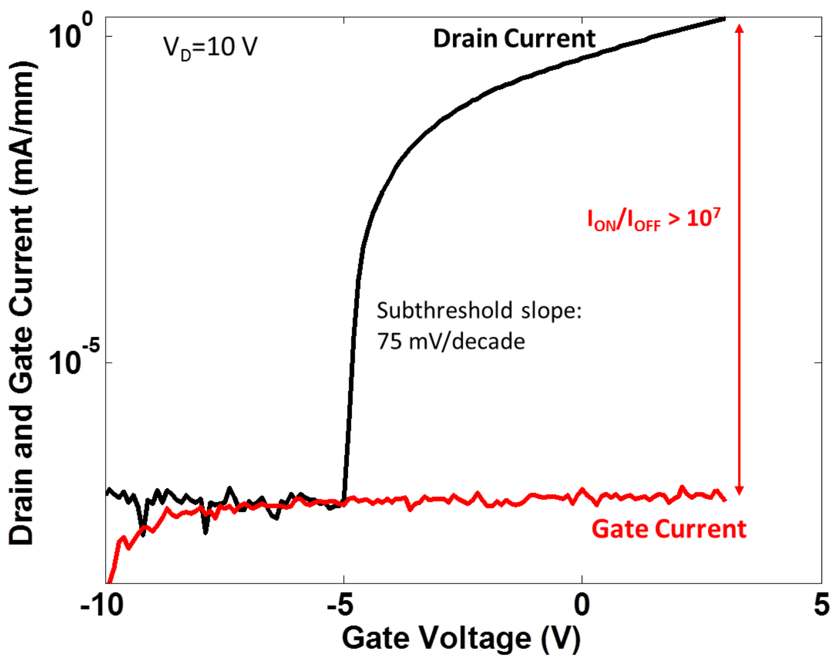


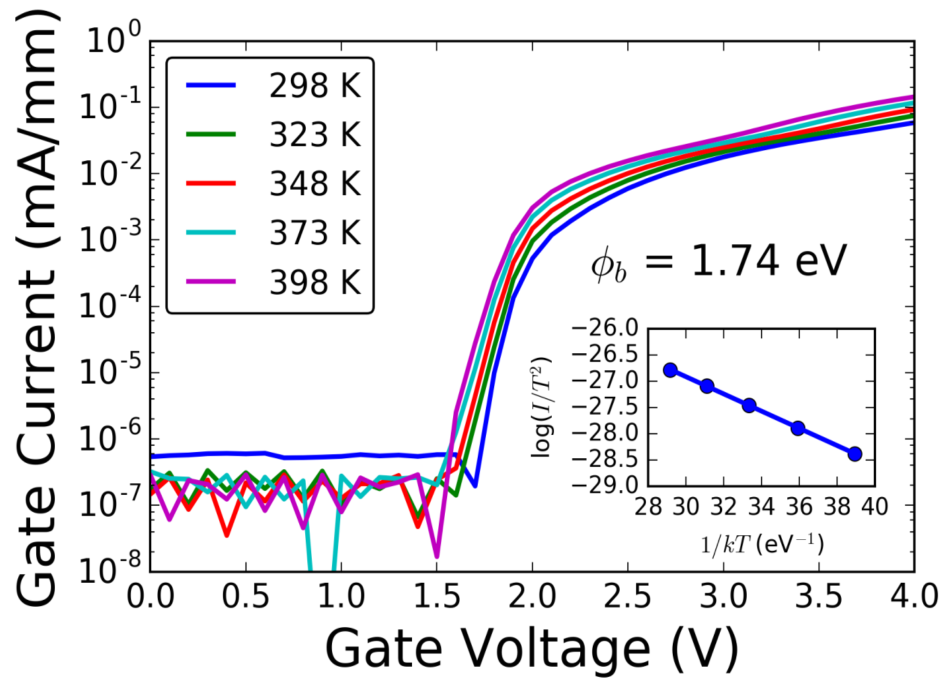
Comparison: $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ HEMT with state-of-the-art Ohmic contacts



- Midrange $Al_xGa_{1-x}N$ alloy channel composition
  - Source/drain contacts with low 10^{-5} Ω-cm^2
  - HEMT channel resistivity (and I_{max} approaching 100 mA/mm) constrained by mobility, not contacts
  - Low drain and gate leakage currents
- FOM will be limited by modest Al composition
  - But may have applications as phototransistors or harsh environment electronics

Low Off-State and Gate Leakage Currents for AlN/$Al_{0.85}Ga_{0.15}N$ HEMT

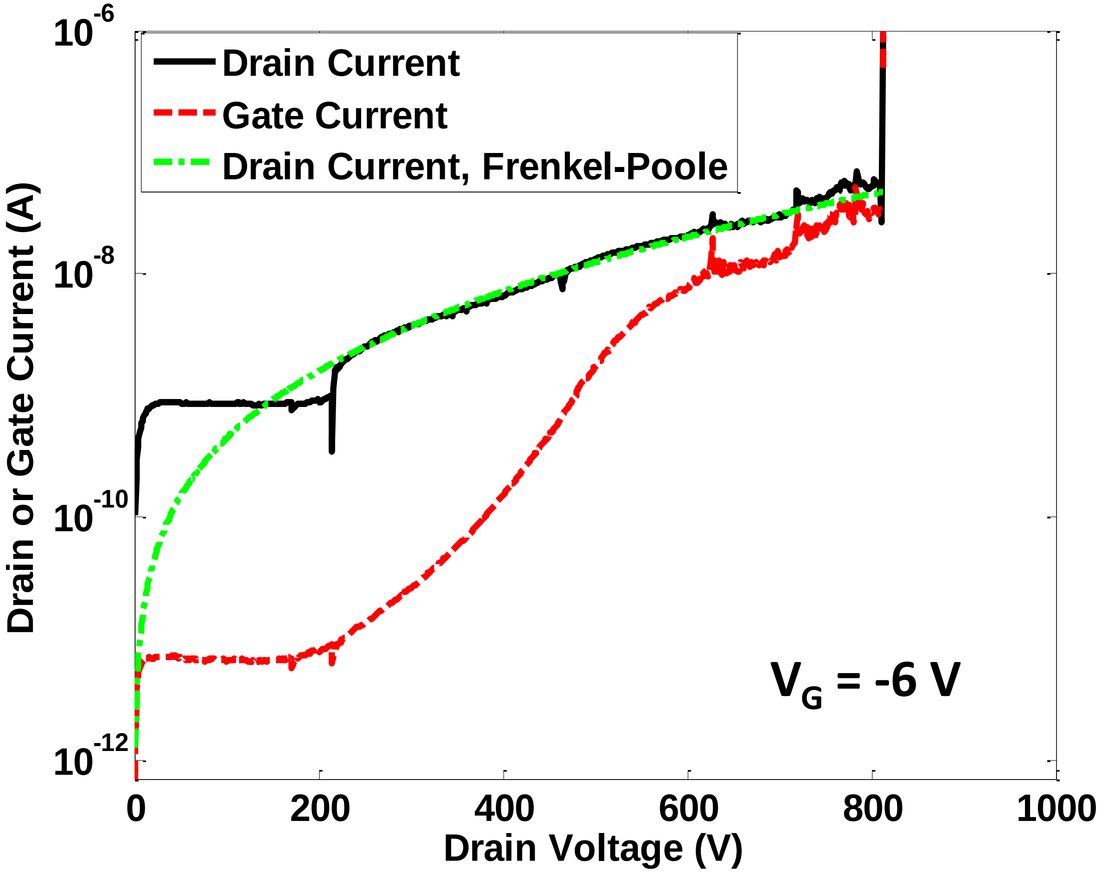




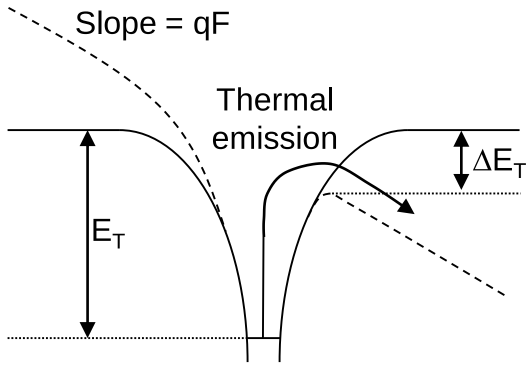
- **Leakage current near measurement limit**
  - **Similarly low gate leakage in $Al_{0.25}Ga_{0.75}N$/GaN requires insulated gate**
  - **Enabled by high Schottky barrier**
  - **Excellent subthreshold slope, 75 mV/decade**
  - **Excellent I_{ON}/I_{OFF} ratio >10^7**

A. G. Baca et al., Appl. Phys. Lett. 109, 033509 (2016)

Promising Breakdown Voltage for AlN/$Al_{0.85}Ga_{0.15}N$ HEMT



- **Standard gate (no field-plate), 10 μm gate-drain spacing**
  - **V_B = 810 V**
  - **Well below theoretical**
- **Drain current fit with Frenkel-Poole emission model**
  - **$I = AV\cdot\exp[(BV)^{1/2}]$**
  - **$A = 1.1\times10^{12}\ V^{-1}$**
  - **$B = 5.0\times10^{-4}\ V^{-1}$**



A. G. Baca et al., Appl. Phys. Lett. 109, 033509 (2016)

Summary

- **The UWBG semiconductor AlGaN has potential to push the state-of-the-art in power electronics**
  - **Strong scaling of critical electric field with bandgap**
  - **Alloy scattering points to high Al composition**
- **Demonstrated kV-class vertical AlGaN PiN diodes**
  - **30 and 70% drift regions**
  - **Drift region, edge termination, spreading resistance are key**
- **Demonstrated UWBG AlGaN/AlGaN HEMTs**
  - **Good gate control and leakage current**
  - **AlN barrier device limited at present by S/D contact resistance**

The contributions of the entire UWBG Grand Challenge team and the support of the Sandia LDRD office are gratefully acknowledged

Coalescing a National Community: The UWBG Working Group (“Guild”)

Technical Exchange on UWBG Semiconductors: Research Opportunities and Directions

Basic Research Innovation and Collaboration Center | Arlington, VA

~60 Attendees, representing academia, industry and government (DoD and DOE)

Purpose of the Technical Exchange:

- Nucleate a community of like-minded researchers
- Share technical information and R&D
- Better understand the needs of potential end-users
- Establish collaborations and partnerships
- “Build the Guild”

SNL co-organized UWBG Technical Exchange in Arlington, VA on April 24-25 2016

Four breakout sessions:

- Materials and Epitaxial Growth
- Physics (Transport, Breakdown, Defects)
- Device Design, Architecture, and Processing
- Applications Enabled by UWBG

- **Comprehensive report being published in Advanced Electronic Materials**
- **Special out-brief session this afternoon at 3:30**