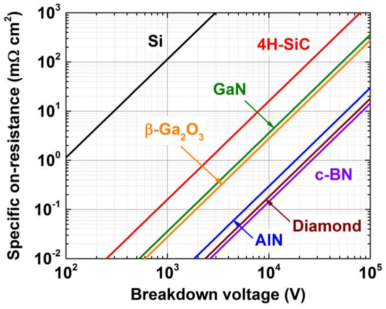
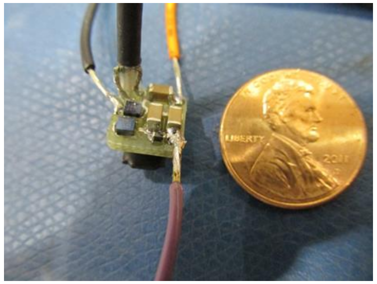
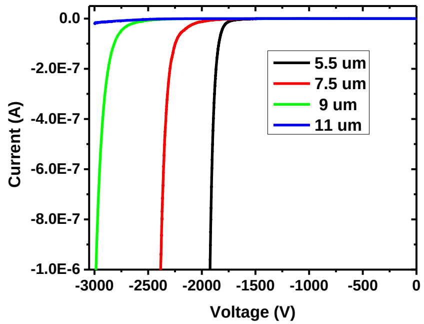
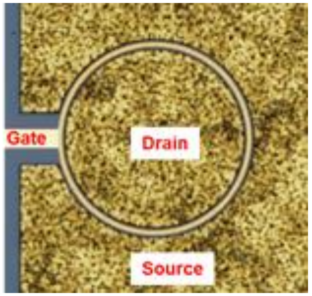
SAND2017-13122PE

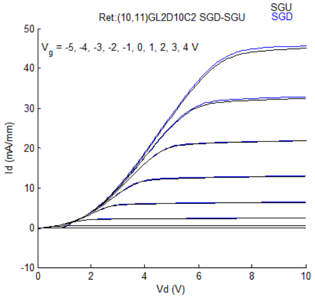
Exceptional service in the national interest











CHPPE Center for High Performance Power Electronics

Ultra-Wide-Bandgap Aluminum Gallium Nitride Devices for Power Electronics

CHPPE Annual Review
Ohio State University
Columbus, OH
November 20, 2017

R. J. Kaplar, A. A. Allerman, A. M. Armstrong, M. H. Crawford, G. W. Pickrell, J. R. Dickerson, J. D. Flicker, J. C. Neely, M. P. King, K. C. Cross, C. E. Glaser, M. van Heukelom, A. G. Baca, S. Reza, B. Klein, and E. A. Douglas

Sandia National Laboratories, Albuquerque, NM USA

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Outline

- Motivation for UWBG Materials in Power Electronics
- Quasi-Vertical AlGaN PiN diodes
- Al-Rich AlGaN High Electron Mobility Transistors
- Other WBG PE Projects

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- Motivation for UWBG Materials in Power Electronics
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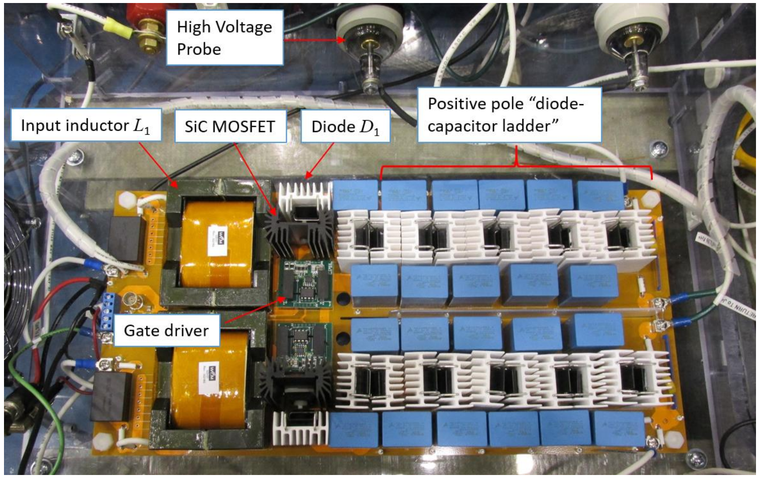
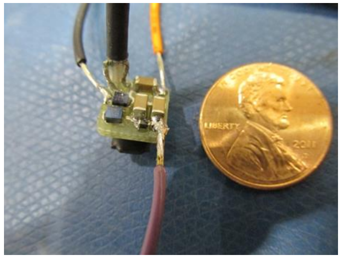
Efficient and Compact Power Conversion Enabled by WBG Semiconductors





SNL GaN HEMT "Coin Converter"
90 V, 90 mA → 215 W/in³

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

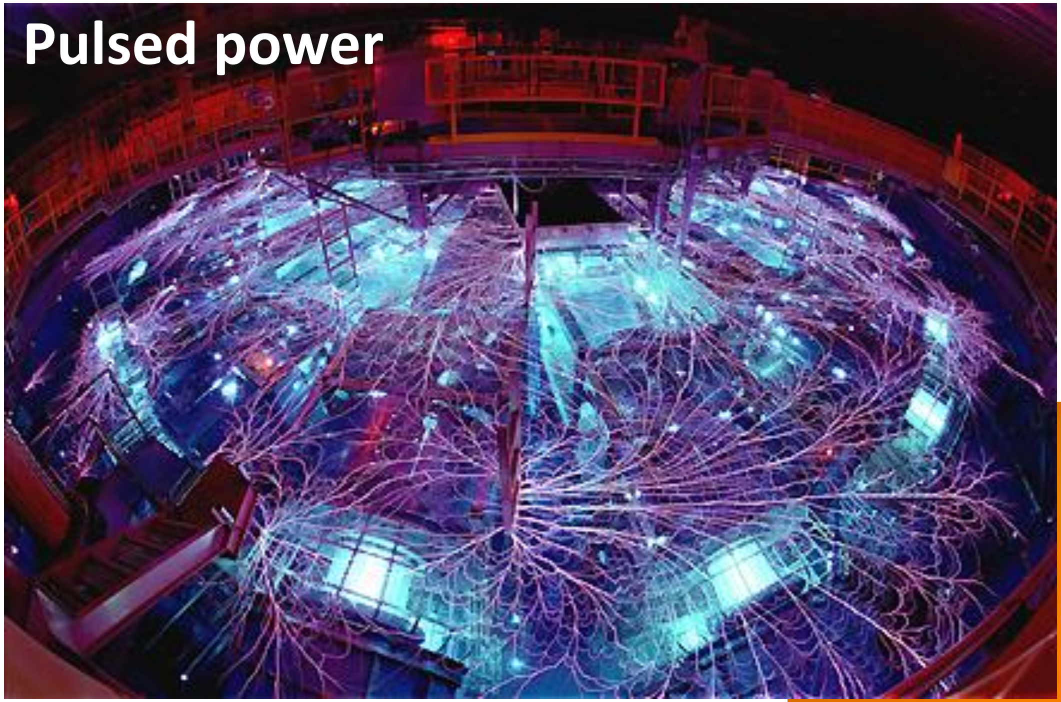
- **Latest prototype: 0.48 kV → 10.0 kV (gain > 20) at 5.0 kW, 97.9% efficient, 230 in³**

SNL GaN HEMT microinverter
400 W in 2.4 in³ → 167 W/in³

Over an order of magnitude improvement in power density is enabled by WBG semiconductors compared to Si

SOA commercial microinverter
250 W in 59 in³ → 4.2 W/in³

Ultra-High-Voltage Applications



Conservative but critically important power device markets

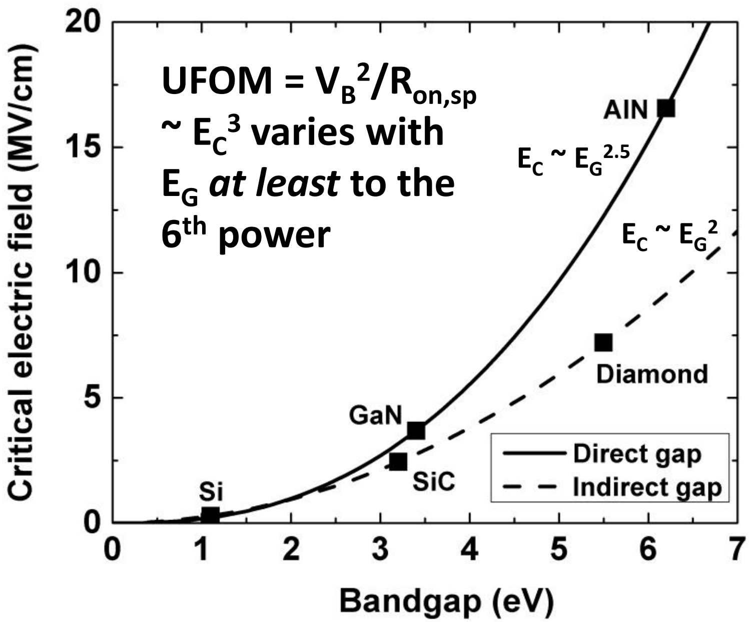
10's of kV semiconductor switches are possible using WBG semiconductors!

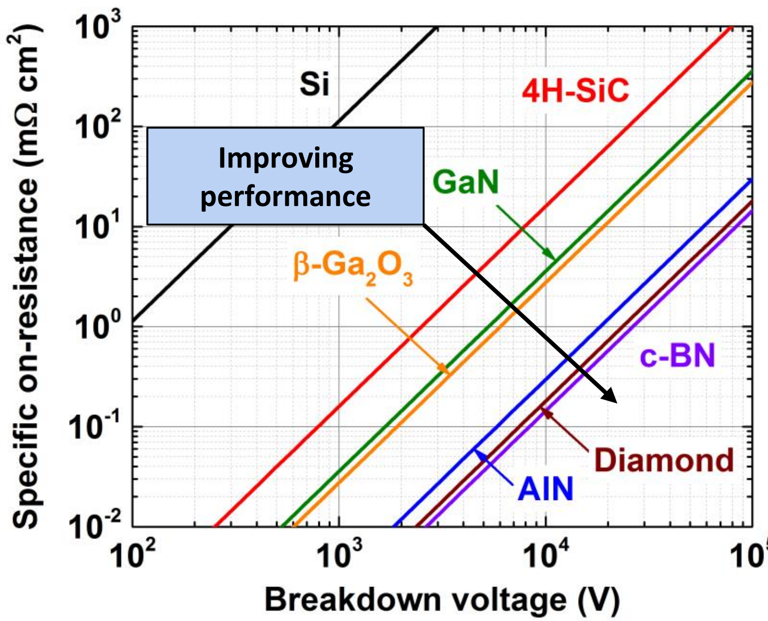
III-Nitride Semiconductors Are Outstanding WBG and UWBG Materials

Fundamental Materials Capabilities

	Conventional		WBG		UWBG
Property	**Si**	**GaAs**	**4H-SiC**	**GaN**	**AlN**
Bandgap (eV)	1.1	1.4	3.3	3.4	6.0
Critical Electric Field (MV/cm)	0.3	0.4	2.0	4.9	13.0

III-N





Hudgins et al., *IEEE Trans. Pwr. Elec.* 18, 907 (2003); J. Y. Tsao et al., *Adv. Elec. Mat.* (in press); Coltrin and Kaplar, *JAP* 121, 055706 (2017)

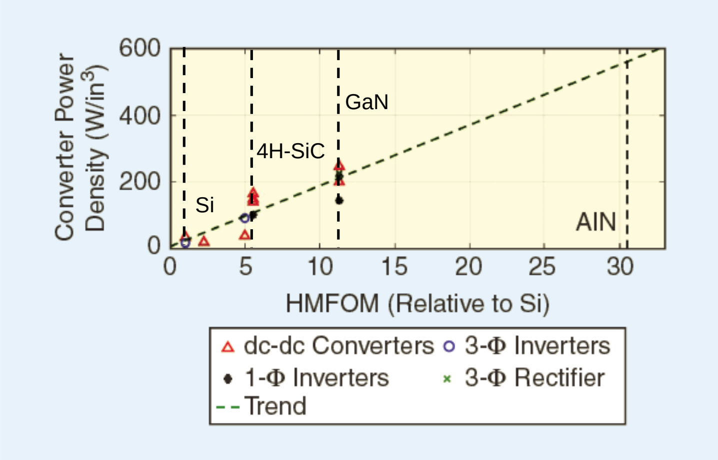
Unipolar FOM = $V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$

Power Density Scaling with Semiconductor Material Properties

Table 1. Comparison of material properties and FOM values [12], [16]–[18].

		Conventional	WBG			UWBG		
Properties	Property	Silicon	6H-SiC	4H-SiC	GaN	$Al_{0.3}Ga_{0.7}N$	$Al_{0.85}Ga_{0.15}$	AlN
	Bandgap (eV)	1.1	3.0	3.3	3.4	4.1	5.7	6.2
	$\mu(cm^2/Vs)$	1,400	500	800	1,000	150	150	425
	Diel constant	11.9	9.7	10.1	10.4	10.3	10.2	10.1
	E_C (MV/cm)	0.3	2.5	2.2	4.0	5.9	13.4*	16.6*
	σth (W/cmK)	1.5	4.9	4.9	1.4	0.4	0.5	2.9
FOMs	vUFOM (rel)	1	168	191	1,480	705	8,100	43,650
	HMFOM (rel)	1	5.0	5.5	11.3	6.4	14.6	30.5

*Calculated using the method in [18].



Relative Figures of Merit:

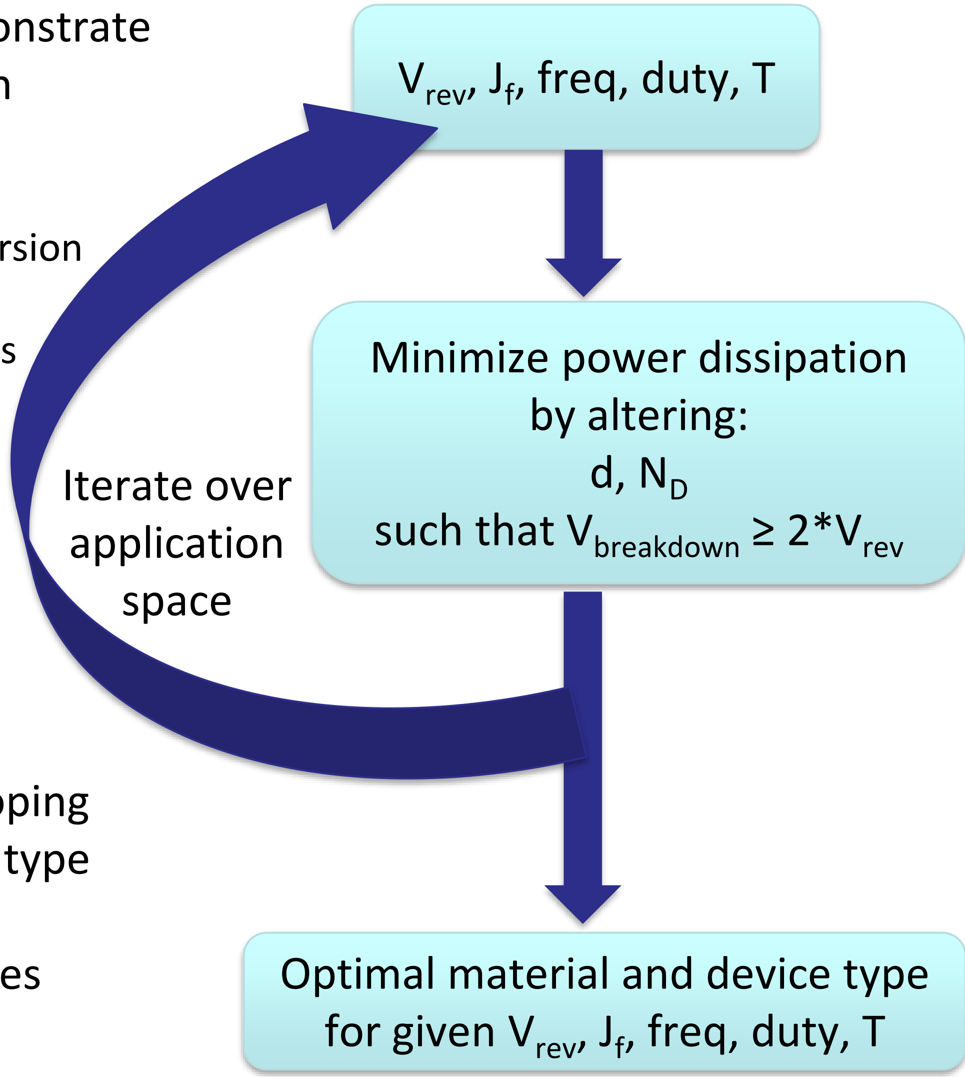
- **Vertical UFOM = $\varepsilon\mu_n E_C^3$**
- **Huang Material FOM = $E_C\mu_n^{1/2}$**

HM-FOM seems to be a good predictor of power density in a variety of power converter types

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

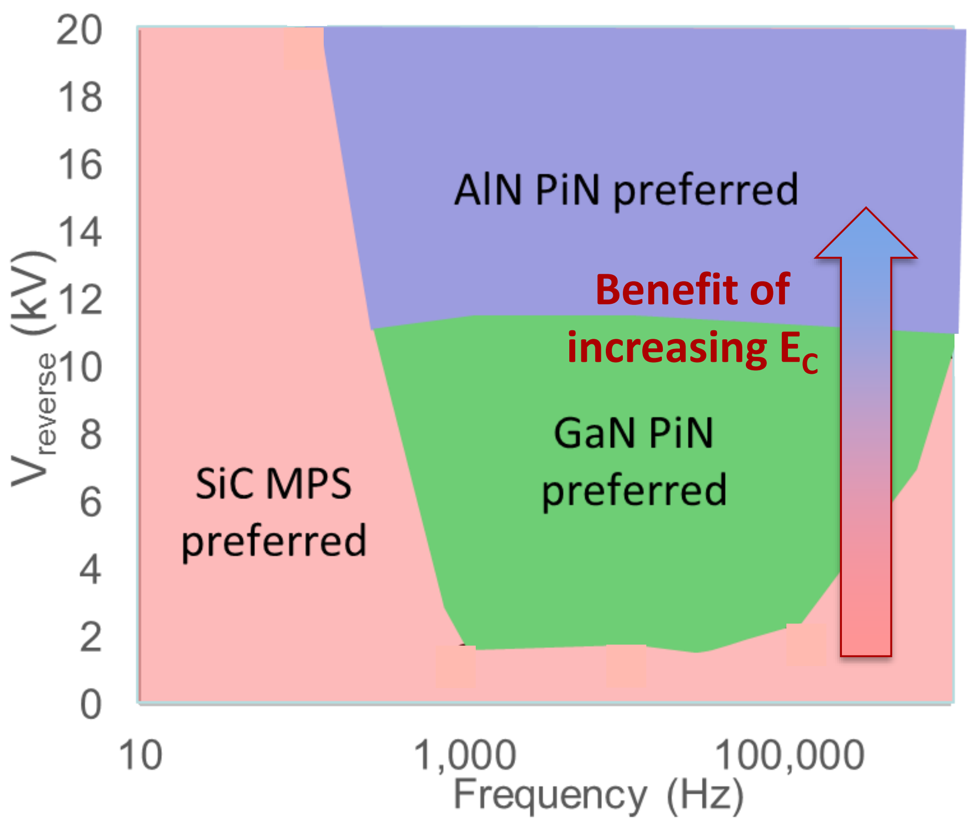
WBG/UWBG Device Optimization

- Developed optimization tool to demonstrate device/material favorability for given application area
  - Treatment for 2-terminal devices
  - Focused on traditional power conversion applications
  - Neglects non-idealities and parasitics
  - Ideal materials comparison
- Given application parameters:
  - $V_{reverse}$ (V)
  - $J_{forward}$ (A/cm^2)
  - Frequency (Hz)
  - Duty cycle (%)
  - Temperature (K)
- Determines optimal thickness and doping
  - Function of material and device type
- Materials: SiC, GaN, $Al_xGa_{1-x}N$
- Devices: PiN, SBD, JBS, and MPS diodes

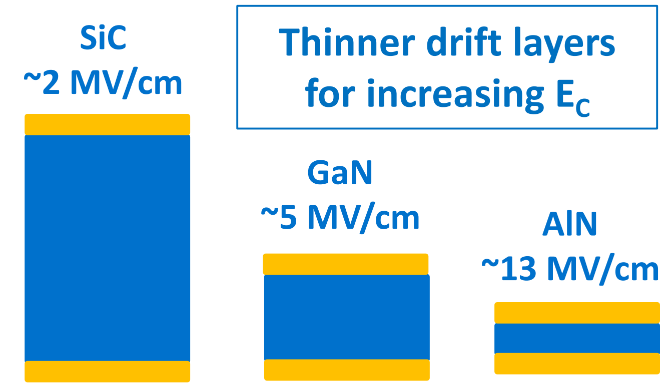


Based on Morisette and Cooper, TED 49(9), 1657 (2002); Details presented at WiPDA 2017 (Flicker and Kaplar)

WBG/UWBG Preferred Application Ranges



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**

Details presented at WiPDA 2017 (Flicker and Kaplar)

Outline

- Motivation for UWBG Materials in Power Electronics
- **Quasi-Vertical AlGaN PiN diodes**
- Al-Rich AlGaN High Electron Mobility Transistors
- Other WBG PE Projects

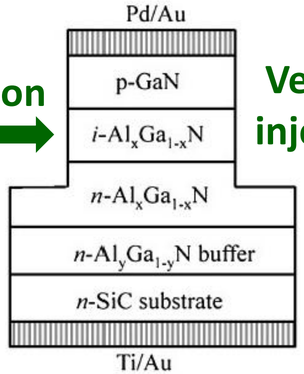
Prior AlGaN PiN Diode Results (Nishikawa, NTT, 2007)

$Al_xGa_{1-x}N$ *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)**

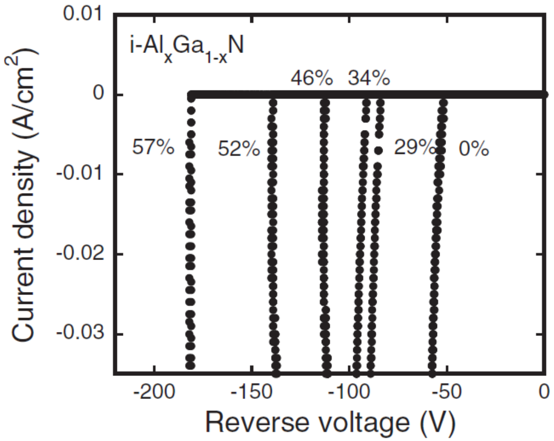
Drift region

Conducting SiC substrate

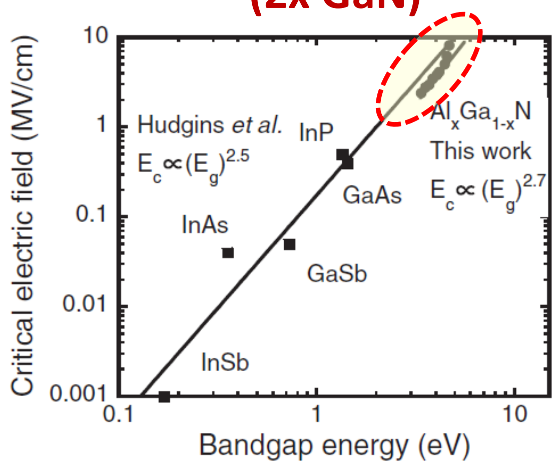


Vertical injection

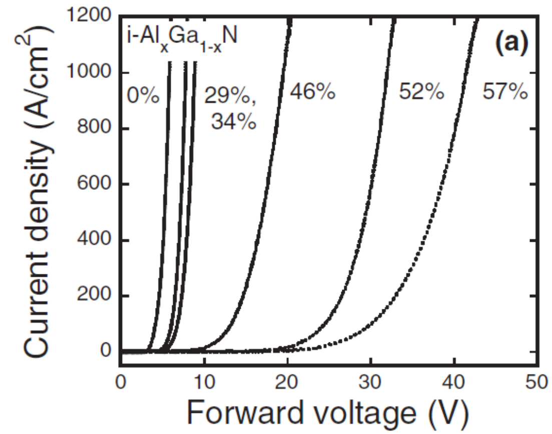
Reverse breakdown < 200 V



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 $E_G^{2.7}$**

$Al_xGa_{1-x}N$ Quasi-Vertical PiN Diode Structures

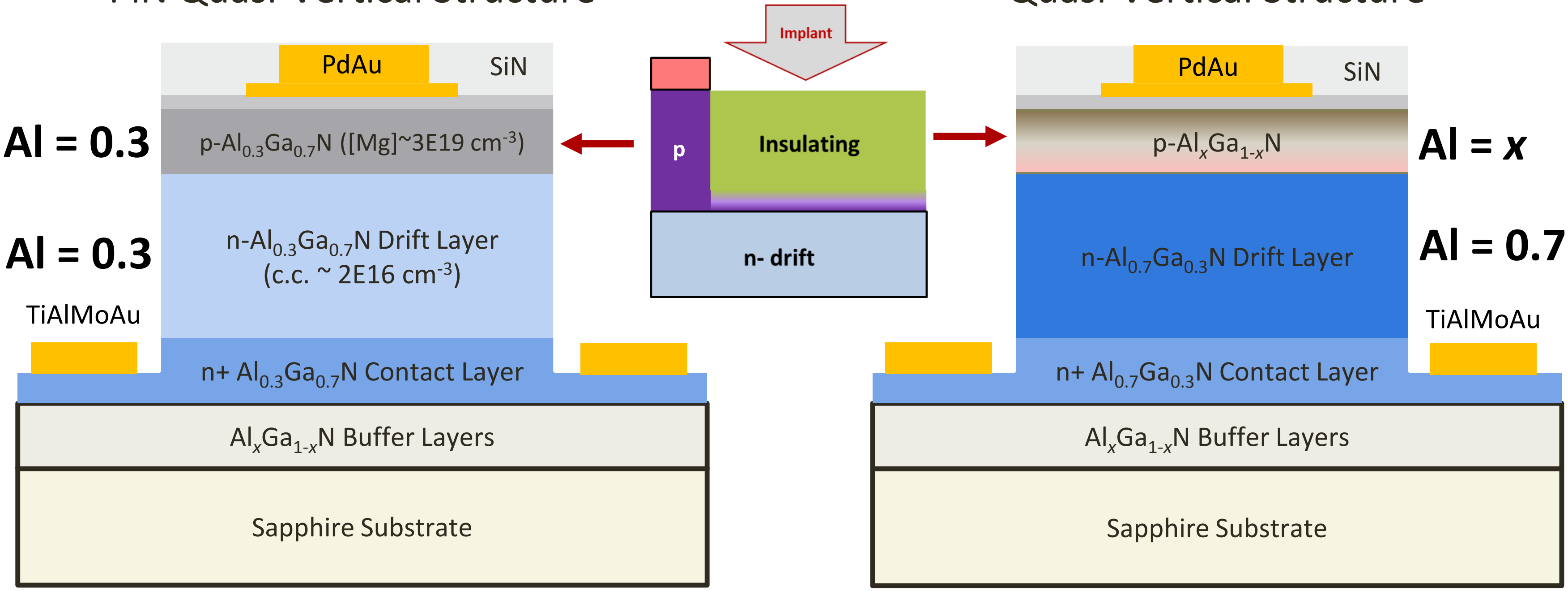
Device Type #1

$Al_{0.3}Ga_{0.7}N$ Homojunction PiN Quasi-Vertical Structure

Implanted JTE

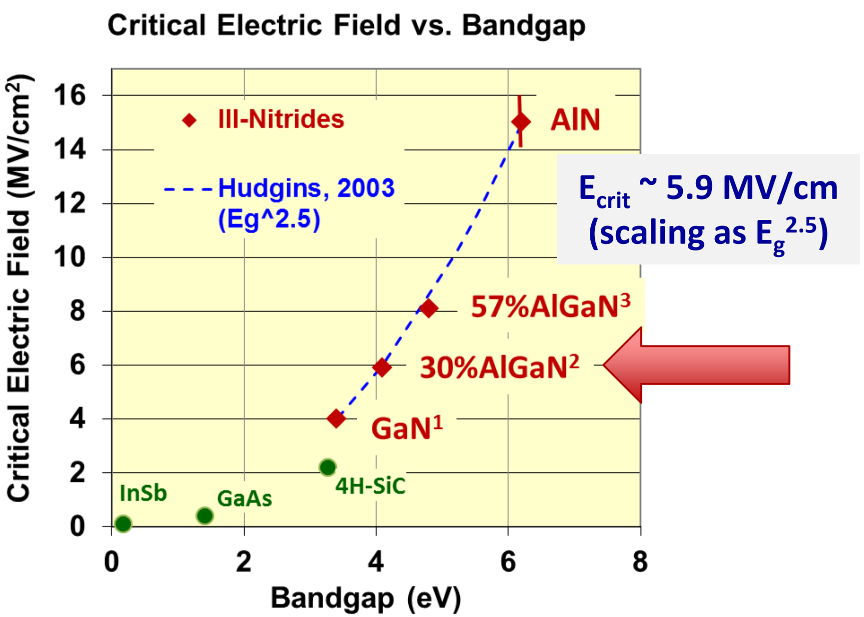
Device Type #2 (a-d)

$Al_xGa_{1-x}N$ / $Al_{0.7}Ga_{0.3}N$ PiN Quasi-Vertical Structure

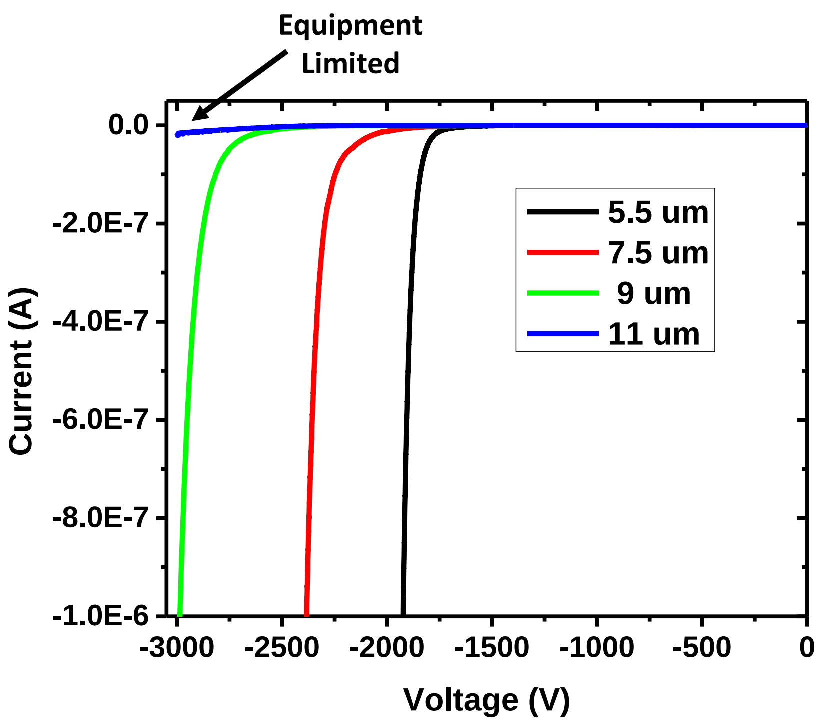


- **Critical design parameters:**
  - **Drift layer thickness and doping level**
  - **Electric field management using junction termination extensions (JTEs)**
  - **p-type material conductivity**

Critical Electric Field Scaling and Thicker Drift Regions for Higher V_B



- **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**

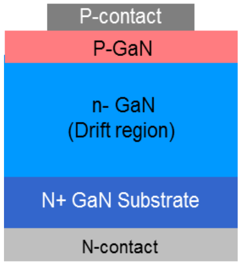


SNL 30% Al homojunction PiN diodes show breakdown scaling with drift region thickness

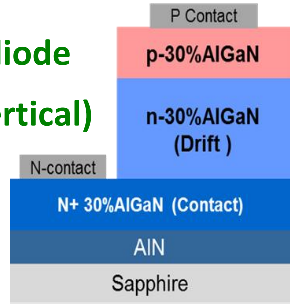
1 – Armstrong EL 2016; 2 – Allerman EL 2016; 3 – Nishikawa et al. JJAP 46 (4B), 2316 (2007)

Comparison of Breakdown Voltages Reported for III-N PiN Diodes

GaN diode (Vertical)



AlGaN diode (Quasi-vertical)



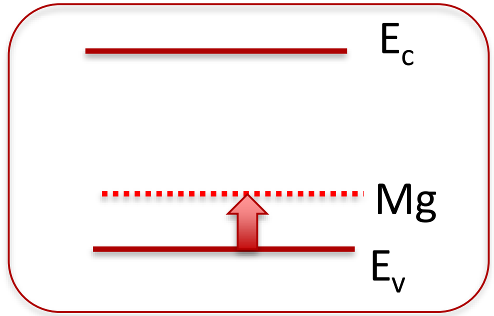
Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7	2-16e15	33	GaN	Hosei Univ.	EDL 36 p1180 (2015)
4.0	2-5e15	40	GaN	Avogy	EDL 36 p1073 (2015)
3.9	3e15	30	GaN	Sandia	EL 52 p1170 (2016)
3.7	5e15	>30	GaN	Avogy	EDL 35 p247 (2014)
3.5	1-12e15	32	GaN	Hosei Univ.	IEDM15-237 (2015)
>3	0.8-3e16	11	30%-AGaN	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?

Approaches to 70% AlGaN PiN Diodes

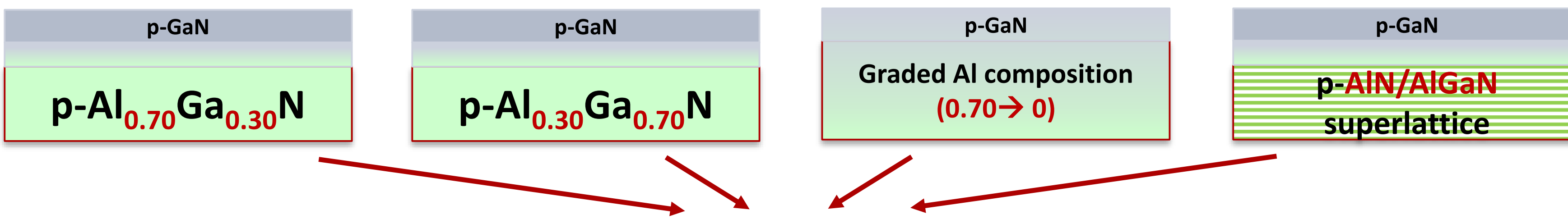
p-type doping very challenging with increasing Al:
E_a (GaN) ~160 meV
E_a (AlN) ~ 500 meV



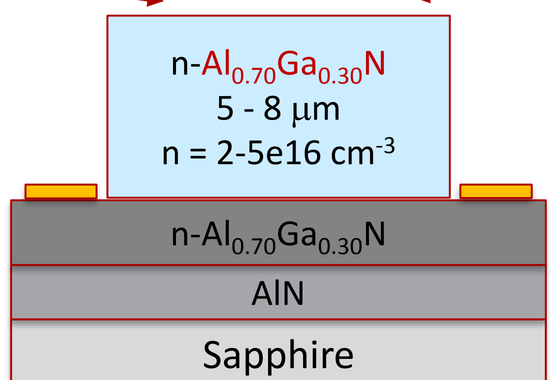
kT ~ 0.026 eV

Thermal activation of holes not viable for high-Al alloys

Homojunction | Heterojunction | Polarization-doped | p-Superlattice



"Quasi-vertical" on sapphire: Common design except for p-side

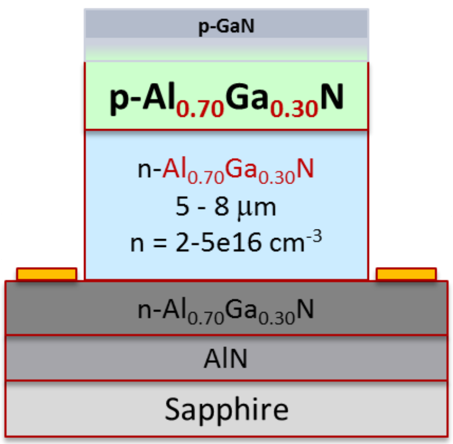


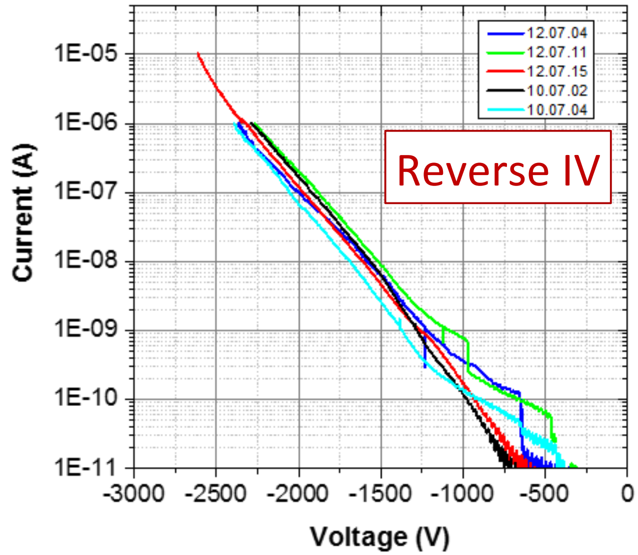
Vertical on n-GaN: Ultimate goal

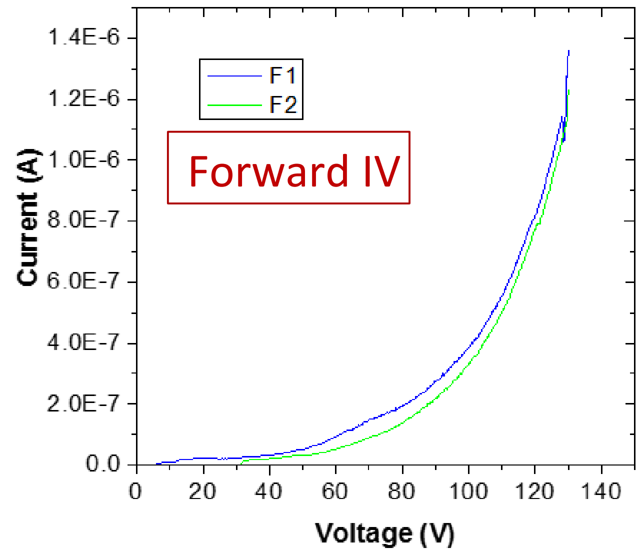
50-350 μm diameter

70% AlGaN Homojunction PiN Diodes

Homojunction



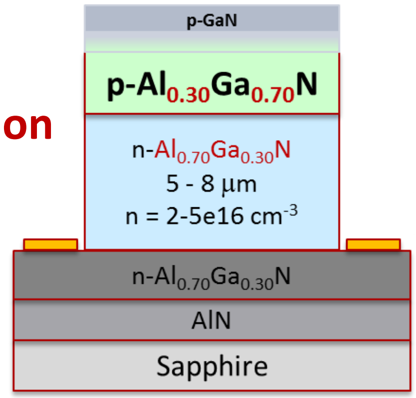




- ➢ **Robust to 2.6 kV (10 µA leakage) with no clear breakdown**
  - **Currently investigating possible transport mechanisms**
- ➢ **Extremely resistive forward IV: ~1 µA @ ~130 V**
  - **Likely due to low hole concentration in p-$Al_{0.7}Ga_{0.3}N$**

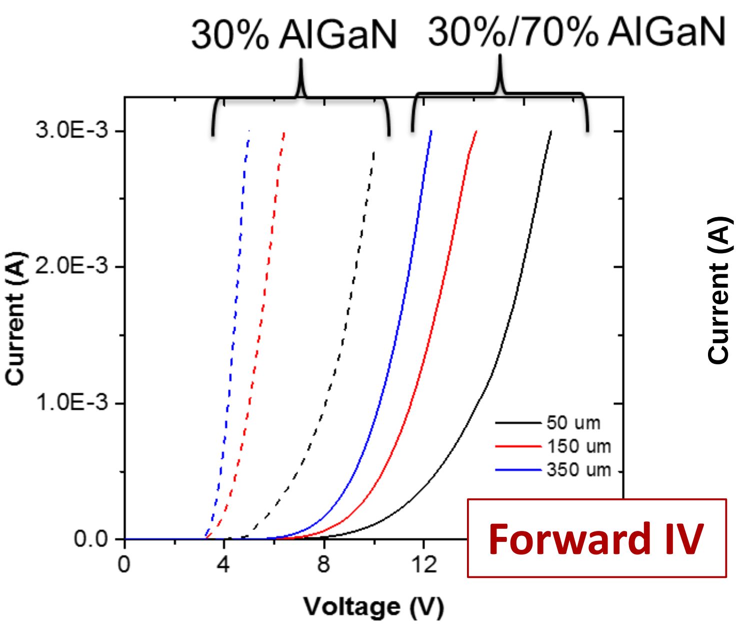
70% AlGaN Heterojunction PiN Diodes

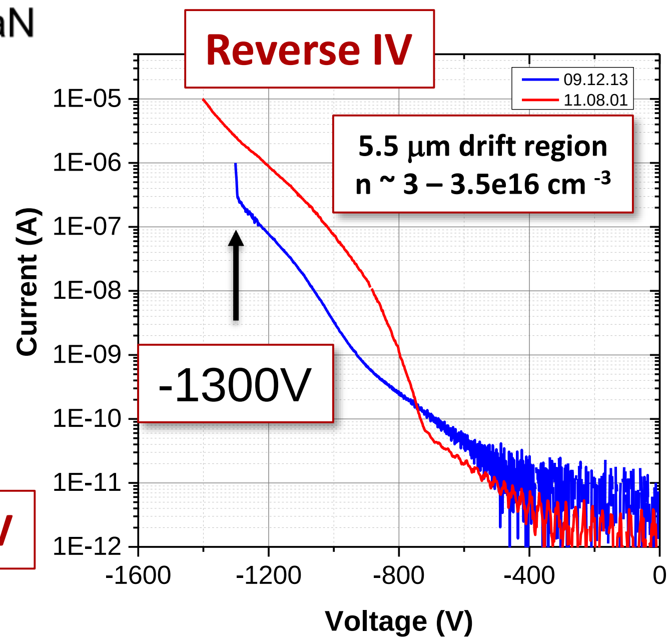
Heterojunction



- **Much lower turn-on voltage than 70% homojunction**
  - **Consistent with improved conductivity of p-layer**

- **Two distinct reverse behaviors, majority do not show abrupt breakdown up to 10 µA (~50 A/cm²)**
- **Not achieving the breakdown voltages predicted by E_C scaling**
  - **Excess leakage current may mask 70% Al performance potential**
  - **<u>30% Al p-layer may impact breakdown</u>**

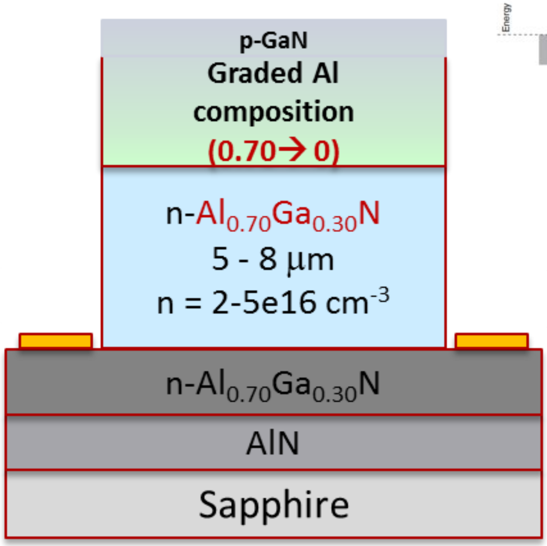


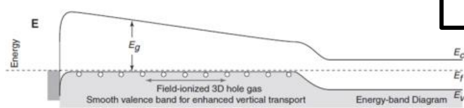


Polarization charge present at heterojunction

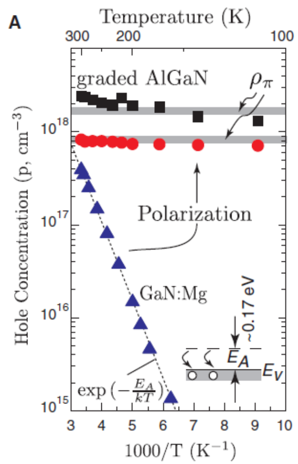
70% AlGaN Polarization-Doped PiN Diodes

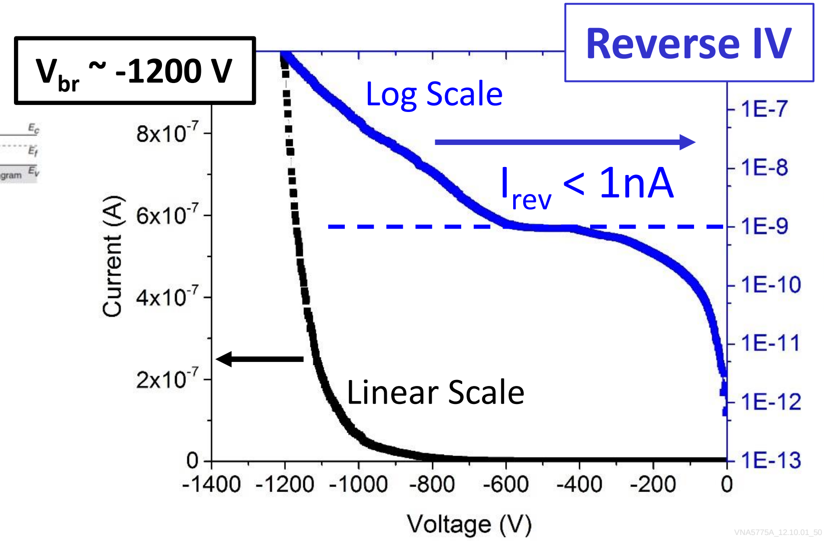
Polarization-doped

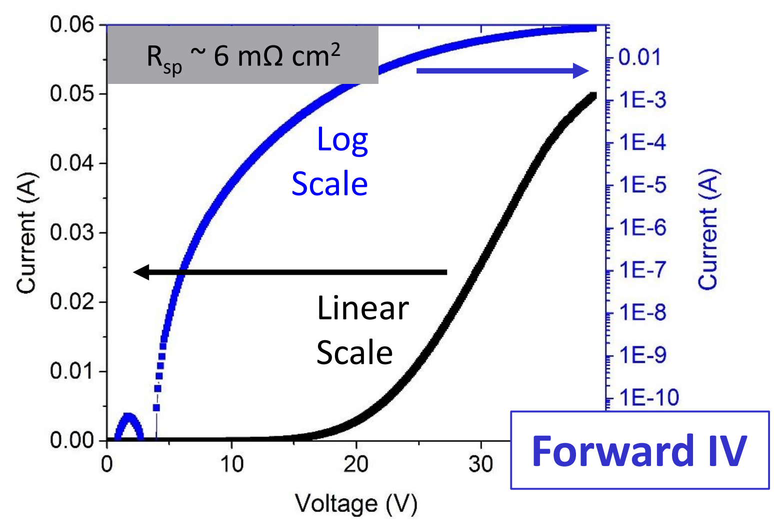




Simon, Science 327, 60 (2010)



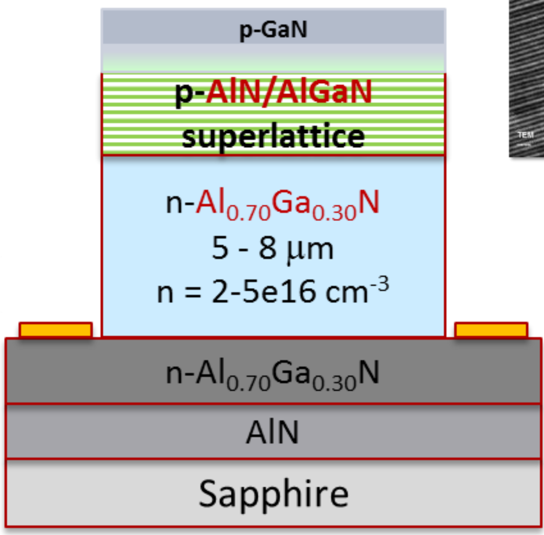


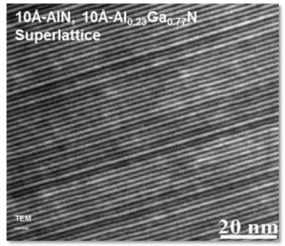


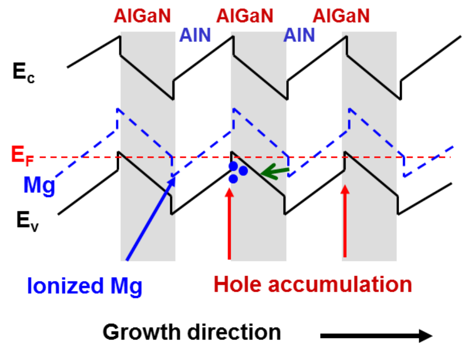
- 150 nm grade from $Al_{0.70}Ga_{0.30}N$ to $Al_{0.05}Ga_{0.95}N$
- Similar reverse voltages for heterostructure PiNs and polarization-doped PiNs for similar drift layer thickness
  - May be due to interaction of implanted JTE with polarization-induced charge in p-layer

70% AlGaN Superlattice PiN Diodes

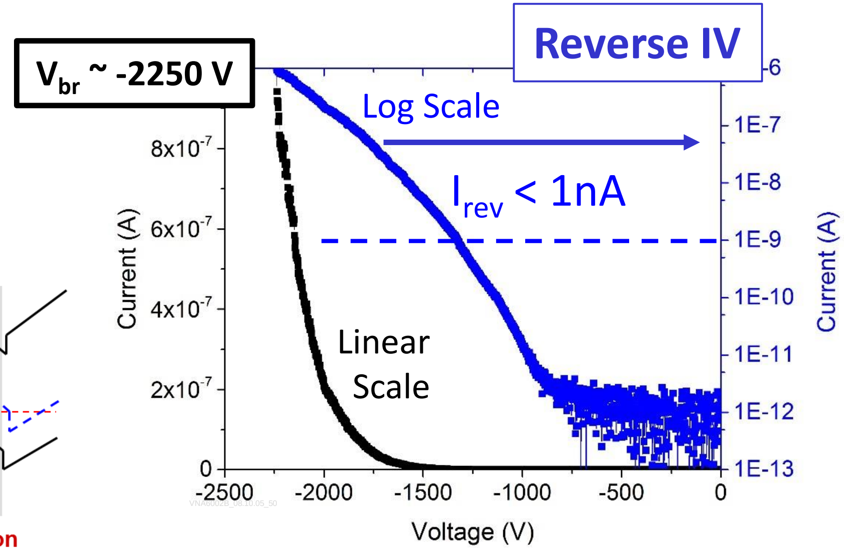
p-Superlattice

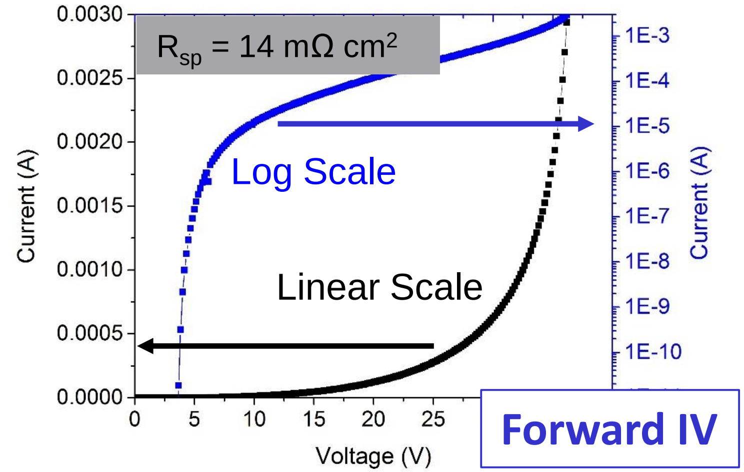






Field ionization





- **p-type superlattice design***
  - **Barriers: AlN (10 Å)**
  - **Wells: $Al_{0.25}Ga_{0.75}N$ (10 Å)**
  - **160 pairs, total thickness 3200 Å**
- **Higher breakdown voltage for similar drift region thickness and doping – better JTE?**
- **Higher R_{on} – due to hetero-barriers?**

* Allerman et al., JCG 2010

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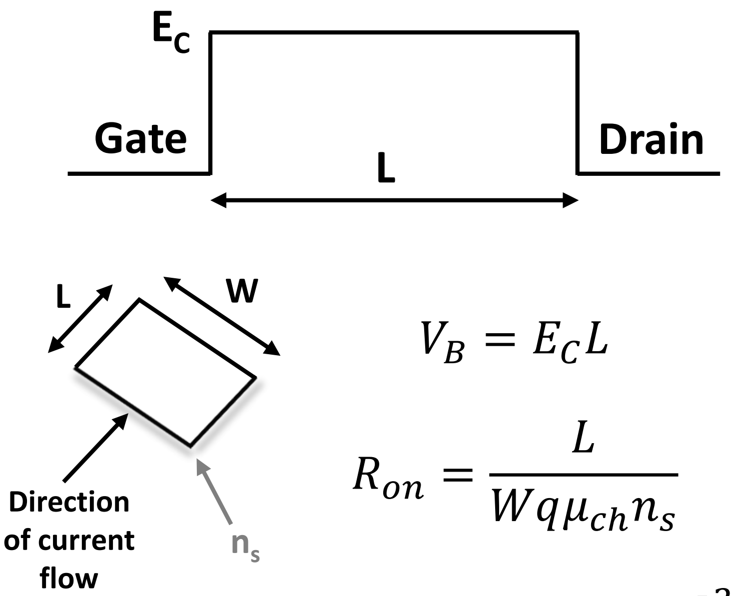
- Quasi-Vertical AlGaN PiN diodes
- **Al-Rich AlGaN High Electron Mobility Transistors**
- Other WBG PE Projects

Lateral Power Device Figure of Merit

Not as widely known as the vertical UFOM

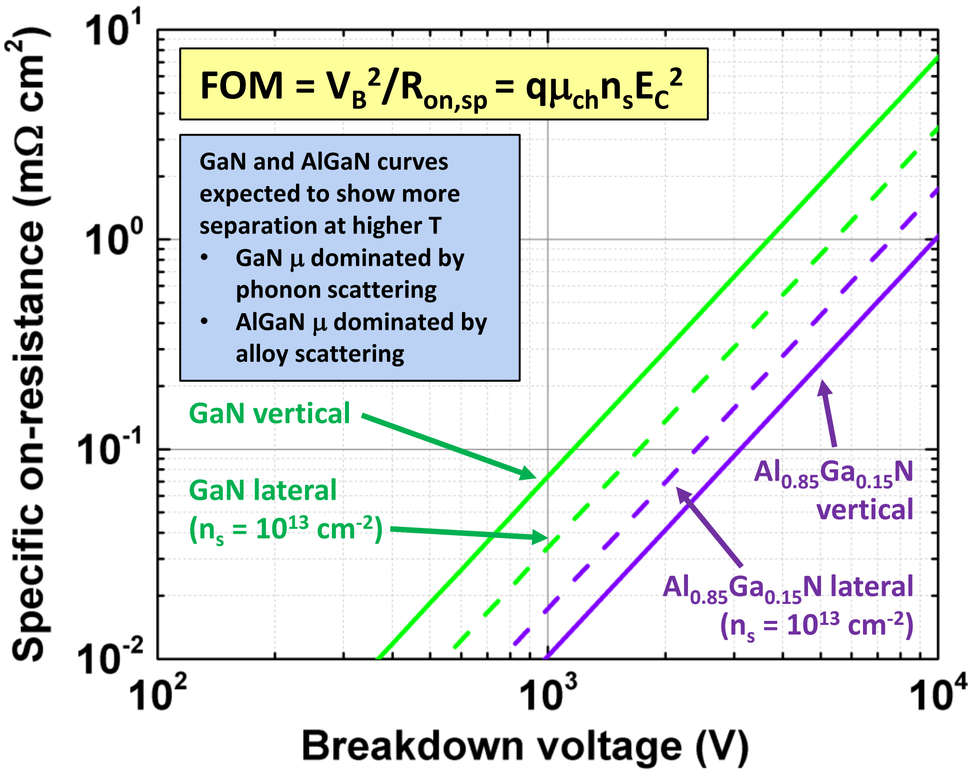


$$V_B = E_C L$$

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

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

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

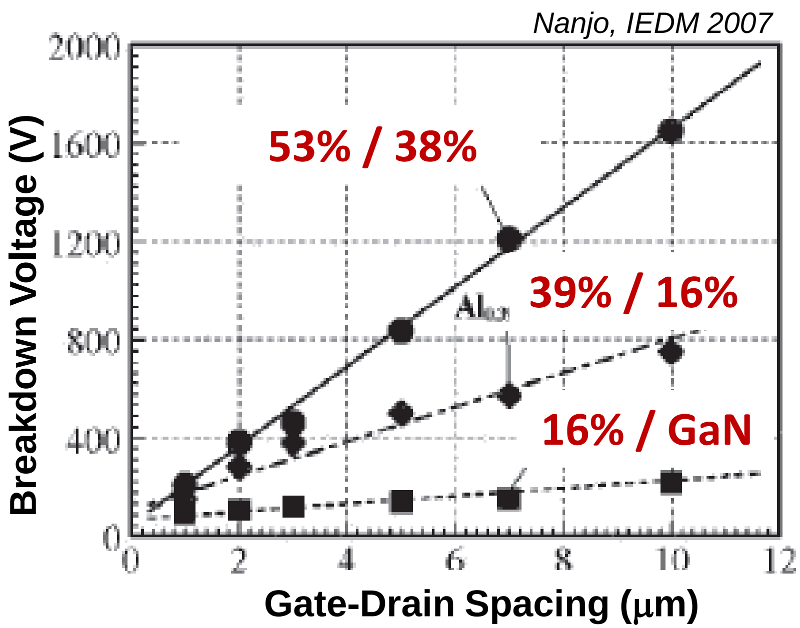


- Proportional to E_C^2 rather than E_C^3, but high n_s can result in high FOM

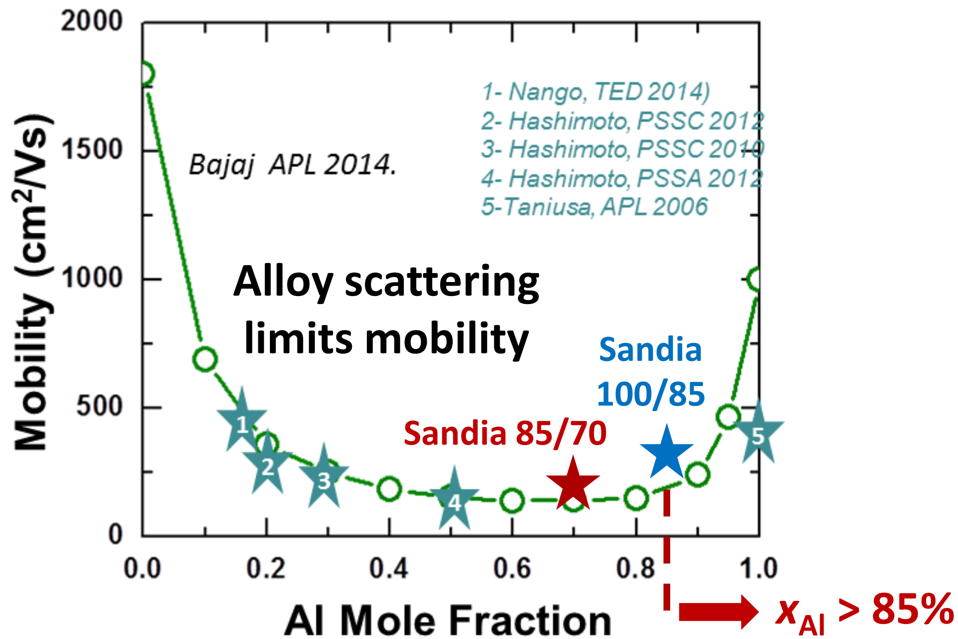
Coltrin et al., *ECS JSSST* 6 (11), S3114 (2017)

Benefits and Challenges of Higher Al Content

Breakdown voltage of AlGaN HEMTs vs. G-D spacing



Electron mobility vs. AlGaN channel composition



Higher Al compositions:

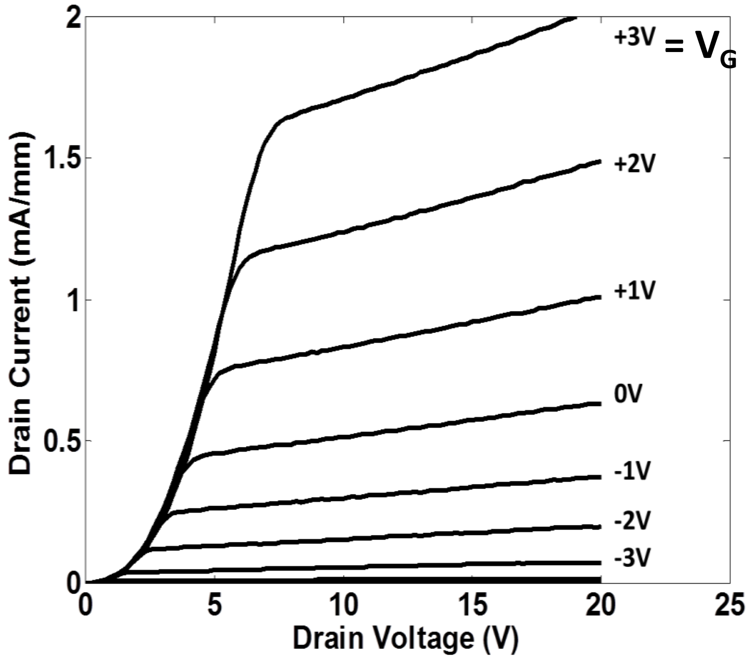
➡ ***Higher breakdown voltages***

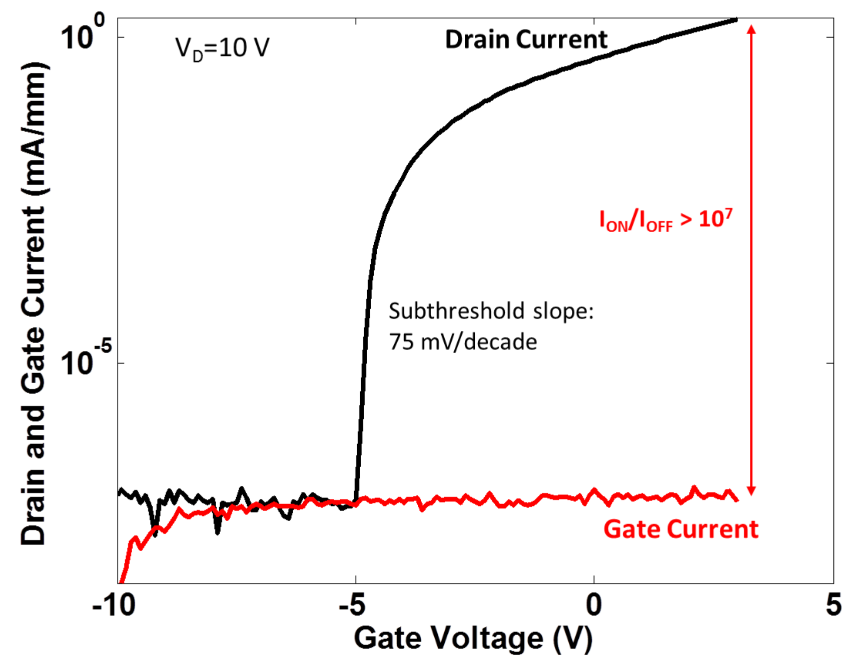
Highest Al compositions:

➡ ***Higher mobility is predicted***

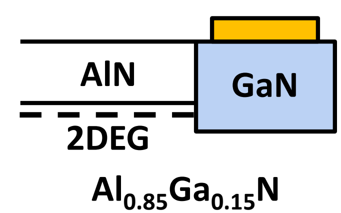
Bajaj et al., *APL* 105, 263503 (2014); Coltrin et al., *ECS JSSST* 6 (11), S3114 (2017)

Previous Result: $AlN/Al_{0.85}Ga_{0.15}N$ HEMT



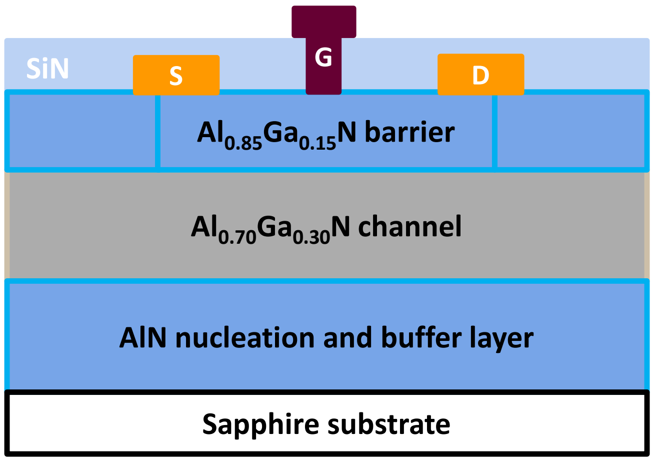


- Recessed, re-grown Ohmic contacts
- Some aspects of performance are good
  - Good gate control
  - Low gate and drain leakage, steep sub-threshold slope (~ 75 mV/decade)
  - Breakdown voltage ~810 V for 10 μm G-D device (81 V/μm ≈ 0.8 MV/cm)
  - Excellent I_{ON}/I_{OFF} ratio $>10^7$

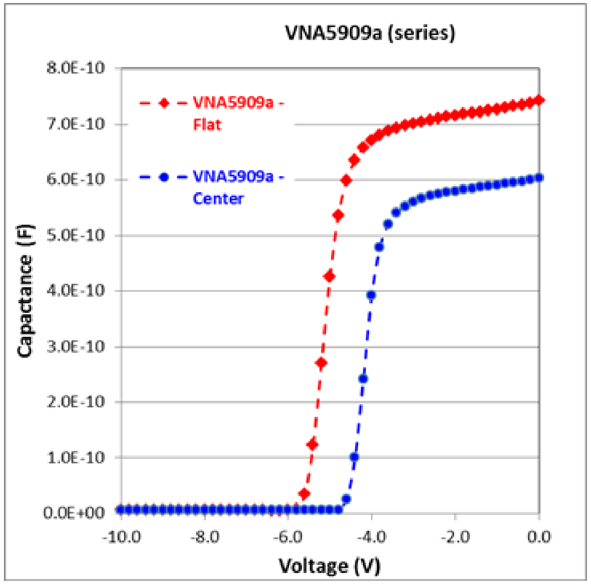


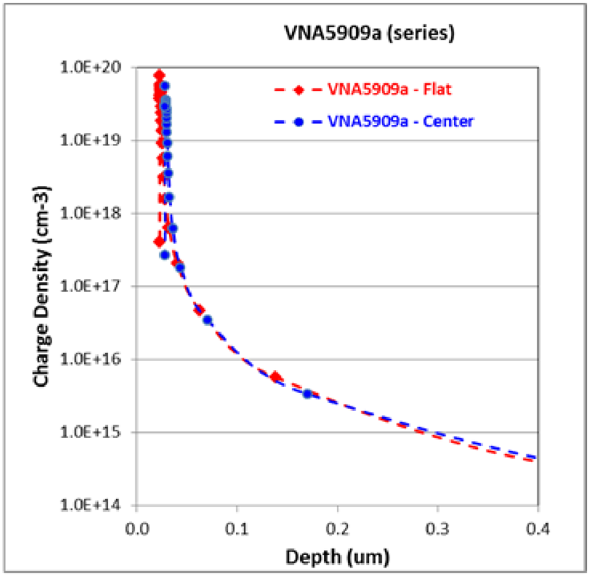
- But current density is limited by high resistance of quasi-Ohmic contacts (< 40x expected)

Second-Generation HEMT: $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ Structure



CV Characterization





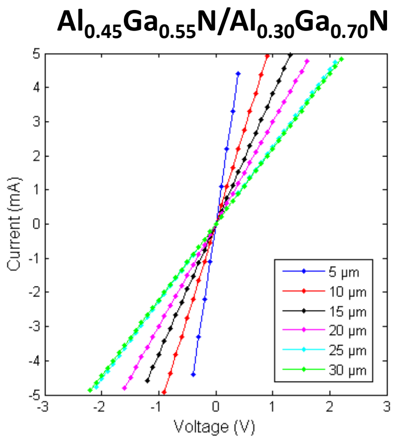
<u>Process Steps</u>:

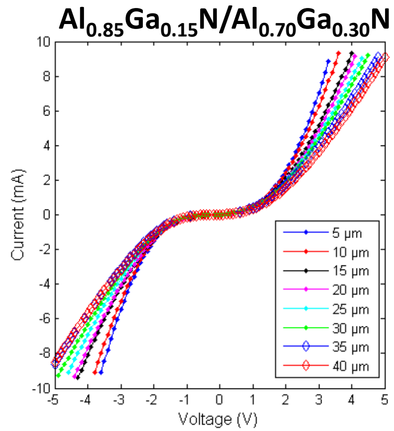
1. Photolithography, ohmic metal deposition, litoff, RTA
2. SiN deposition, photolithography, SiN etch (gate stem)
3. Gate photolithography, evaporation, liftoff

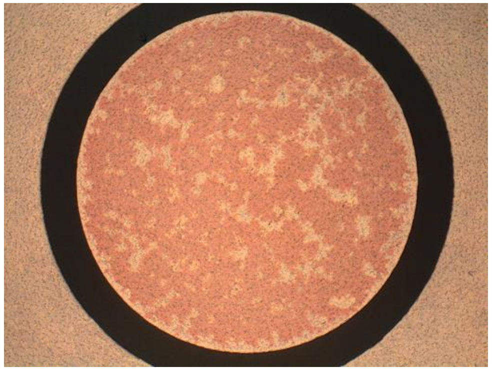
Planar source and drain contacts

- Sheet resistance: 2200 Ω/□
- Pinch-off voltage: -4.5 V (center)
- Sheet charge density: 6×10^{12} cm^{-2}
- Inferred mobility: 250 cm^2/Vs

Ohmic Contact Development





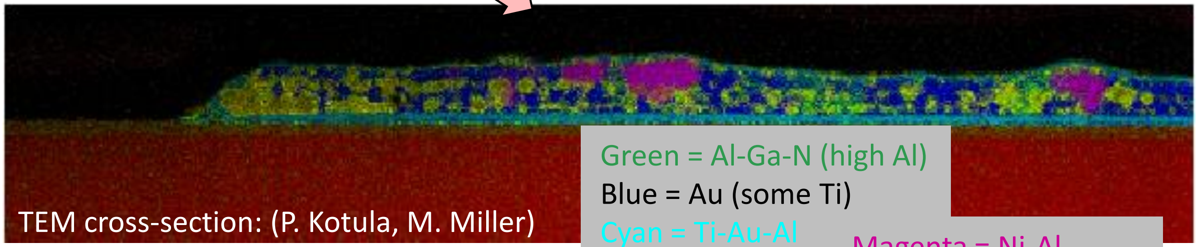


Au 50 nm
Ni 15 nm
Al 100 nm
Ti 25 nm
AlGaN/Substrate

900°C anneal

50 nm $Al_{0.45}Ga_{0.55}N$
4.15 µm $Al_{0.3}Ga_{0.7}N$
1.6 µm AlN
Sapphire Substrate

25 nm $Al_{0.85}Ga_{0.15}N$
400 nm $Al_{0.7}Ga_{0.3}N$
Graded Layer 50 nm
2.9 µm AlN
Sapphire Substrate



Green = Al-Ga-N (high Al)
Blue = Au (some Ti)
Cyan = Ti-Au-Al
Magenta = Ni-Al
Yellow = Al-O
Red = Al-Ga-N (low Al)

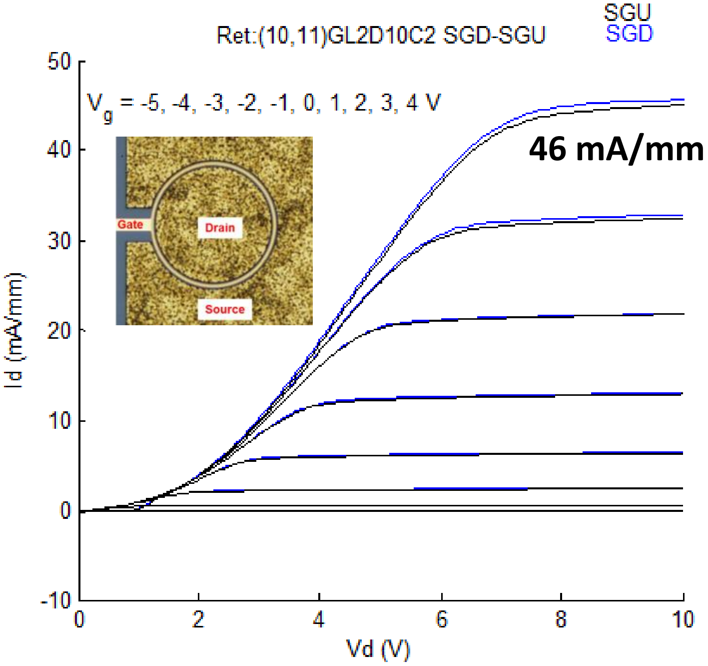
Observations:

- **Conventional planar contacts work well for $Al_{0.3}Ga_{0.7}N$ channels (ρ_c mid-10^{-5} Ω cm^2)**
- **Quasi-Schottky for $Al_{0.7}Ga_{0.3}N$ channels, but still have > 20x higher currents than 1st gen HEMTs**

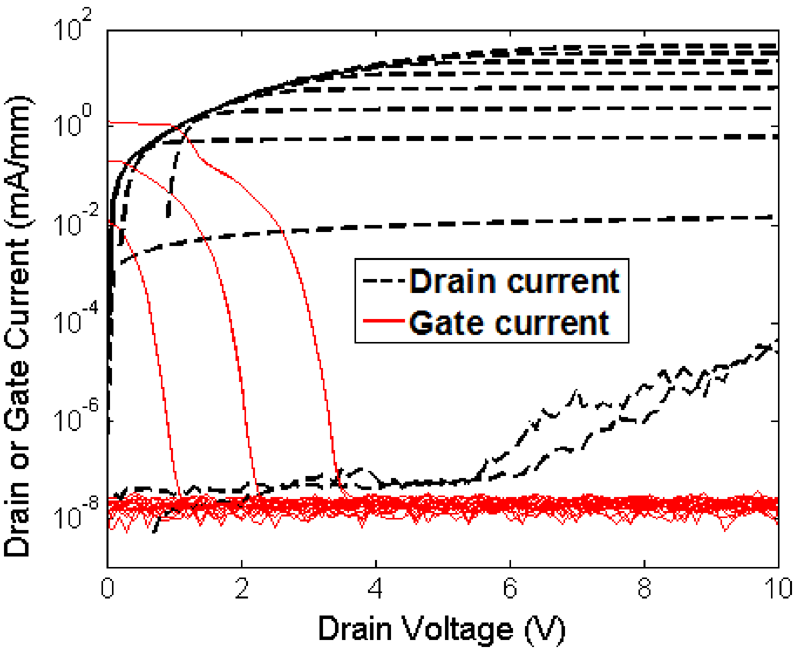
B. Klein *et al.*, planar contact development

Electrical Characteristics of $Al_{0.85}Ga_{0.70}N/Al_{0.70}Ga_{0.30}N$ HEMT

Linear Scale

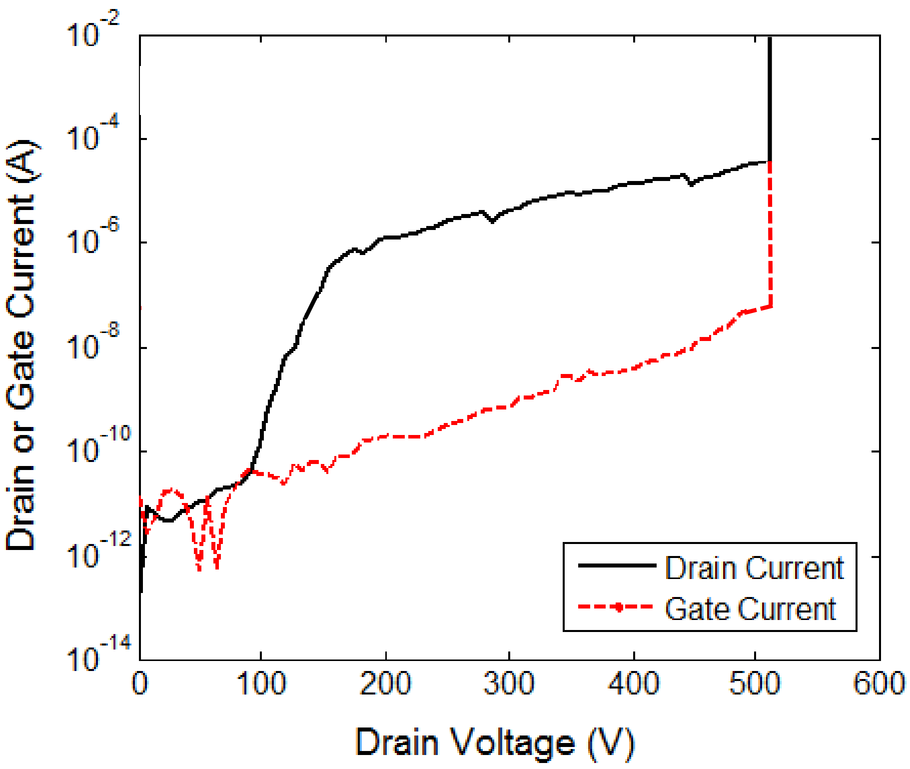


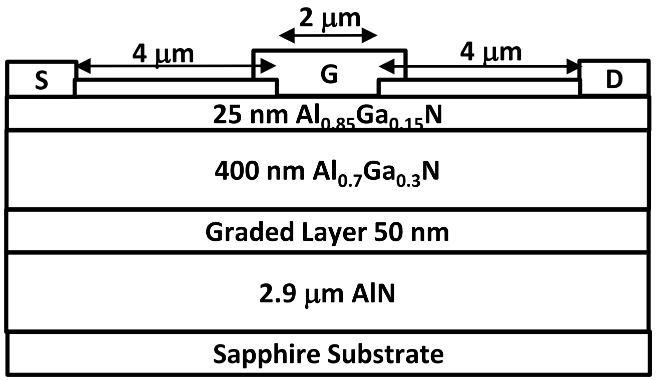
Log Scale



- **Better Ohmic contacts**
  - **Current density of 46 mA/mm > 20x better than first generation, but still < 2x expected**
  - **Due to remaining rectifying behavior in source and drain contacts**
  - **Again have low gate and drain leakage current**
- **Sub-threshold slope comparable to first generation ~ 75 mV/decade**

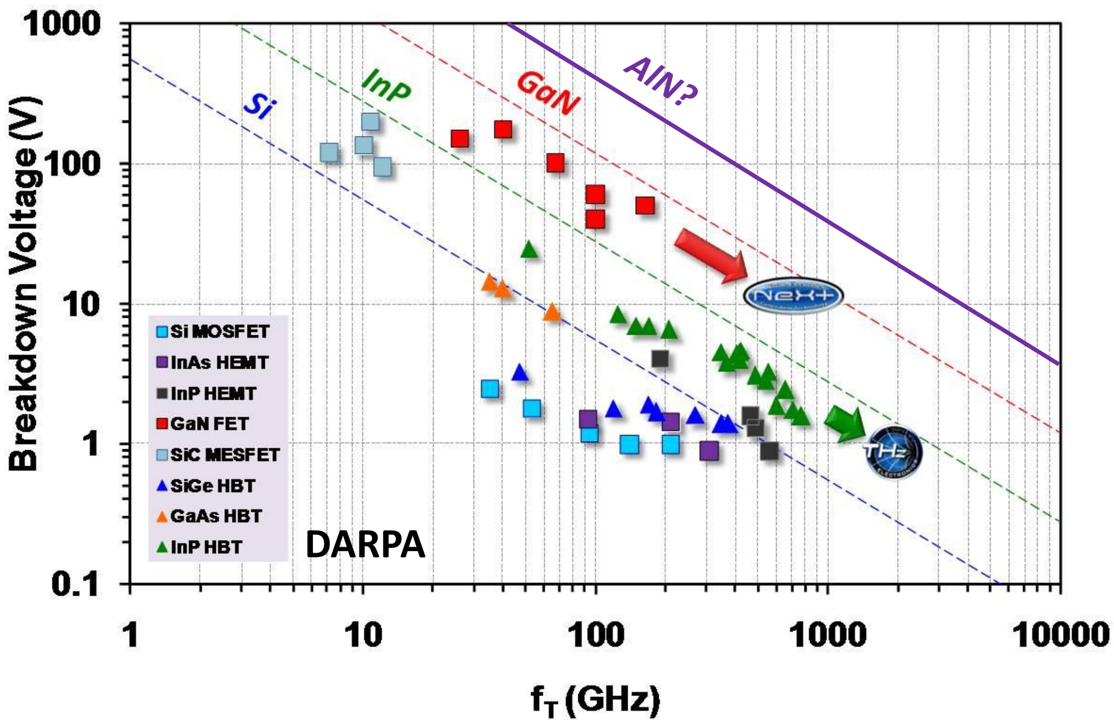
Breakdown Voltage of $Al_{0.85}Ga_{0.70}N/Al_{0.70}Ga_{0.30}N$ HEMT





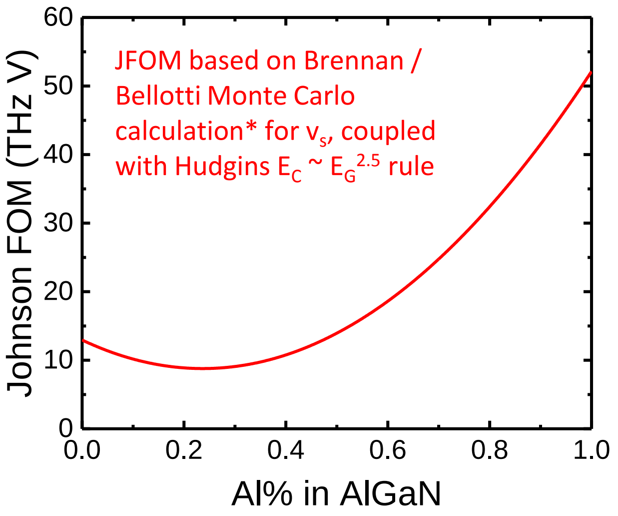
- **Field plate with SiN dielectric**
- **Misalignment with a circular gate leads to L_{GD} (actual) < L_{GD} (drawn)**
- **V_{br} = 511 V**
  - **L_{GD} = 1.6-5.4 μm (single device with misalignment)**
- **Breakdown field = 95-320 V/μm (≈ 0.8-3.2 MV/cm)**
  - **Exceeds previous generation device (81 V/μm)**
  - **GaN HEMT typical breakdown field ≈ 100 V/μm**

Advantages of UWBGs for Radio-Frequency Devices



Johnson FOM:

$$V_B f_T = E_C v_s / 2\pi$$



Al-rich AlGaN yields better JFOM than GaN due to higher E_C and comparable v_s

* M. Farahmand et al., TED 48(3), 535 (2001)

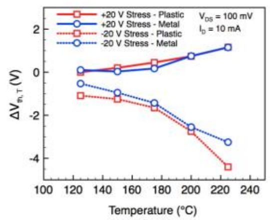
Outline

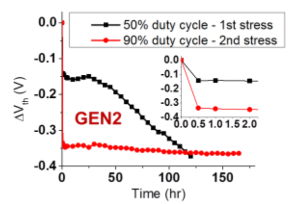
- Motivation for UWBG Materials in Power Electronics
- Quasi-Vertical AlGaN PiN diodes
- Al-Rich AlGaN High Electron Mobility Transistors
- **Other WBG PE Projects**

WBG PE Reliability

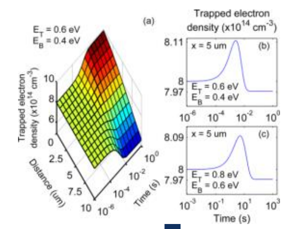
Suggested reliability improvements for components, software, and operation of Silicon Power Corporation's Solid-State Current Limiter

Characterized and evaluated commercial SiC MOSFETs, including the impacts of bias, temperature, packaging, and AC gate stress on reliability





Created a physics-based model for GaN HEMTs linking defect properties to device design



Characterizing switching reliability of vertical GaN PiN diodes using double-pulse test circuit

2009

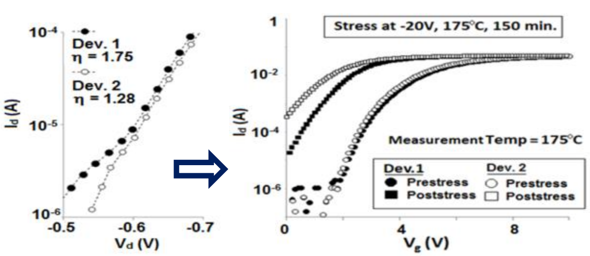
Developed and documented a general process for analyzing the reliability of any power electronics system

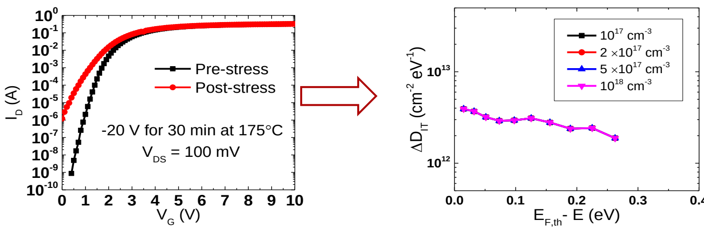
Developed models for SiC threshold voltage instability, and identified the free-wheeling diode ideality factor as a potential screening metric for threshold voltage shifts

Developed an easy to use method that can be used by circuit designers to evaluate the reliability of commercial SiC MOSFETs

Participating in JEDEC WBG reliability working group

O. Slobodyan, S. Sandoval, C. Matthews, S. DasGupta, D. Hughart, J. Flicker, R. Kaplar, S. Atcitty, I. Gyuk





Hybrid Switched Capacitor Circuit Development for Use of GaN Diodes in High Gain Step-Up Converters (Hy-GaiN)

PROJECT OBJECTIVES

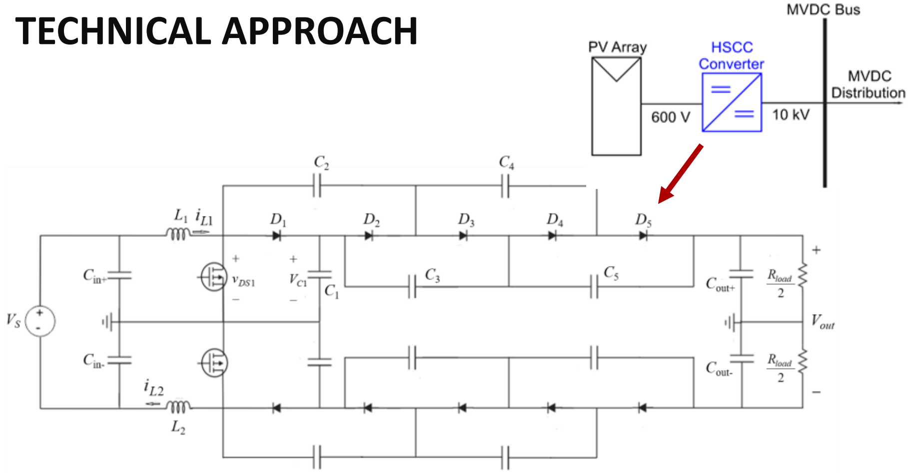
- *To greatly accelerate the adoption of photovoltaics into the grid by enabling cheaper and more efficient DC distribution networks*
- *Project will develop compact (>100 W/in^3), Efficient (>95% CEC equivalent), Medium Voltage capable (>10 kV) converters*
- *Project combines the use of Wide Band Gap based devices with novel converter topologies*

PROPOSED TASKING

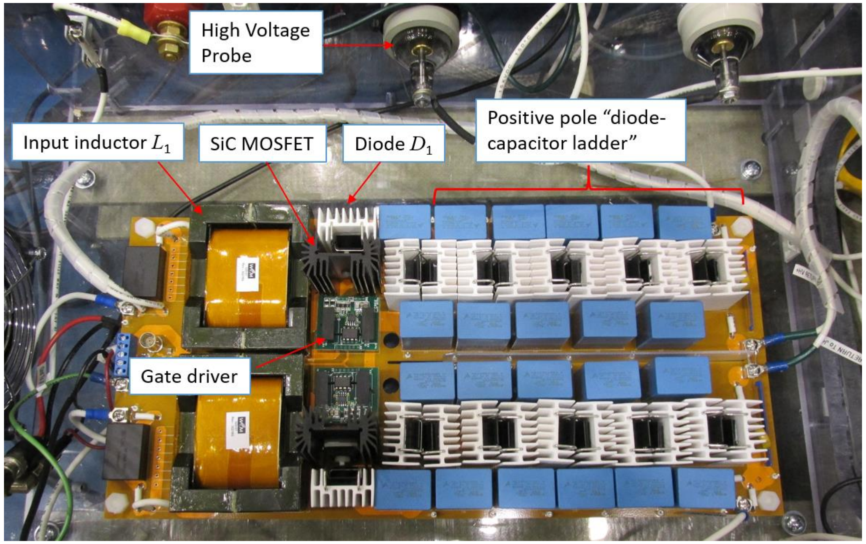
- *Develop new HSCC-based power converters that use SiC and GaN components*
- *Optimize the parameter selection and develop new packaging schemes to achieve power density and efficiency targets*
- *Demonstrate converter at 10 kV and 10 kW in laboratory and relevant operating environments*

J. Neely, J. Delhotal, J. Stewart, R. Brocato, S. Gonzalez, J. Richards, I. Kizilyalli

TECHNICAL APPROACH



Have thus far demonstrated 5.0 kW at 97.9% efficiency



MVDC/HVDC Power Conversion with Optically-Controlled GaN Switches

PROJECT OBJECTIVES

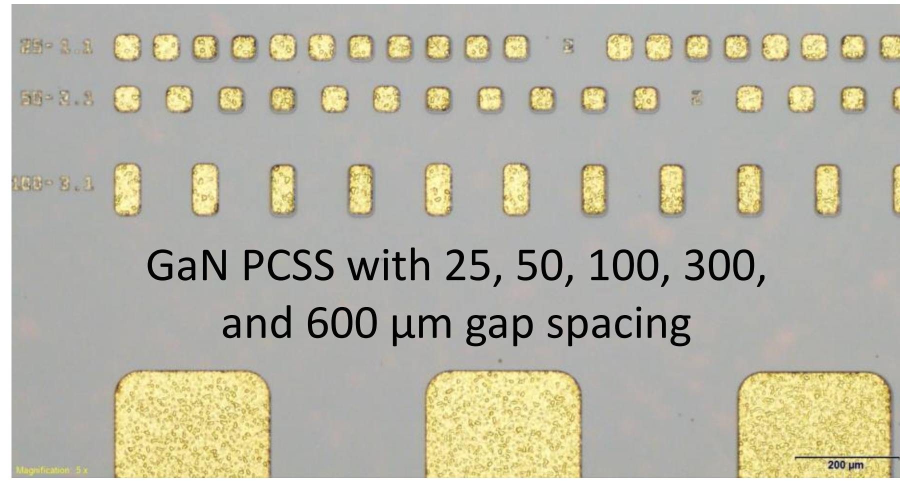
- *Produce "high voltage switching transistors" for high average power applications with GaN photoconductive switches (PCSS)*
- *Measure high field photoconductive properties (determine high gain or linear triggering and sub-bandgap triggering) of GaN*
- *A high voltage transmission line driven pulser will clearly distinguish between high gain and linear photoconductive switching*

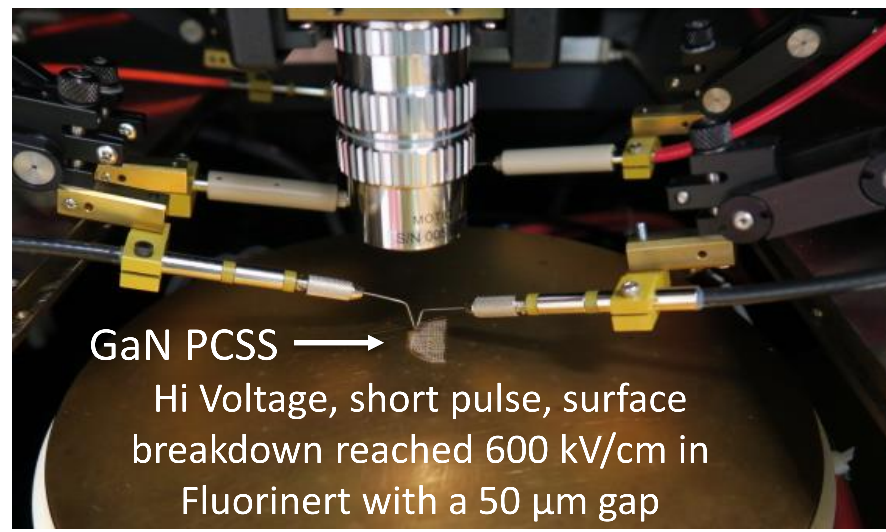
PROPOSED TASKING

- *Fabricate GaN PCSS and measure high field photoconductive properties*
- *Iterate fabrication to optimize device for high average power operation*
- *Demonstrate device operation in a high average power circuit*

F. Zutavern. J. Lehr, G. Pickrell, R. Gallegos,
M. van Heukelom, I. Kizilyalli

TECHNICAL APPROACH





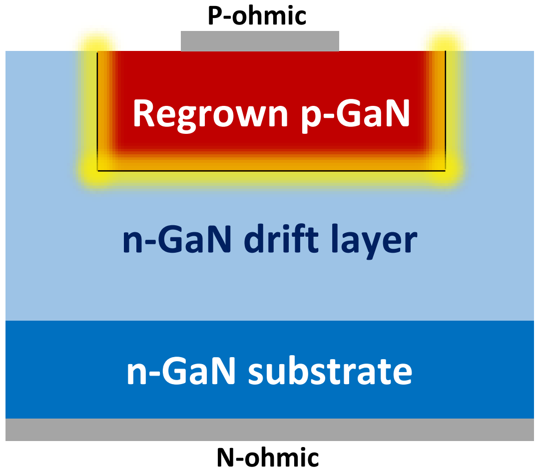
PNDIODES

Project Goals

A) *Develop a mechanistic understanding of selective area epitaxy (SAE) of p-GaN by MOVPE regrowth processes*

B) *Demonstrate a GaN PN diode formed by SAE of p-GaN that is electrically equivalent to "as-grown" PN diodes.*

Key Performance Metrics



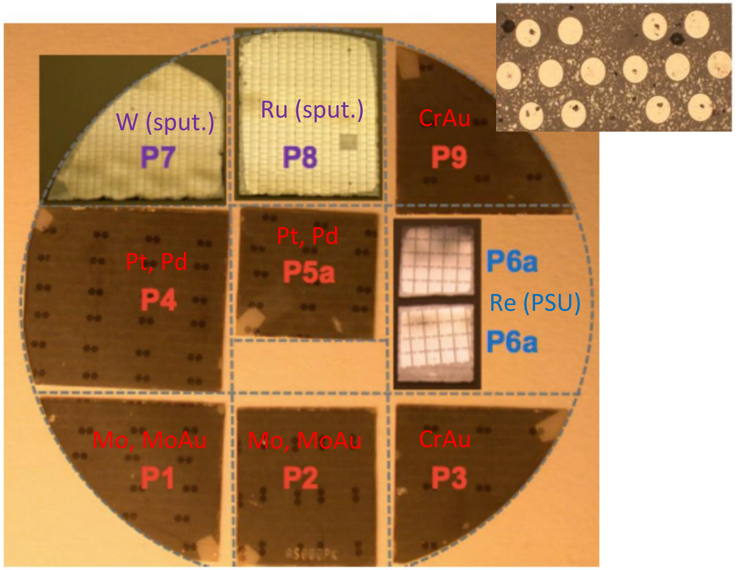
- **Identify and reduce both impurity concentrations and point defects (traps) at the regrowth interface**
- **Quantitatively correlate mitigation strategies for particular impurities and defects with electrical properties of SAE diodes**
- **Demonstrate SAE-PN diode with:**
  - **Reverse leakage < 1 nA @ 600V**
  - **V_{br} > 1200 V with avalanche capability**

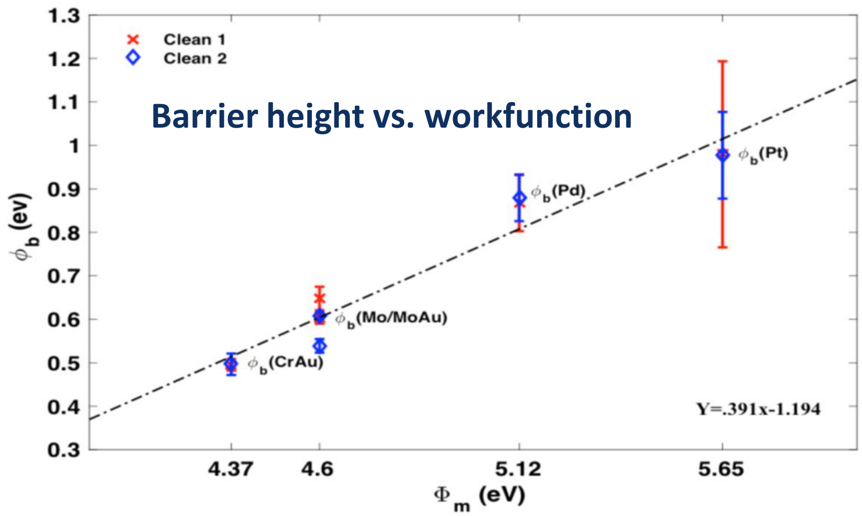
➡ Understanding of SAE provides the foundation for GaN-based vertical power transistors and diodes

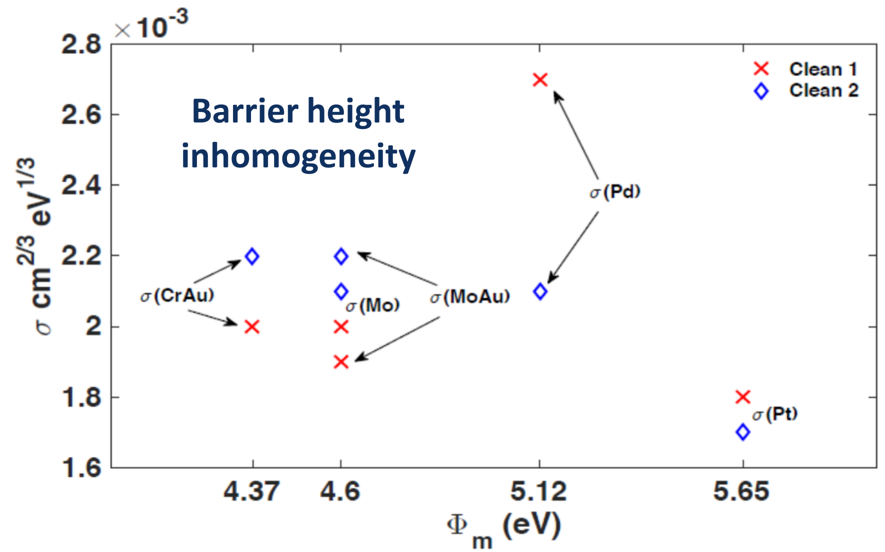
A. Armstrong, A. Allerman, G. Pickrell, M. Crawford, A. Talin, F. Leonard, P. Kotula, D. Feezell, I. Kizilyalli

Stable GaN-Based Schottky Interfaces

150 µm diameter







- Stress Schottky barriers under high current density and observe changes in:
  - Mean barrier height
  - Barrier height inhomogeneity
- Important for SBDs, JBS diodes, etc.

A. Allerman, A. Fischer, G. Pickrell, R. Kaplar, M. Porter,
M. Gardner, T. Weatherford, P. Specht, L. Petersen

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
- Demonstrated kV-class vertical AlGaN PiN diodes
  - 30% Al diodes show good behavior
  - Several approaches to p-side of 70% Al diodes examined
- Demonstrated Al-rich $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ HEMTs
  - Second-generation device has planar source and drain contacts
  - Higher current density and breakdown field achieved
- Several other WBG PE projects ongoing

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