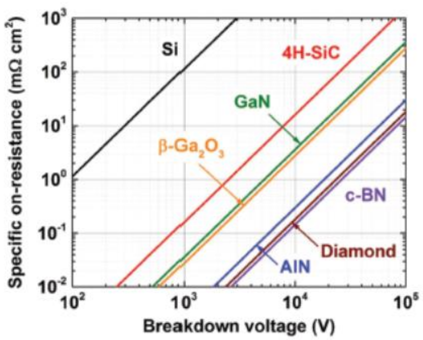
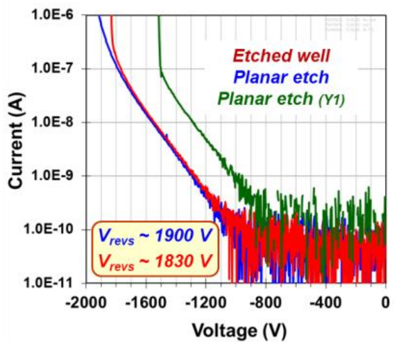
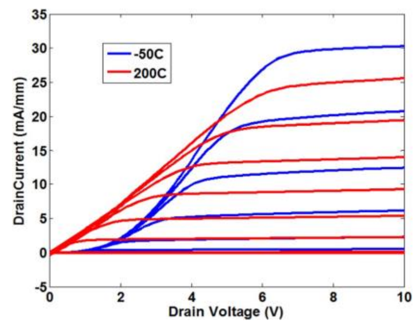
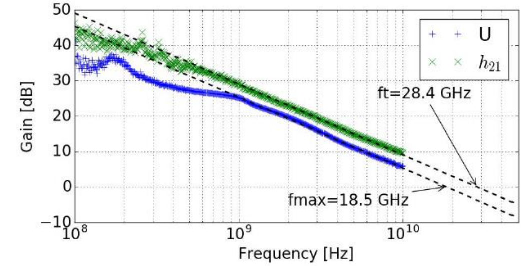
Exceptional service in the national interest

Sandia National Laboratories









Ultra-Wide-Bandgap Semiconductors: Challenges and Opportunities

NYCREATES

NY CREATES Emerging Technologies Seminar

Bob Kaplar, Sandia National Labs – July 8, 2021

Sandia NL: Andy Allerman, Andy Armstrong, Mary Crawford, Greg Pickrell, Jeramy Dickerson, Jack Flicker, Jason Neely, Elizabeth Paisley, Albert Baca, Brianna Klein, Erica Douglas, Shahed Reza, Andrew Binder, Luke Yates, Oleksiy Slobodyan, Paul Sharps, Jerry Simmons, Jeff Tsao

UWBG Working Group: Mark Hollis (MIT-LL), Noble Johnson (PARC), Ken Jones (ARL), Dimitris Pavlidis (FIU), Ken Goretta (AFOSR)

Ultra EFRC: Bob Nemanich (ASU), Steve Goodnick (ASU), Srabanti Chowdhury (Stanford)

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

Partially supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC (NTESS), a wholly owned subsidiary of Honeywell Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Introduction: Generations of Semiconductors

- **Gen 1: Ge and Si**
- **Gen 2: Conventional III-Vs – Arsenides, Phosphides, Antimonides**
- **Gen 3: Wide-bandgaps – SiC, GaN, InGaN**
- **Gen 4: Ultra-Wide-Bandgaps – $Al_xGa_{1-x}N$, $(Al_xGa_{1-x})_2O_3$, diamond, c-BN, others**

Outline

- **Motivation: Applications of UWBGs**
- **UWBG Properties**
- **Sandia AlGaN Devices:**
  - **Power Electronics**
  - **Radio Frequency**
  - **High-T Logic**
  - **Optoelectronics**
- **UWBG Community Activities**

Outline

- ➢ **Motivation: Applications of UWBGs**
- ➢ UWBG Properties
- ➢ Sandia AlGaN Devices:
  - Power Electronics
  - Radio Frequency
  - High-T Logic
  - Optoelectronics
- ➢ UWBG Community Activities

Military Applications

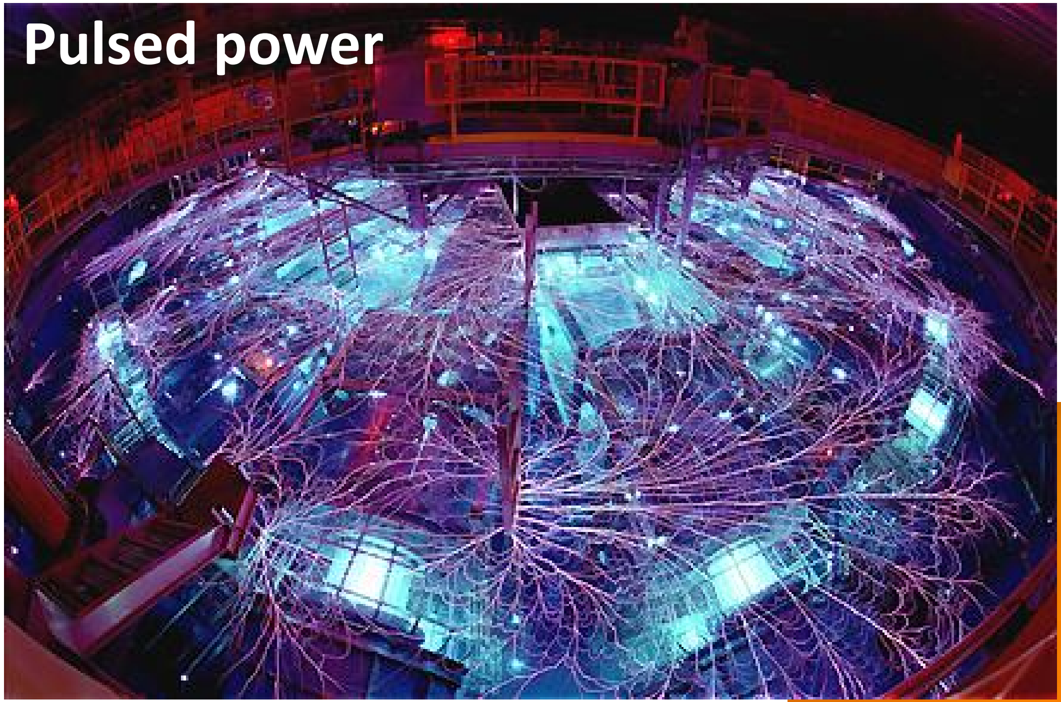
Warship electrification (DC microgrid, pulsed power weapons)

Electromagnetic railgun

Higher degree of electrification and power desired in SWaP-constrained environments

Electromagnetic armor

Ultra-High-Voltage Applications



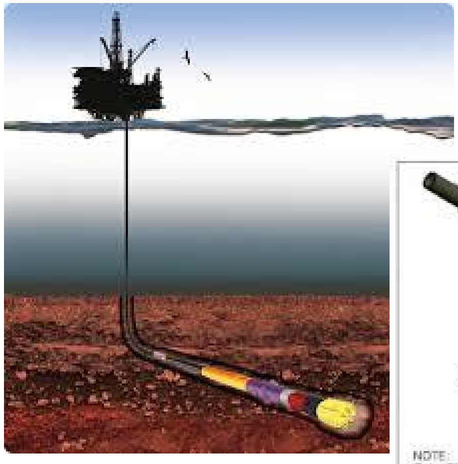
Conservative but critically important power device markets

100 kV switches may be possible using UWBG semiconductors!

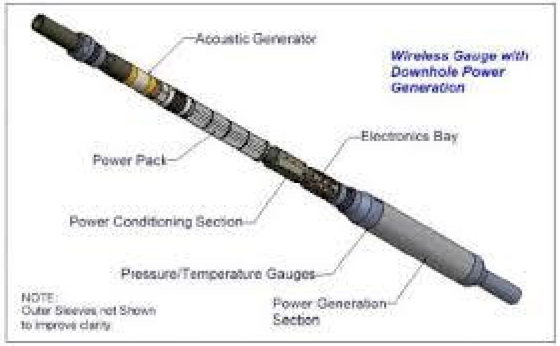
Power Electronics for Extreme Environments

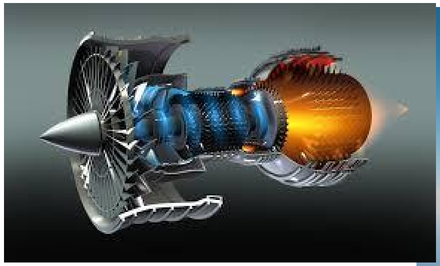
<u>Relevant extreme environments for power electronics:</u>

- Temperature extremes
- Vibration
- Radiation

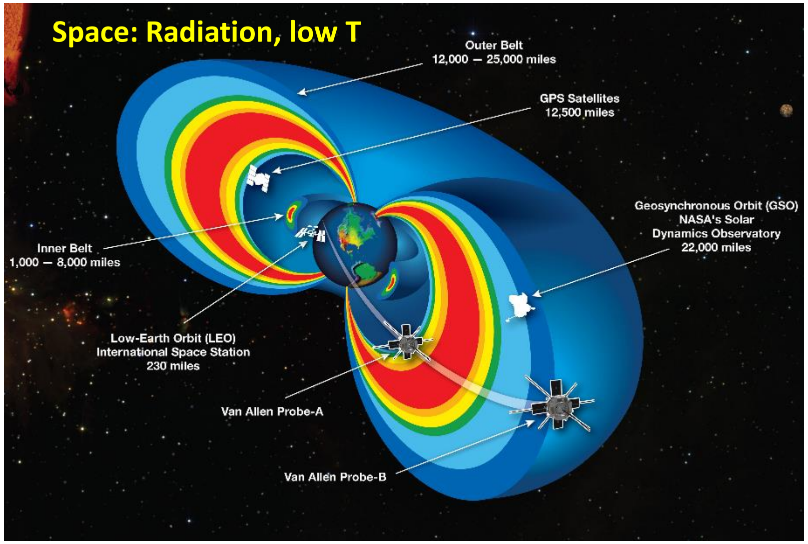


Down-hole: High T, vibration



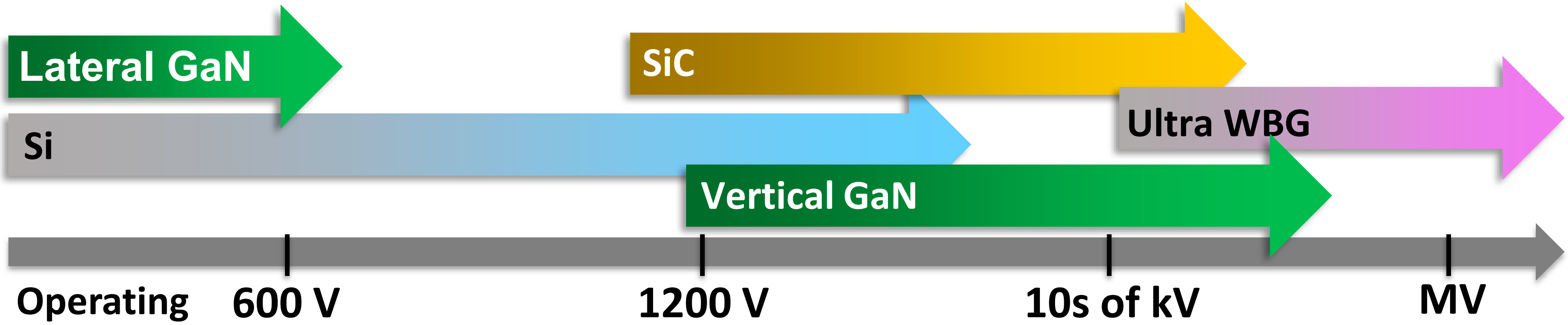


Aviation: High T, vibration



UWBGs are expected to be robust under wide temperature ranges and radiation

Energy-Efficiency Applications



Motor drives
Electric vehicles

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

PV inverters

- Higher voltages, lower resistive losses

Electric distribution
Grid energy storage
Electric rail
Electric aviation

- AC subsystems to 13.8 kV

HV-DC transmission

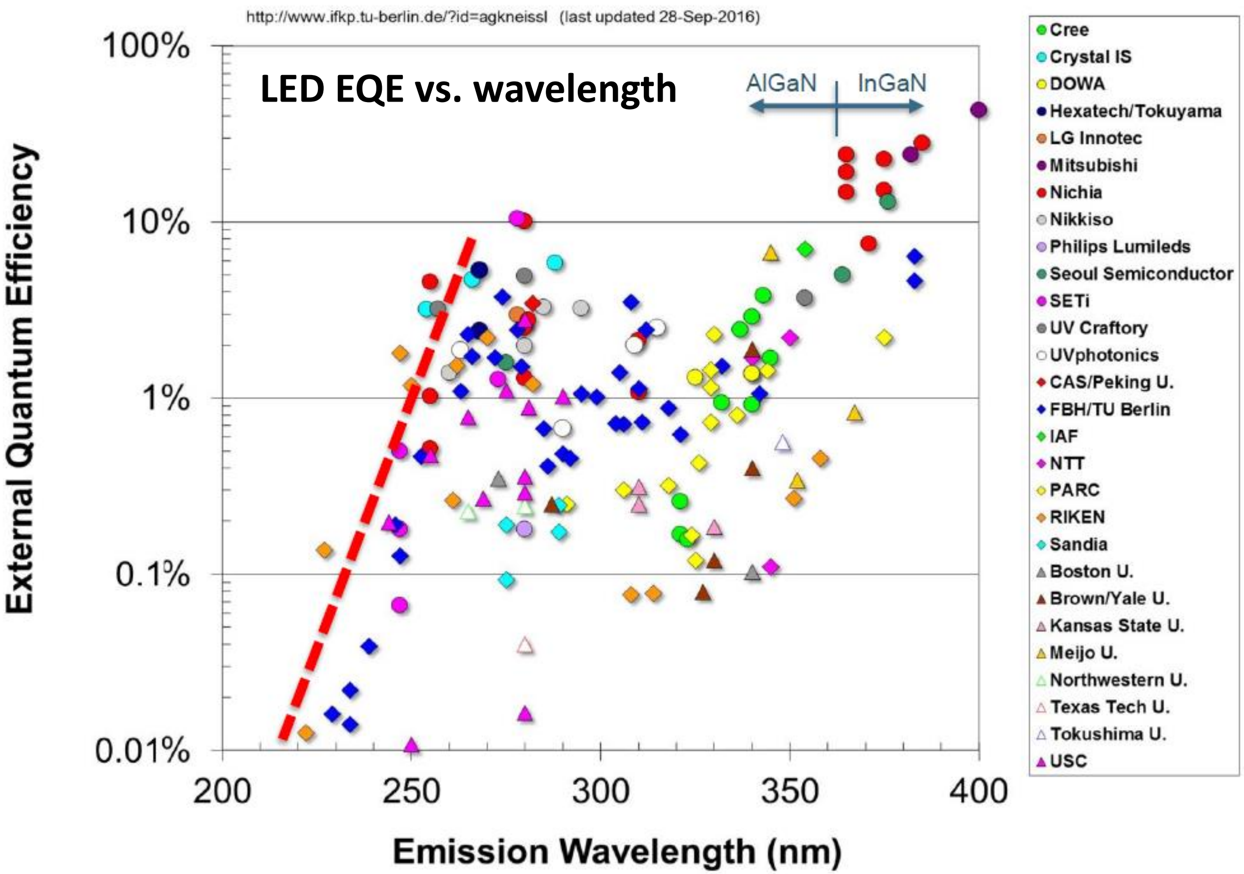
- Increase grid resiliency
- Less resistive energy loss
- Replace expensive IGBT / Thyristor stacks

Radio-Frequency Applications

- More powerful radar has longer range
- Beam can be focused down to interact with incoming target's guidance electronics
- Can be used in smaller directed energy applications to heat opponent's skin
- Can use as a high-power microwave system to locally affect operation of electronics

K. Jones, ARL

Ultraviolet Optoelectronics



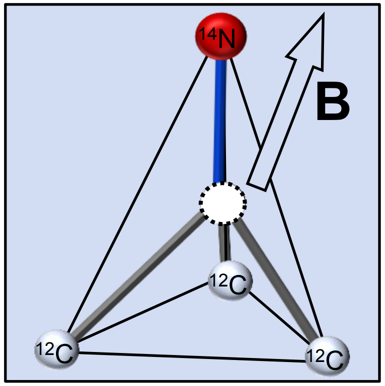
Rapid drop in efficiency for λ < 250nm
due to orientation-dependent TE/TM polarization switching

Applications:

- **Water purification**
- **Bio-agent detection**
- **Non-line-of-sight communication**
- **Solar-blind detectors**

N. Johnson, PARC

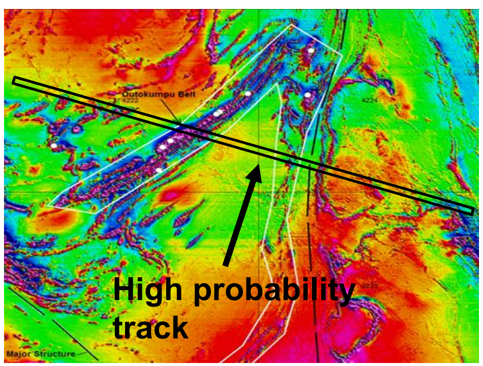
Quantum, Sensing, Navigation, and Other Applications of UWBG Materials



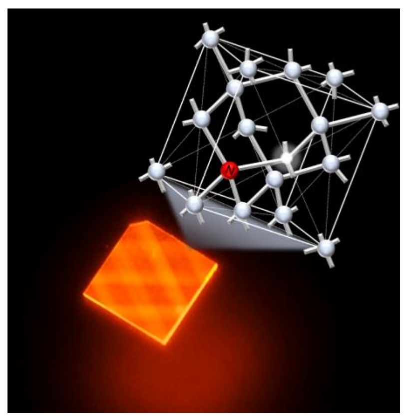
(N^+ Vacancy) in Diamond

- Fine/hyperfine structure of N^+ Vacancy complex in diamond is ultrasensitive to B & E fields
- Optical readout
- Many applications: Navigation, medical/biological imaging, anomaly detection, quantum systems, etc.
- h-BN also being studied

Magnetic Navigation



Quantum Systems



Parameters for Linear Optical Quantum Computing

Parameter	Reported/Demonstrated			Required Value
	Value	Wavelength [nm]	Material	
Optical Loss	8 dB/cm	640	AlN/SiO_2	~2 dB/cm
Linear Electro-Optic Coefficient	0.7 pm/V	628	AlN/SiO_2	~1 pm/V
Single-Photon Emission Efficiency	72%	920	GaAs/InAs	99%
Maximum Quantum Emitter Count Rate	$4x10^6$	625	h-BN	
Photodetector Detection Efficiency	93%	1500	WSi super-conductor	99%
Isotope Purity	99.99%		Diamond	99.99%

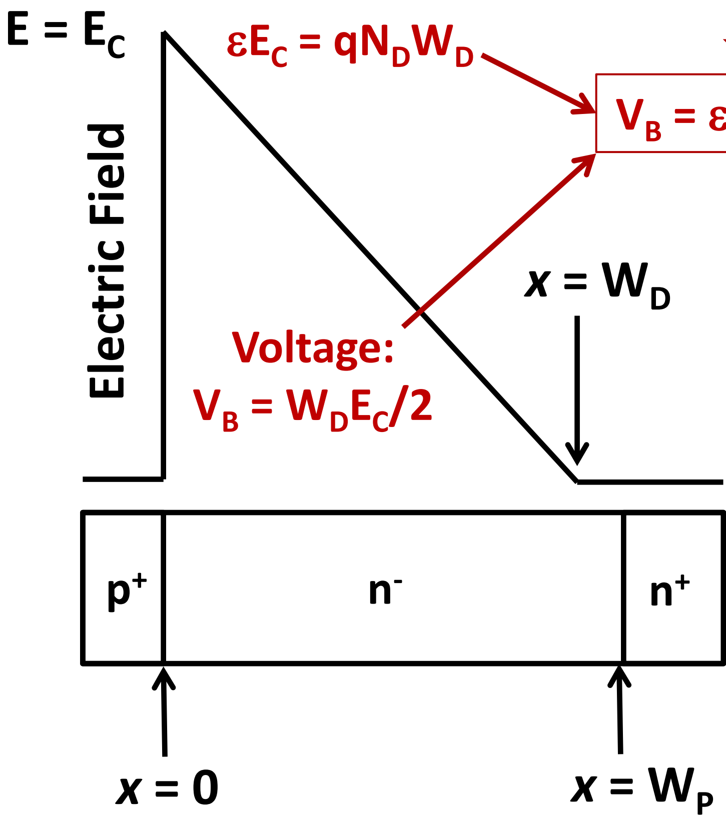
- **The applications of UWBGs are many, and new toolkits are required to exploit them**

M. Hollis, MIT-LL

Outline

- Motivation: Applications of UWBGs
- **UWBG Properties**
- Sandia AlGaN Devices:
  - Power Electronics
  - Radio Frequency
  - High-T Logic
  - Optoelectronics
- UWBG Community Activities

Definition of Critical Electric Field and Unipolar Figure of Merit



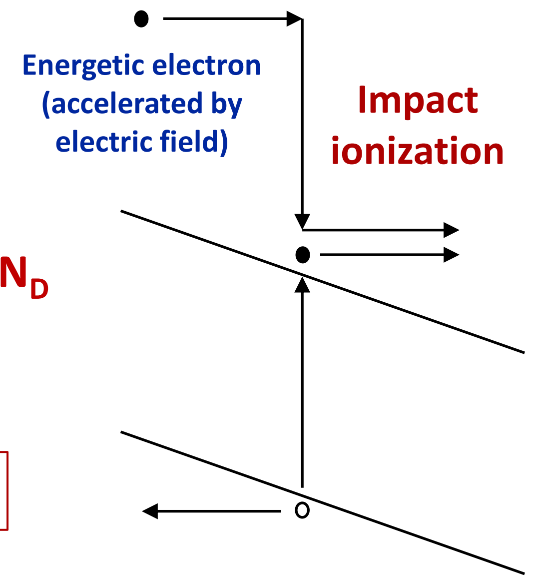
Gauss: $\varepsilon E_C = qN_DW_D$

Voltage: $V_B = W_DE_C/2$

$V_B = \varepsilon E_C^2/2qN_D$

Resistance: $R_{on,sp} = W_D/q\mu_nN_D$

$V_B^2/R_{on,sp} = \varepsilon\mu_nE_C^3/4$

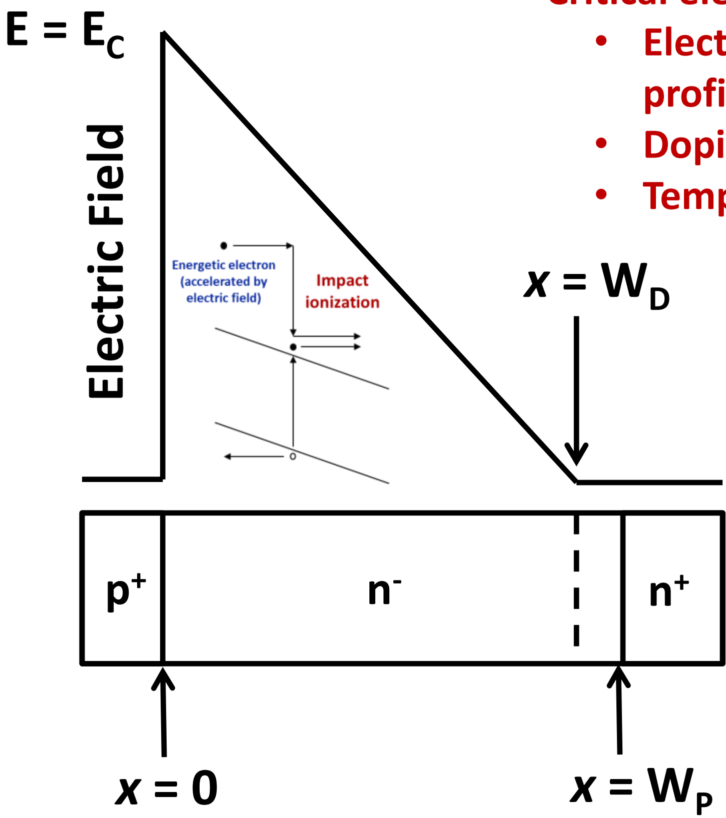


$$N(x) = \frac{exp[\int_0^x(\alpha_p - \alpha_n)dx']}{1 - \int_0^{W(E_C)} \alpha_n exp[\int_0^x(\alpha_p - \alpha_n)dx']dx}$$

Avalanche occurs when denominator approaches zero

The critical field is defined as the maximum electric field that leads to avalanche breakdown in a 1D analytical model

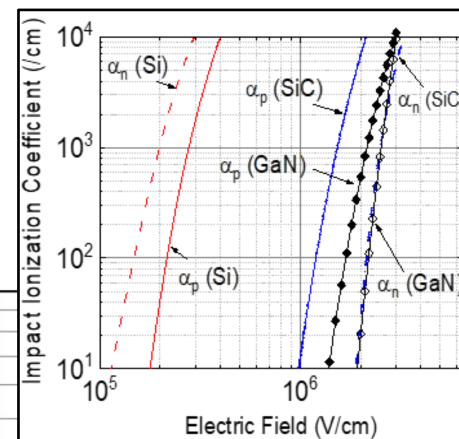
Critical Electric Field Is Not Constant



Critical electric field depends on:

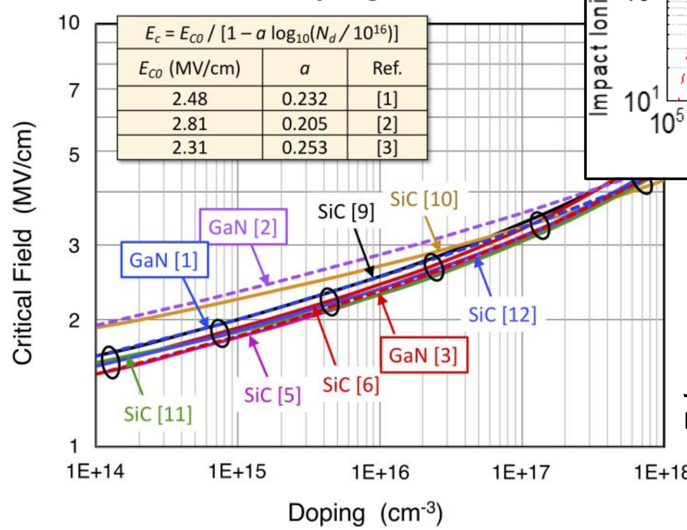
- **Electric field profile (E_C is formally defined for triangular field profile in non-punch-through drift region)**
- **Doping (affects field profile and ionization integral)**
- **Temperature (phonon scattering competes with impact ionization)**

Impact ionization coefficients



D. Ji et al., APL 115 073503 (2019)

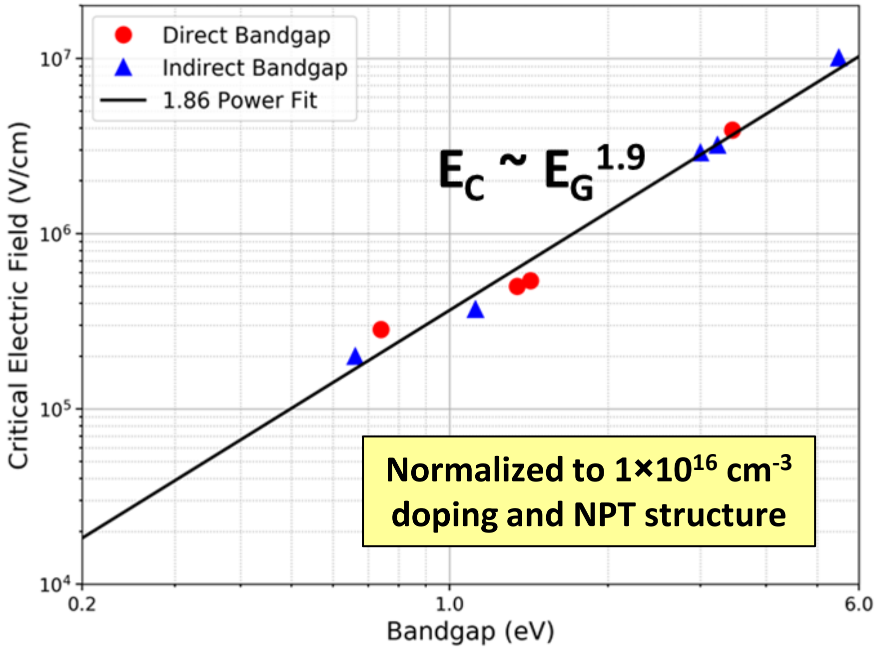
Dependence of critical field on doping

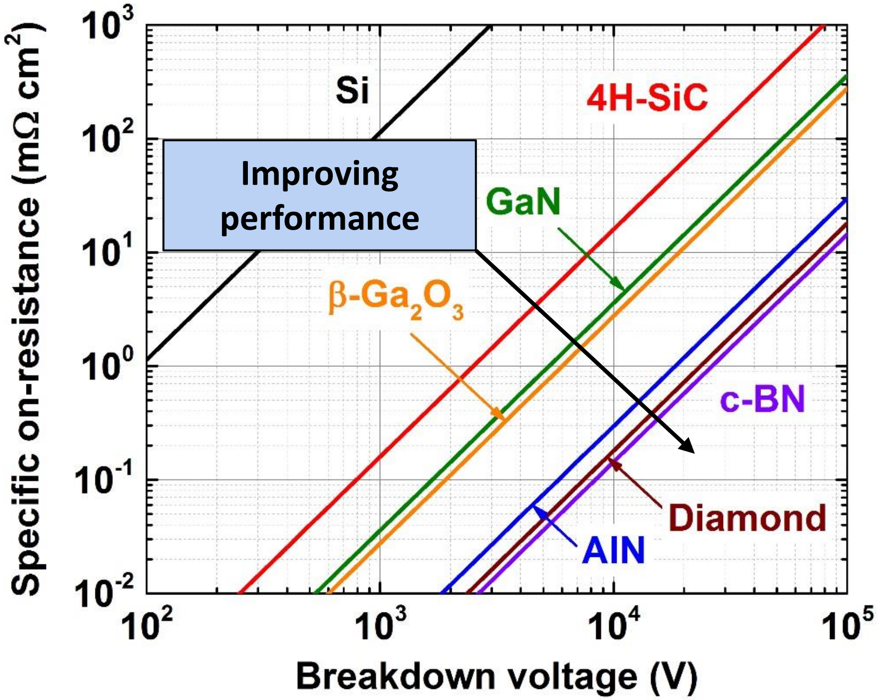


J. A. Cooper and D. T. Morisette, EDL 41(6), 892 (2020)

The critical electric field is defined as the peak electric field that leads to avalanche breakdown in a 1D model

Critical Electric Field Scales with Bandgap and Determines Figure of Merit



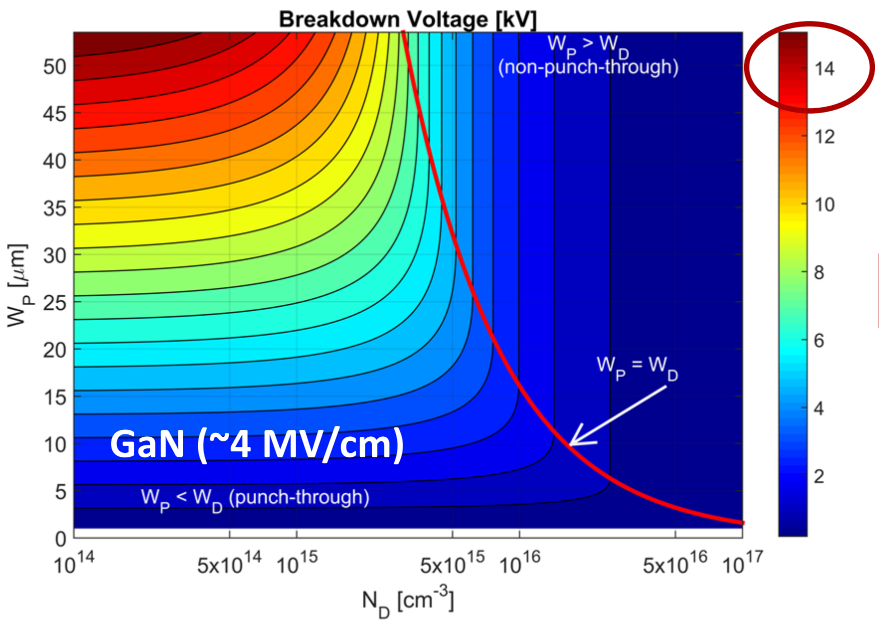


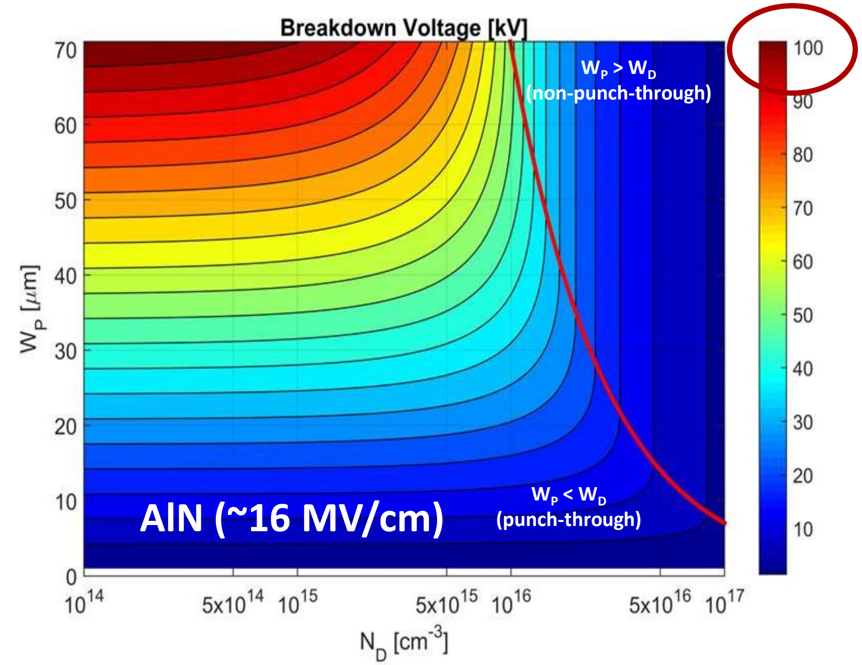
Vertical unipolar device:

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

R. Kaplar et al., ECS (2019); J. Y. Tsao et al., *Adv. Elec. Mat. Adv. Elec. Mat.* 4, 1600501 (2018)

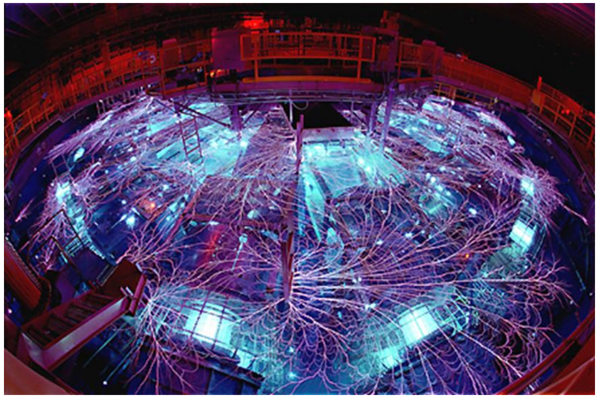
Very High Breakdown Voltage May Be Possible with UWBGs





Increasing E_C may significantly increase V_B

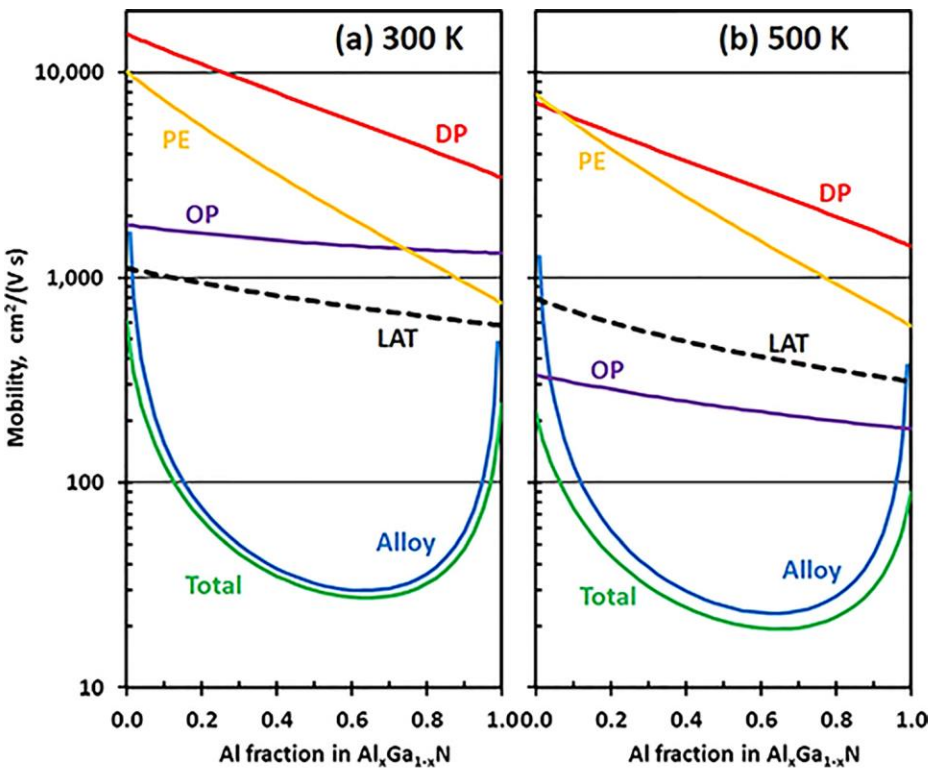
- **100 kV device may be possible using materials like AlN**
- **But low doping and thick drift layers are also required**



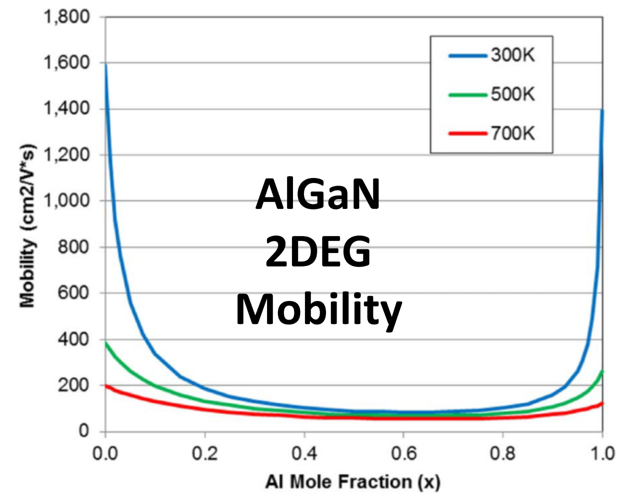
J. Dickerson, SNL

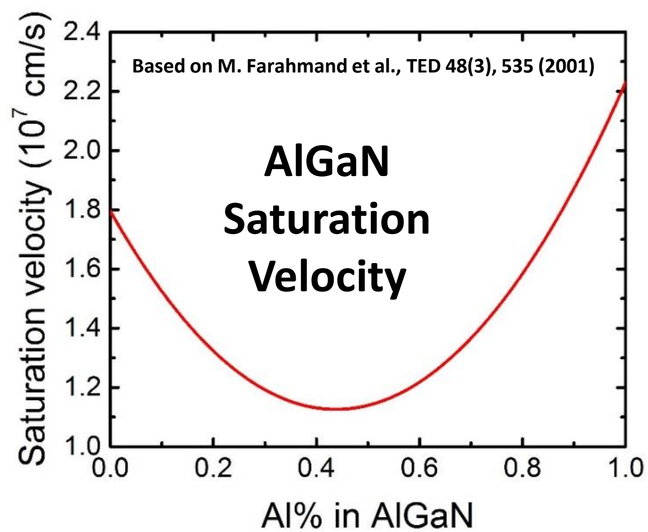
Transport in UWBGs

AlGaN Bulk Mobility



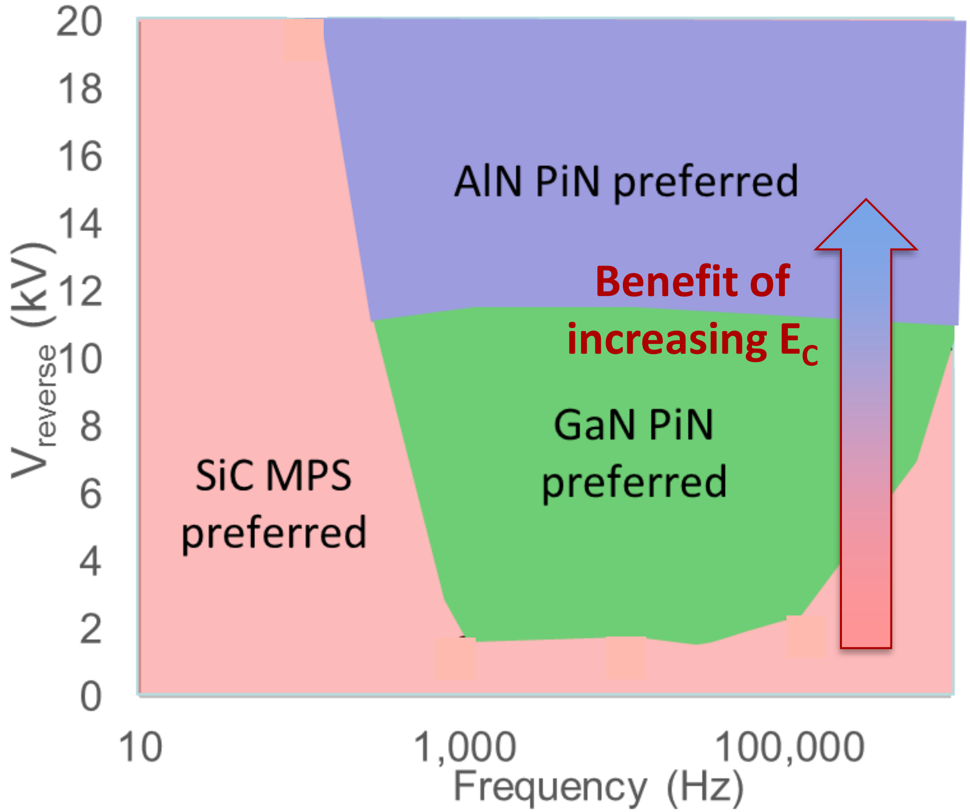
- **Alloy scattering dominates low-field transport in AlGaN**
- **Results in weak temperature dependence**



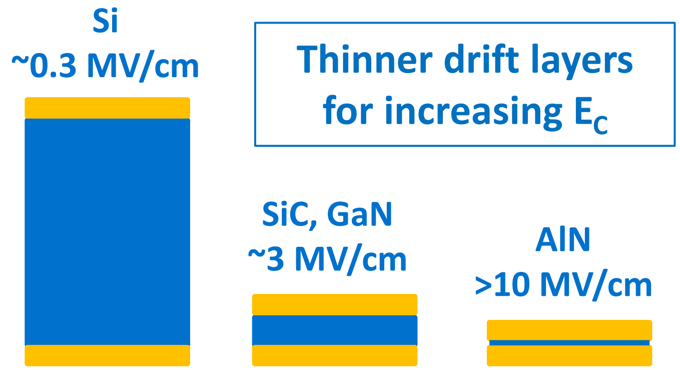


M. E. Coltrin and R. J. Kaplar, J. Appl. Phys. 121, 055706 (2017); M. E. Coltrin, A. G. Baca, and R. J. Kaplar, ECS J. Solid-State Sci. Tech. 6 (11), S3114 (2017)

Analysis of WBG/UWBG Power Switching Application Ranges



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



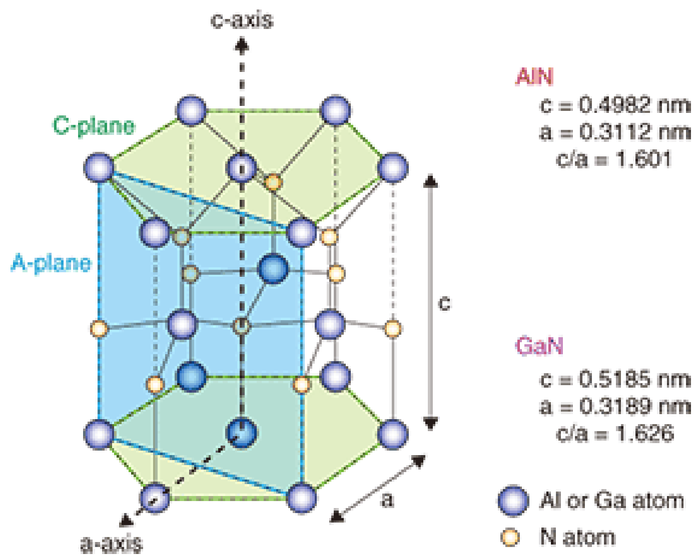
- **GaN and AlN preferred at high voltages over mid-frequency range**
  - **Benefit of higher E_C**
  - **Not as beneficial at low and high frequency (low conductivity modulation and increasing reverse recovery)**
- **Examined PiN diodes since peak field is buried below surface**
  - **Part of more advanced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

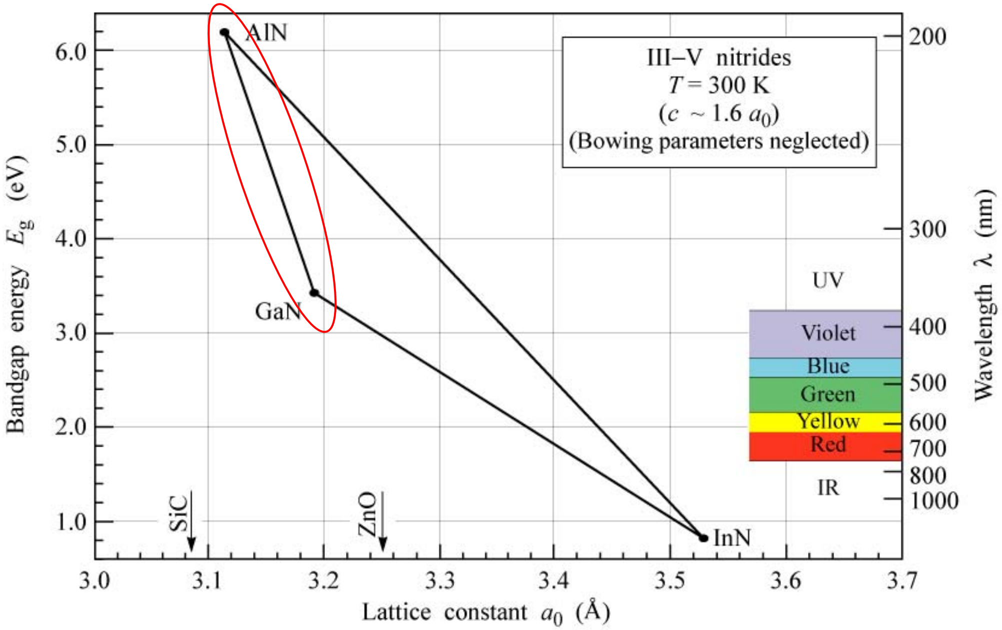
J. Flicker et al., WiPDA 2017
Analysis based on method in Morisette and Cooper, TED 49(9), 1657 (2002)

Outline

- ➢ Motivation: Applications of UWBGs
- ➢ UWBG Properties
- ➢ **Sandia AlGaN Devices:**
  - **Power Electronics**
  - Radio Frequency
  - High-T Logic
  - Optoelectronics
- ➢ UWBG Community Activities

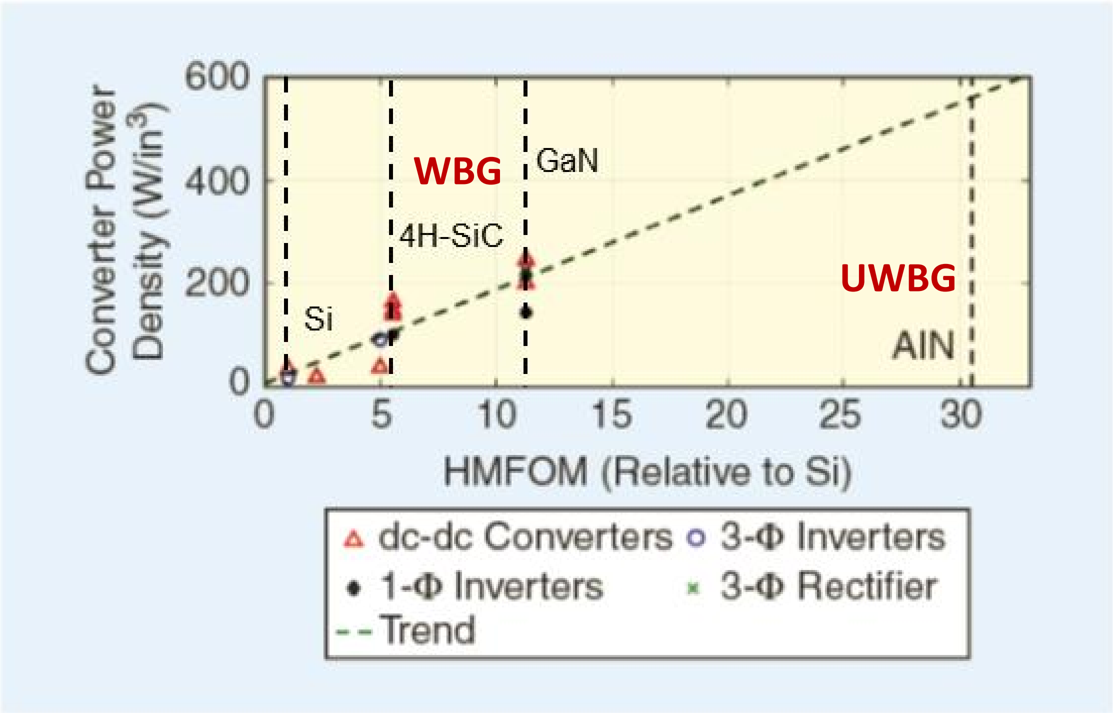
Material Properties of AlGaN

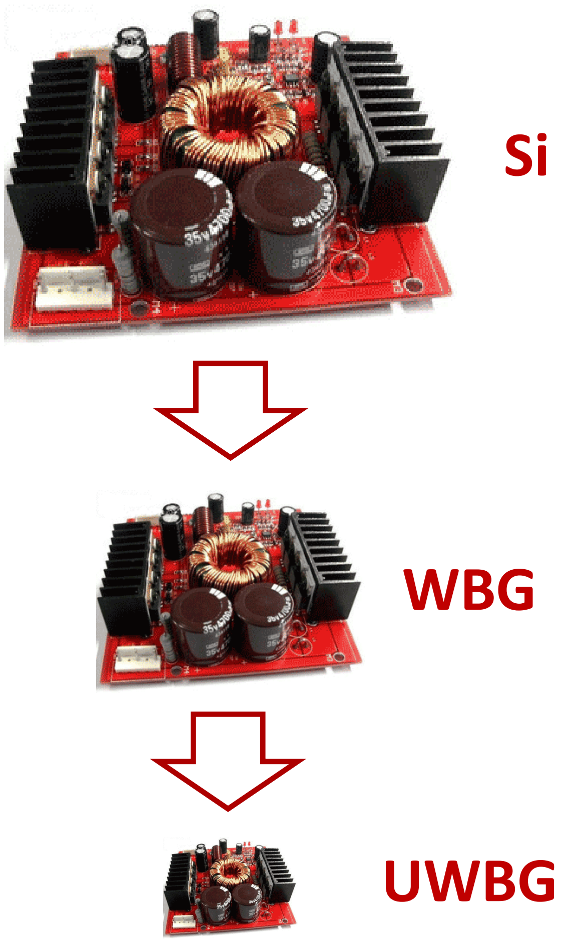




Material	E_g (eV)	E_{crit} ($\times 10^6$ V/cm)	v_{sat} ($\times 10^7$ cm/s)	Mobility (cm^2/ V s)	Thermal Conductivity (W/m·K)
AlN	6.0	15.4	1.3	426	319
$Al_xGa_{1-x}N$	5.0-6.0	13.5-15.4	Interpolation	~150-400	Interpolation
GaN	3.4	4.9	1.4	1000	253
β-Ga_2O_3	4.9	10.3	1.1	180	11-27
Diamond	5.5	13.0	1.9-2.3	4500-7300	2290
SiC	3.3	2.5	2.0	1000	370

Power Density Scaling with Semiconductor Material Properties





Relative Figures of Merit:

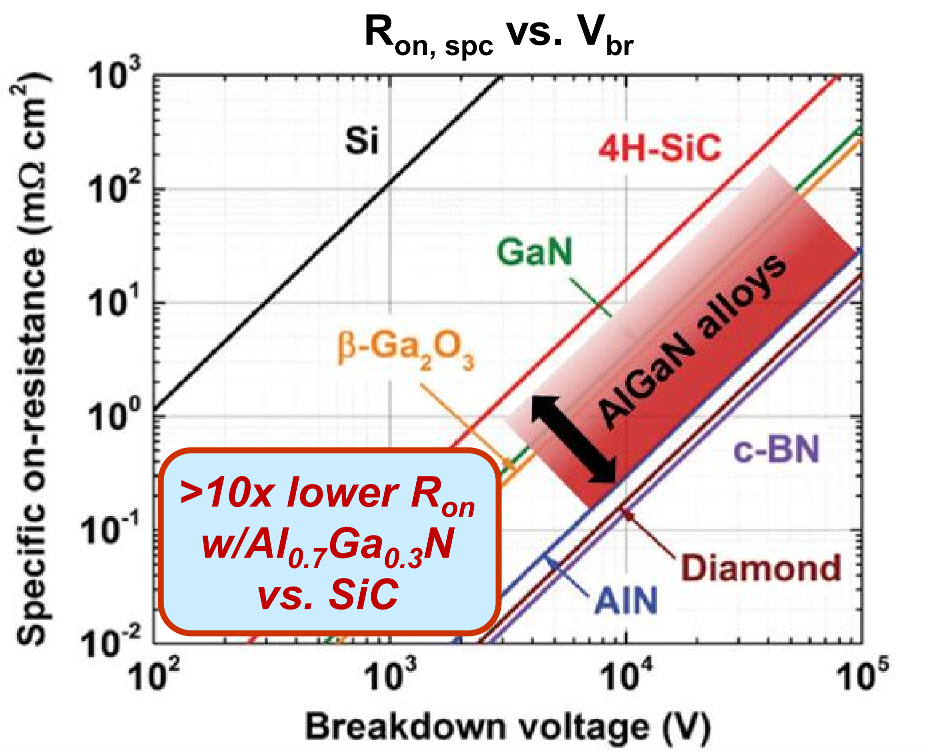
- **Vertical UFOM = $\varepsilon\mu_n E_C^3$**
- **Huang Material FOM = $E_C\mu_n^{1/2}$**
- **HM-FOM seems to be a good predictor of power density**

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

Why AlGaN Alloys for Power Electronics?

Unipolar Figure of Merit (vertical devices)

$$UFOM = \frac{V_{br}^{2}}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_C^{3} \propto E_g^{7.5}$$



Tsao, *Adv. Electron. Mater.* **2018**, *4*, 1600501

A. Allerman, SNL

➡ ***Order of magnitude increase in system performance using UWBG power devices***

- Lower conduction loss
- Higher switching frequency
- Higher power density
- Higher temperature operation
- Fewer parts ➡ higher reliability
- Increased radiation tolerance

➡ ***AlGaN is strong candidate UWBG semi-conductor for next gen power devices***

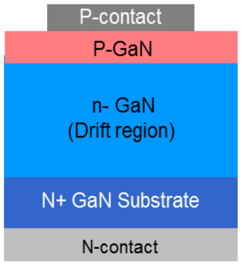
- Ga_2O_3 – No p-type, poor TC, alloys?
- Diamond – Separate reactors for n & p, poor n-type, no alloys
- cBN – Phase impurity, doping?, alloys?, conducting substrate?

AlGaN alloys:

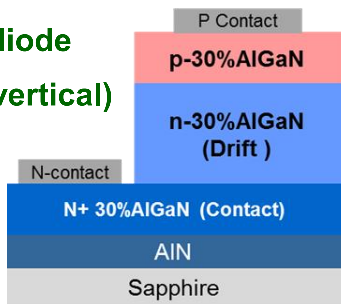
- Polarization fields, n & p doping
- ***Heterostructures!*** (2000 Nobel Prize)

Breakdown Voltages Reported for III-Nitride PN Diodes

GaN diode (vertical)



AlGaN diode (Quasi-vertical)



III-N PN diodes with > 3 kV breakdown voltage

Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7/5.0	2/9/16e15	33	GaN	Hosei Univ.	EDL 36p1180_2015/Jpn J Appl Phys 57 (2018)
4.0	2-5e15	40	GaN	Avogy	EDL 36p1073_2015
3.9	**3e15**	**30**	**GaN**	**Sandia**	**EL 52p1170_2016**
3.7	5e15	>30	GaN	Avogy	EDL 35p247_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

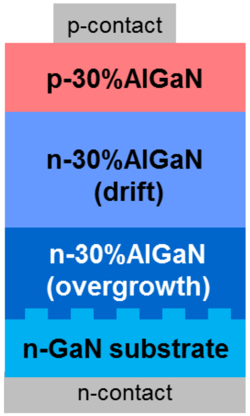
Advantages of wide-bandgap III-Nitride

	GaN	$Al_{0.3}Ga_{0.7}N$	
N_o (cm^{-3})	low e15	low e16	] ← Larger E_c (larger E_g)
Drift (μm)	20-30	~10	
TDD (cm^{-2})	≤ 1e6	low 1e9	← Reverse leakage is still low

A. Allerman, SNL

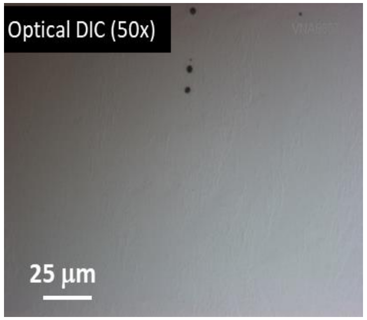
Vertical $Al_{0.3}Ga_{0.7}N$ PN Diode on Conducting GaN Substrates

Vertical PN diode in 30%AlGaN

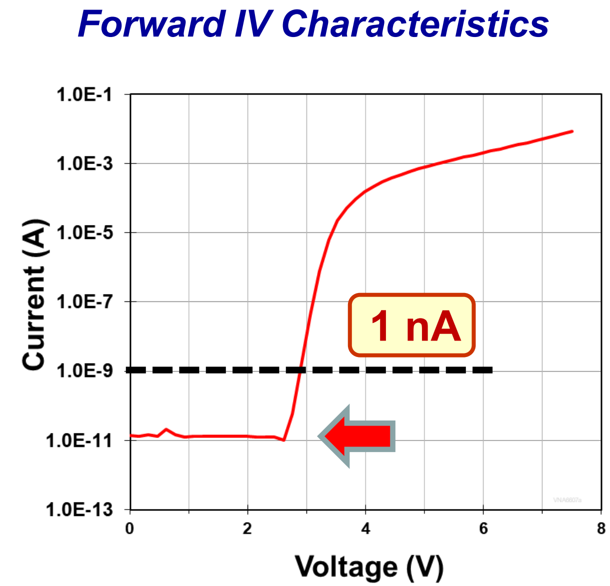


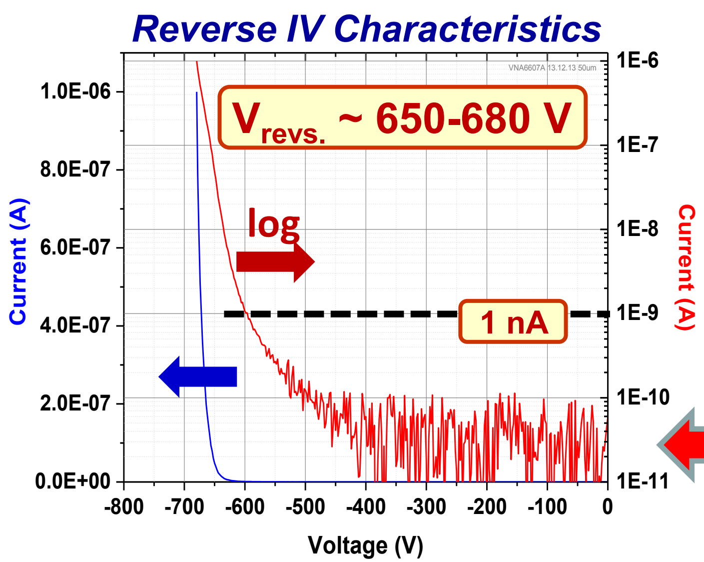
- **Drift: t = 5.3 µm**
  N_o = 2-4 x 10^{16} cm^{-3}
- **Overgrowth:**
  t = 6.2 µm

Total : 11.8 µm



$R_{sp\text{-}on}$ = 1 mΩ-cm²





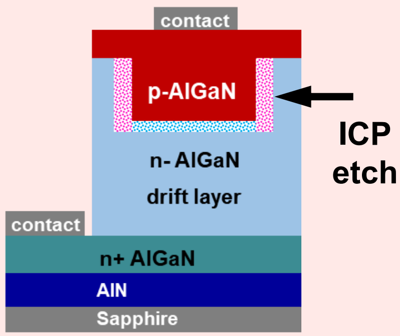
- **Reverse voltage 650-680 V (@1uA)**
- **Low reverse current leakage**
- **Simple JTE for field control**

$I_{revs.}$ < 100 pA to 500V

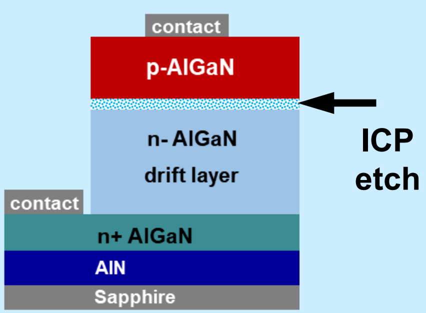
A. Allerman, SNL

Selective-Area Regrowth of p-30% AlGaN

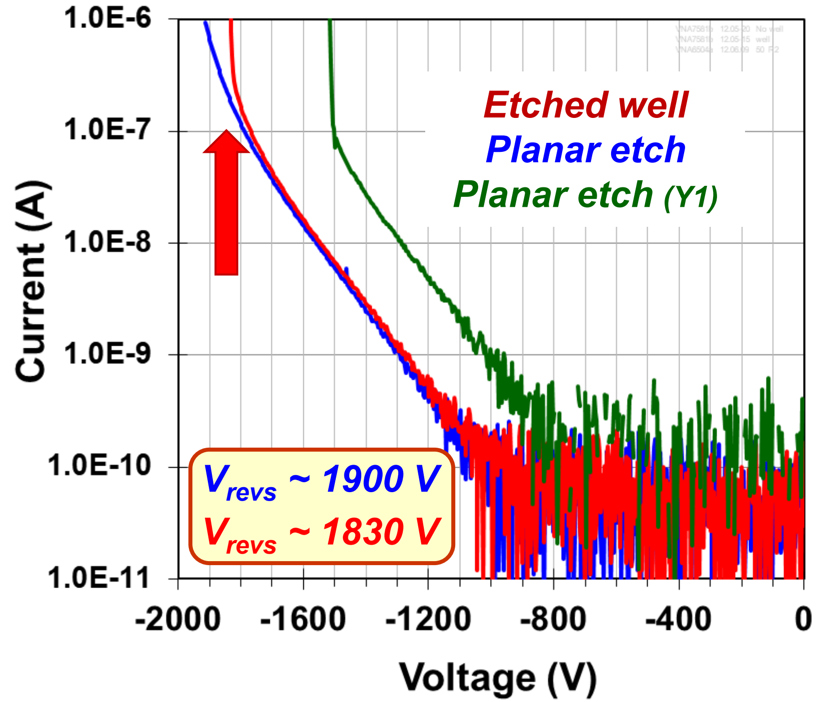
P- anode regrowth in *etched well* in drift layer



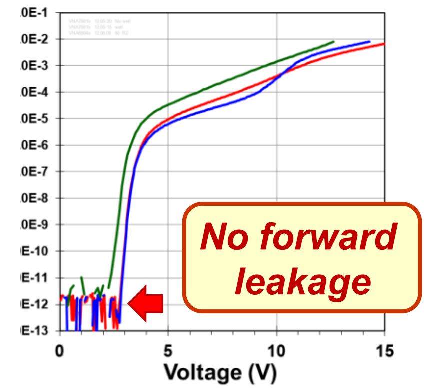
P- anode regrowth on planar etch drift layer



Reverse IV



Forward IV



Reverse leakage < 10^{-10} A out to 1kV (noise floor)

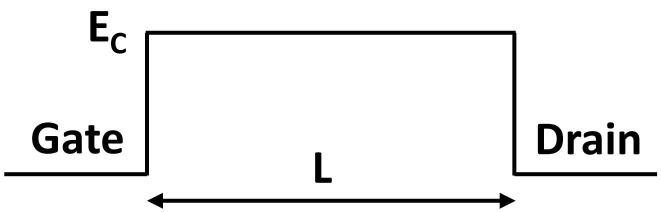
I_{revs}~ 2e-6 A/cm^{-2}

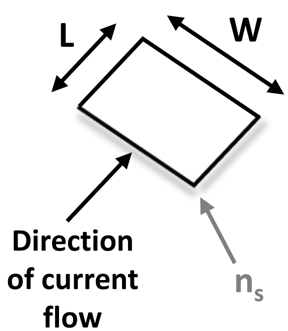
- ***NO difference between regrowth in etched well, planar etch and continuous growth!***
- ***First III-N SArG PN junction equal to continuously grown PN junction***
- ***Achieved foundational element for practical power devices: Junction Barrier Schottky and vertical-JFET***

A. Allerman, SNL

Lateral Power Device Figure of Merit

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



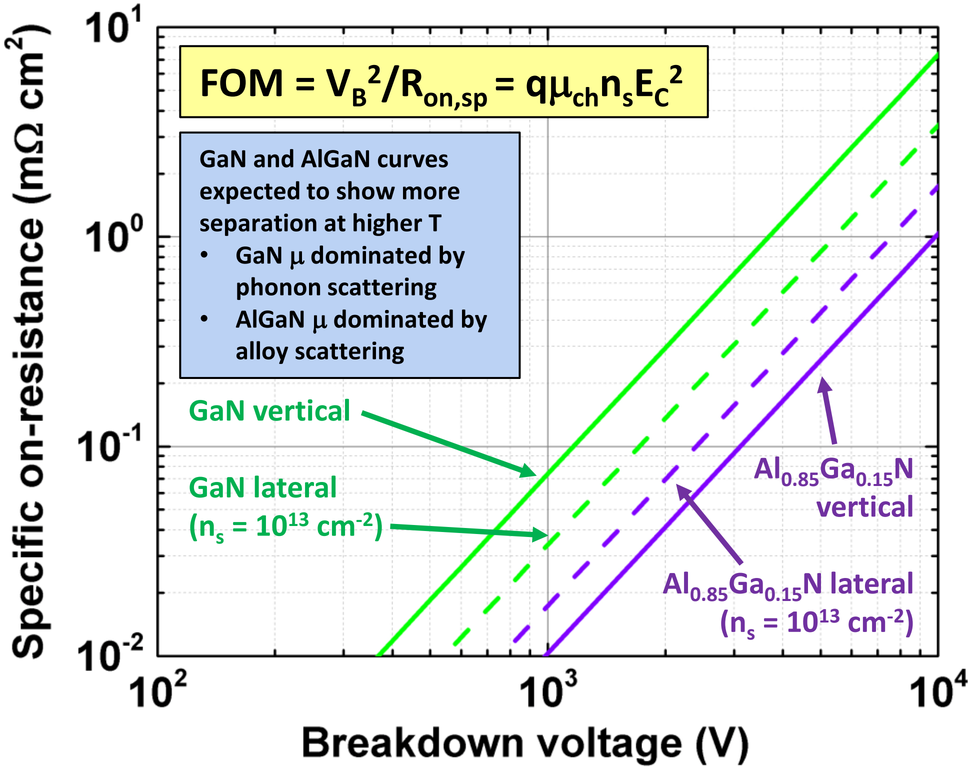


$$V_B = E_C L$$

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

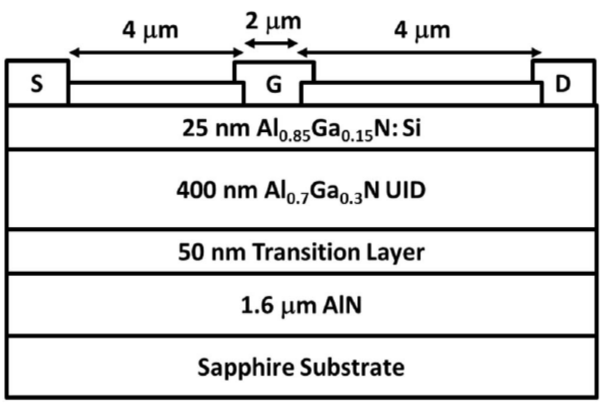
$$R_{on,sp} = R_{on}WL = \frac{L^2}{q\mu_{ch}n_s}$$

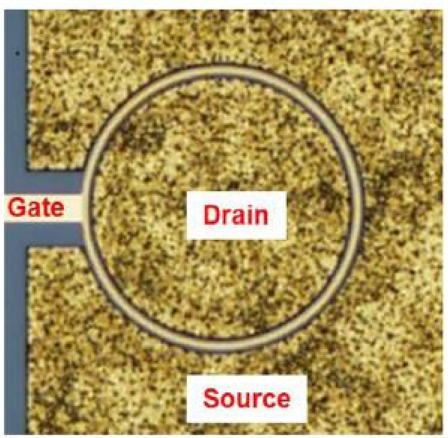
$$FOM = \frac{V_B^2}{R_{on,sp}} = q\mu_{ch}n_s E_C^2$$



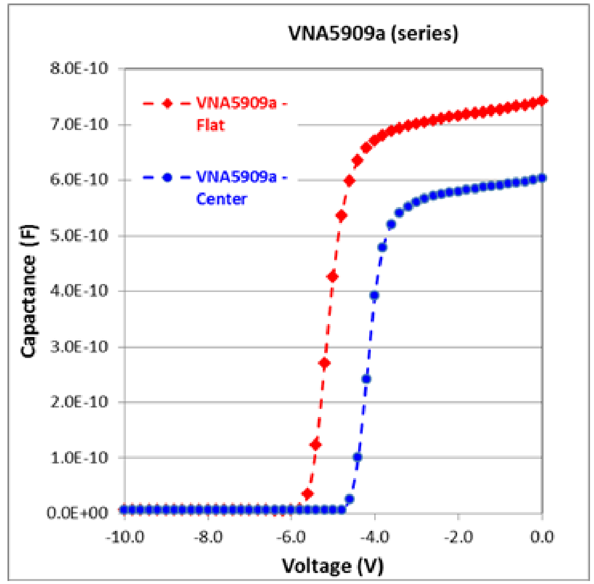
- **Proportional to E_C^2 rather than E_C^3, but high n_s can result in high FOM**

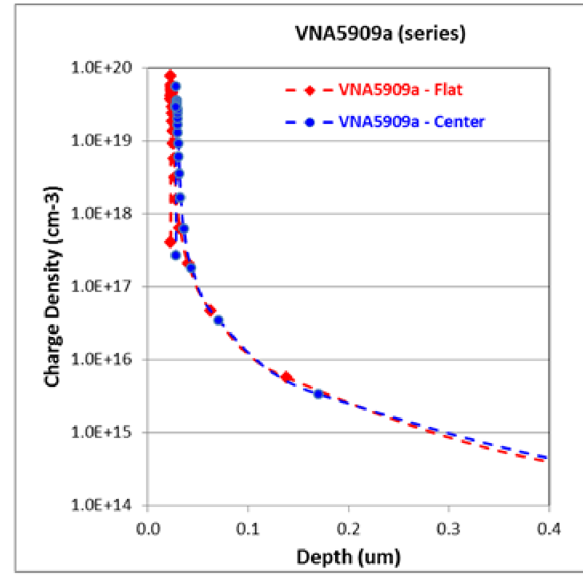
Sandia $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ UWBG HEMT Structure





CV Characterization



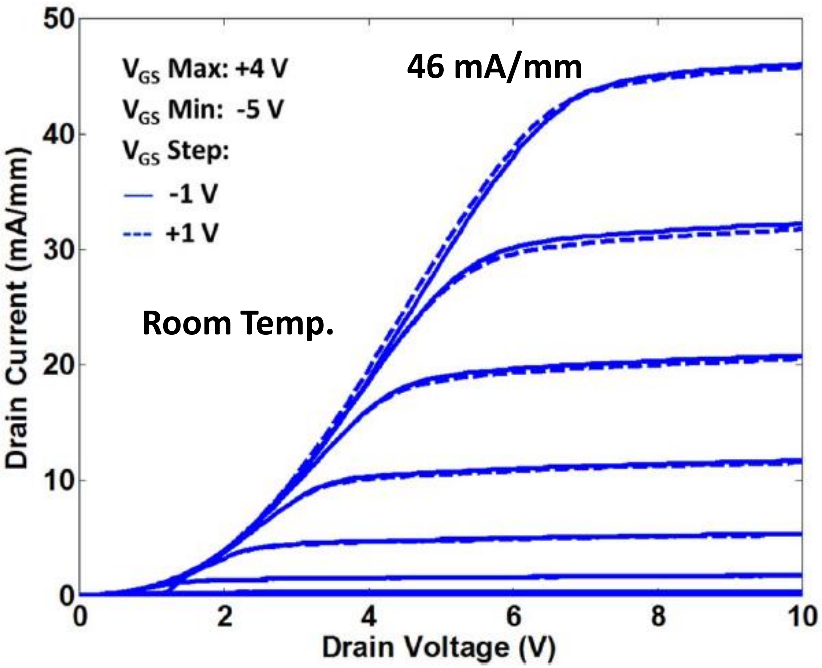


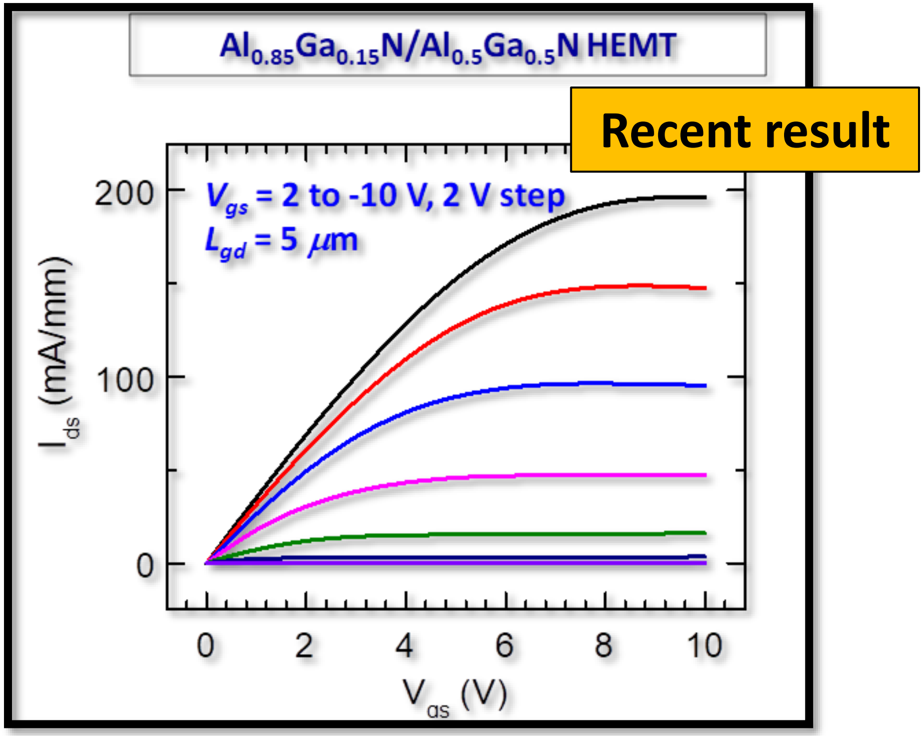
- MOCVD growth on sapphire substrate
- Planar source and drain contacts

- 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

A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017)

Electrical Characteristics of Al-Rich AlGaN HEMTs

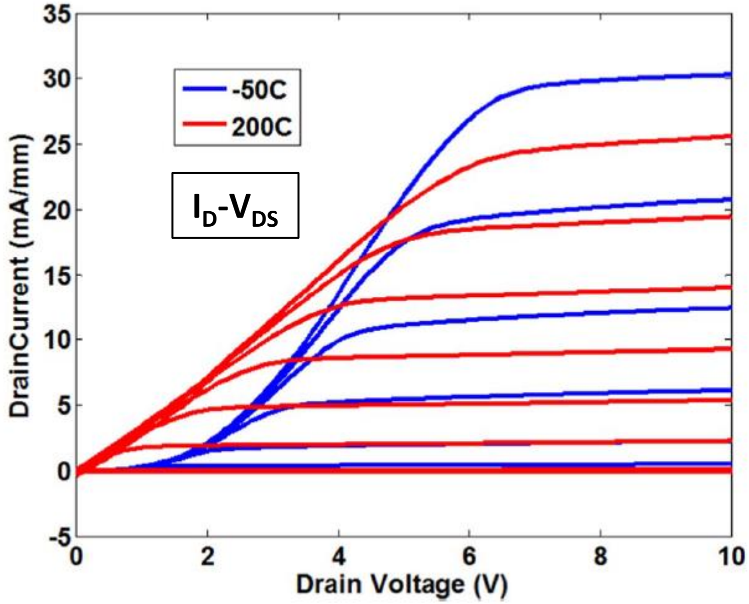


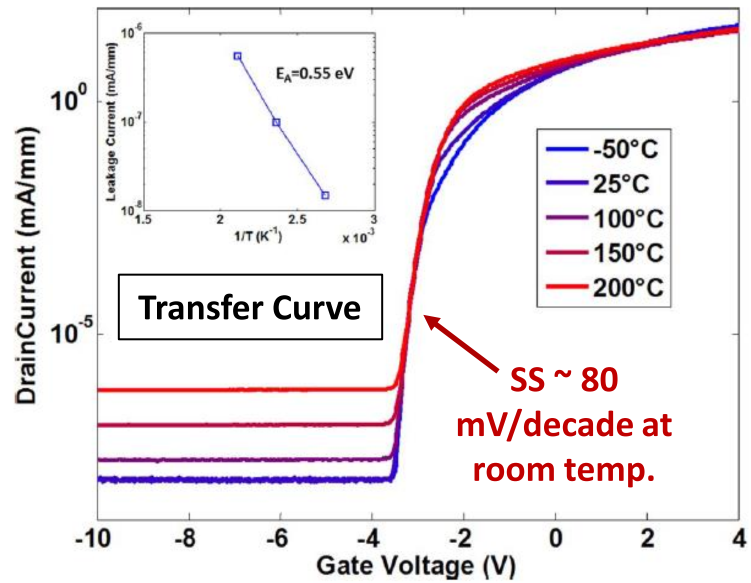


- Current density of 46 mA/mm (reasonable, but < 2x expected based on 2DEG density and mobility)
- Likely due to quasi-rectifying behavior in source and drain contacts

A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017)

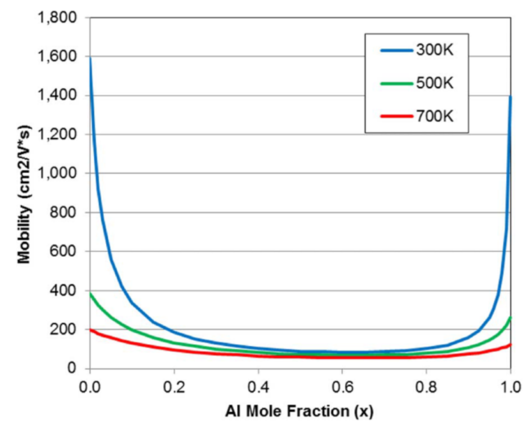
$Al_{0.85}Ga_{0.70}N/Al_{0.70}Ga_{0.30}N$ HEMT Operates Over Wide Temperature Range





I_{on}/I_{off} ~ 10^{10} at room temp.

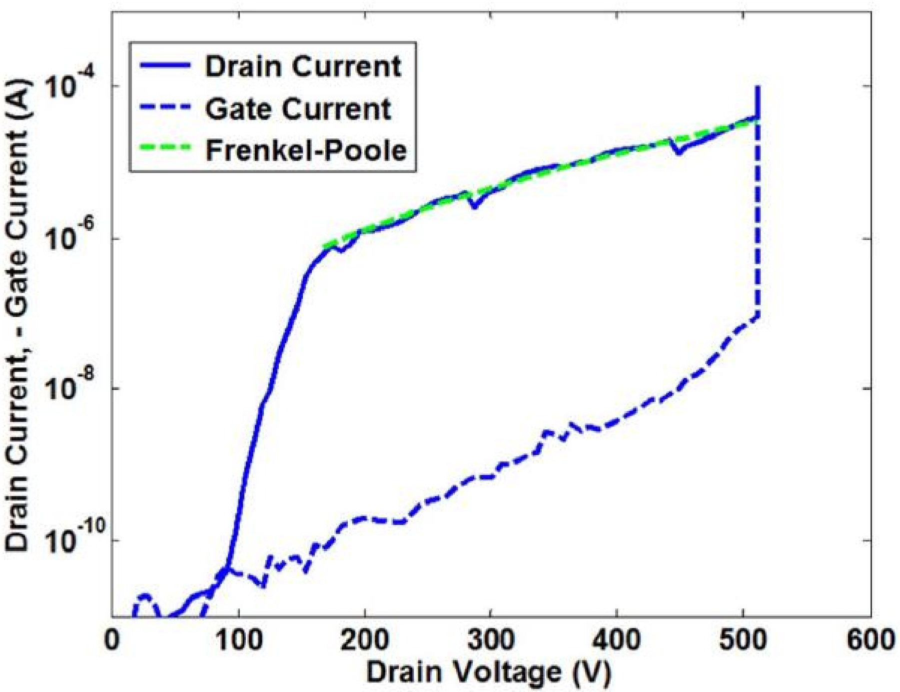
- Relatively weak dependence of performance on temperature
- Likely due to insensitivity of channel mobility to temperature
- Ohmic contacts improve at high temperature

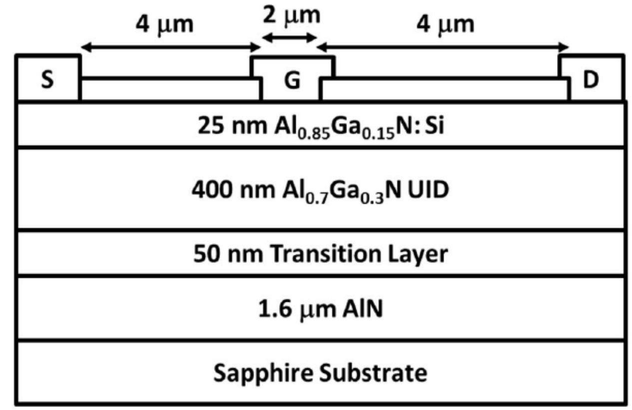


Channel mobility vs. temperature for 2DEG in AlGaN/AlGaN heterostructure

A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017); M. E. Coltrin, A. G. Baca, and R. J. Kaplar, ECS J. Solid-State Sci. Tech. 6 (11), S3114 (2017)

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



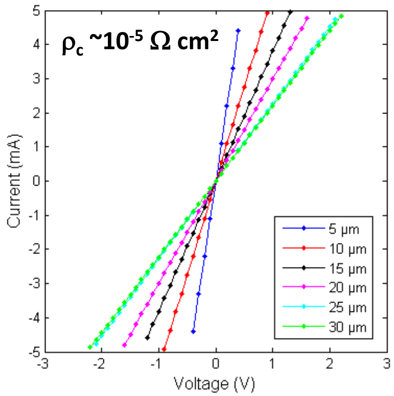


- **Field plate with SiN dielectric**
- **Misalignment with a circular gate leads to L_{GD} (actual) < L_{GD} (drawn)**
- **V_{br} = 511 V**
  - **L_{GD} = 1.6-5.4 μm**
- **Maximum breakdown field = 320 V/μm**
  - **= 3.2 MV/cm**
  - **Exceeds GaN HEMT typical breakdown field ≈ 100 V/μm**
- **Drain current can be fit with Poole-Frenkel model**

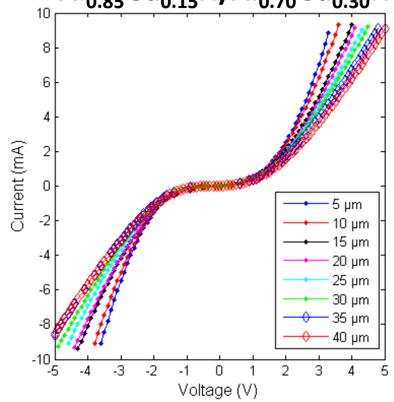
A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017)

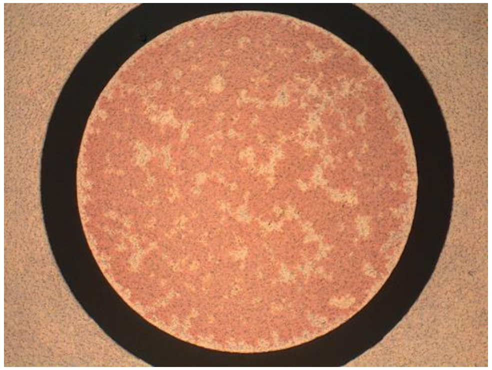
Ohmic Contact Development for Al-Rich AlGTaN HEMTs

$Al_{0.45}Ga_{0.55}N/Al_{0.30}Ga_{0.70}N$



$Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$



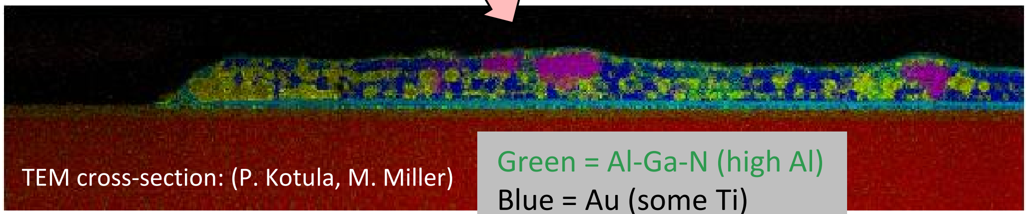


Au 50 nm
Ni 15 nm
Al 100 nm
Ti 25 nm
AlGaN/Substrate

900°C anneal

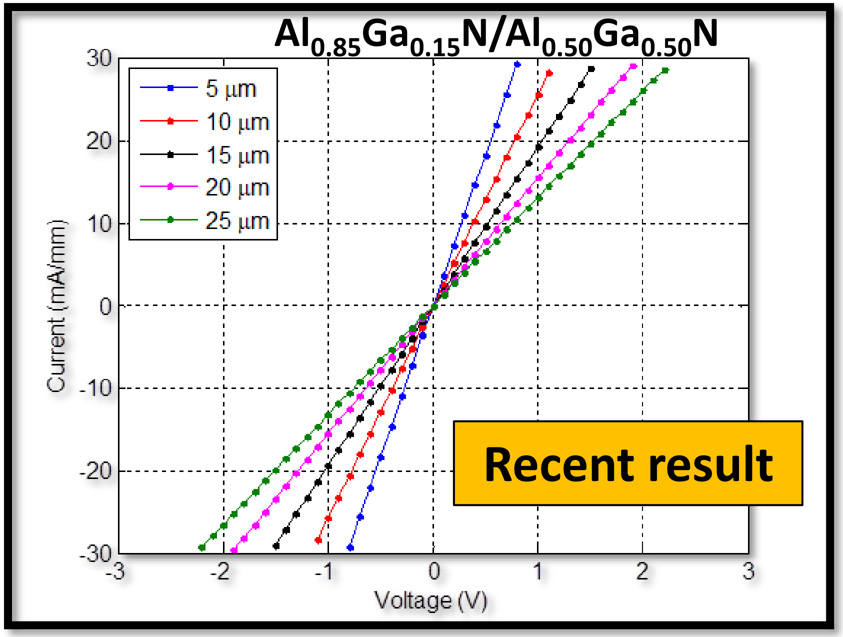
50 nm $Al_{0.45}Ga_{0.55}N$
4.15 mm $Al_{0.3}Ga_{0.7}N$
1.6 mm AlN
Sapphire Substrate

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



TEM cross-section: (P. Kotula, M. Miller)

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)

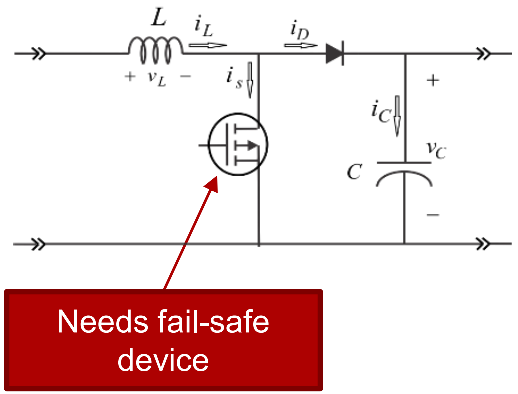


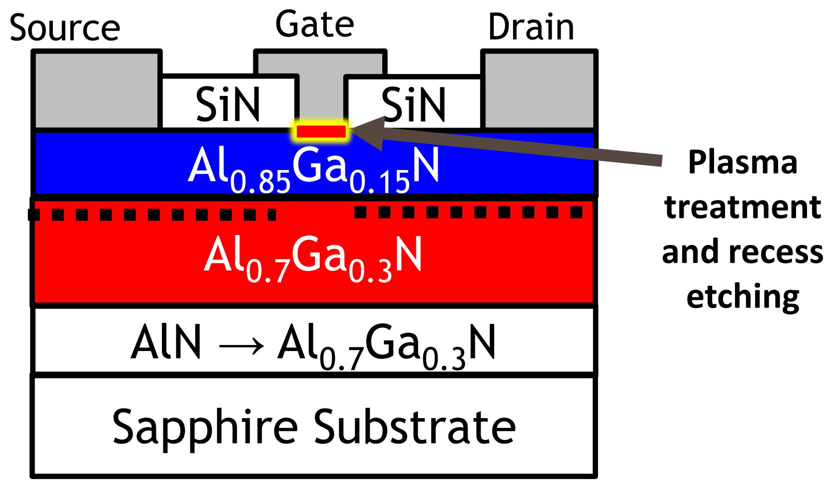
Recent result

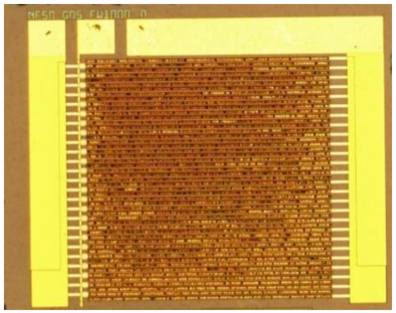
B. Klein, SNL

Enhancement-Mode AlGaN Power Transistor

Power Converter

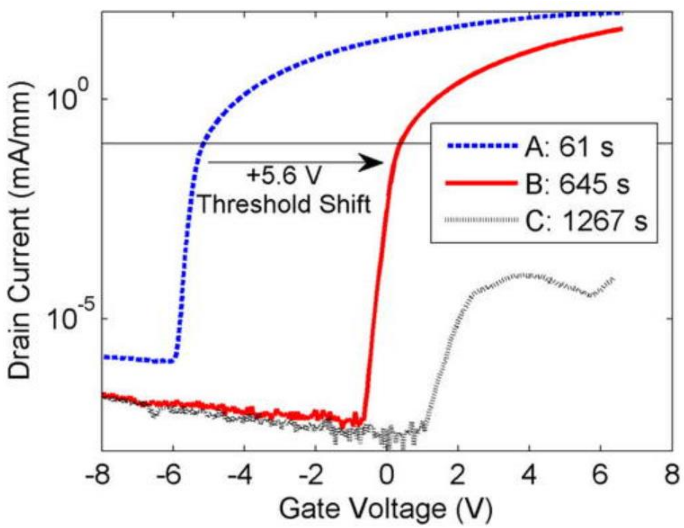






50 mm enhancement mode AlGaN transistor

- **Developed enhancement-mode AlGaN device for fail-safe power conversion applications**
- **+1.5 V gate threshold voltage achieved**
- **Evidence that plasma treatment and recess etching does not degrade HEMT stability**



A. Armstrong, B. Klein, A. Allerman, SNL

NYCREATES

Outline

- Motivation: Applications of UWBGs
- UWBG Properties
- **Sandia AlGaN Devices:**
  - Power Electronics
  - **Radio Frequency**
  - High-T Logic
  - Optoelectronics
- UWBG Community Activities

Higher Power Density RF Amplifiers are Desired

mm-Wave Power Density

GaN (WBG): ~4 W/mm

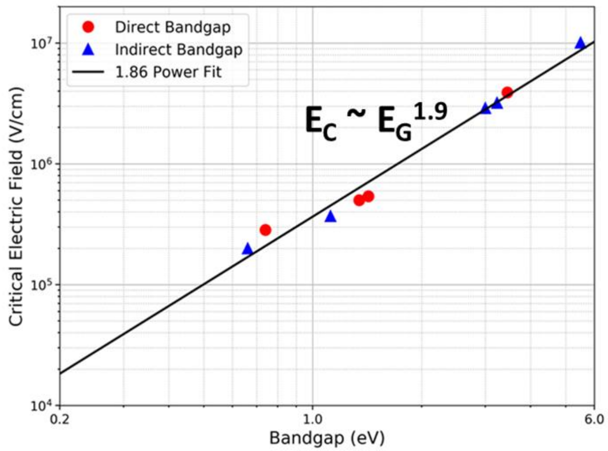
AlGaN (UWBG): >30 W/mm?

Generations of Semiconductors

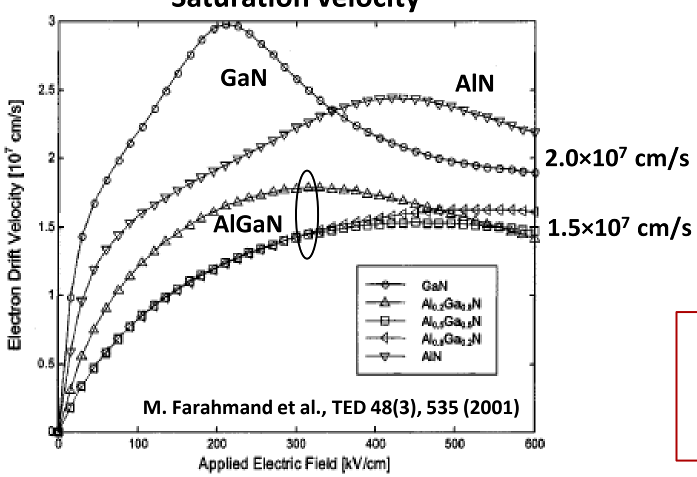
- Gen 1: Ge and Si
- Gen 2: Conventional III-Vs – Arsenides, Phosphides, Antimonides
- Gen 3: Wide-bandgaps – SiC, GaN, InGaN
- Gen 4: Ultra-Wide-Bandgaps – $Al_xGa_{1-x}N$, $(Al_xGa_{1-x})_2O_3$, diamond, c-BN, others

Advantages of AlGaN for Radio-Frequency Devices

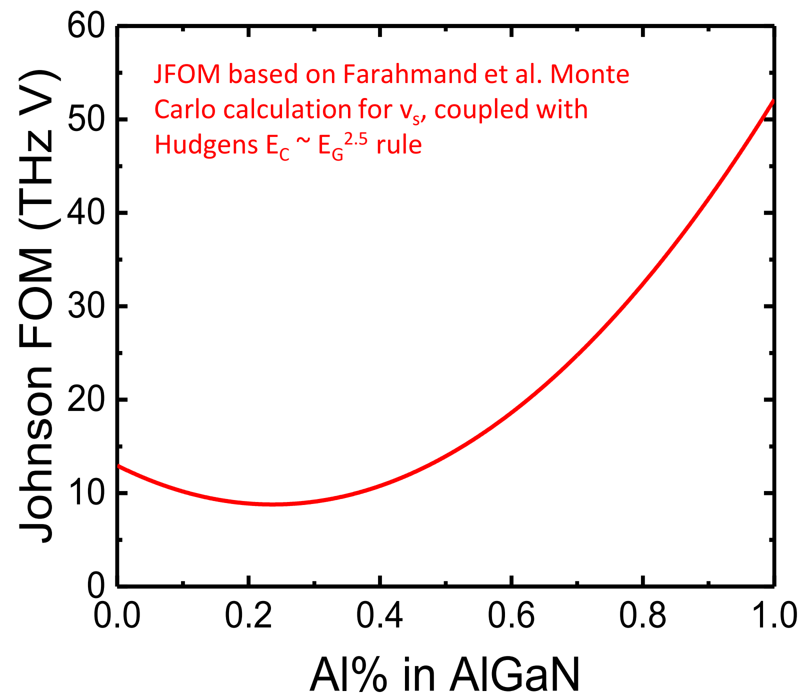
Critical electric field



Saturation velocity



Johnson FOM: $V_B f_T = E_C v_{sat}/2\pi$

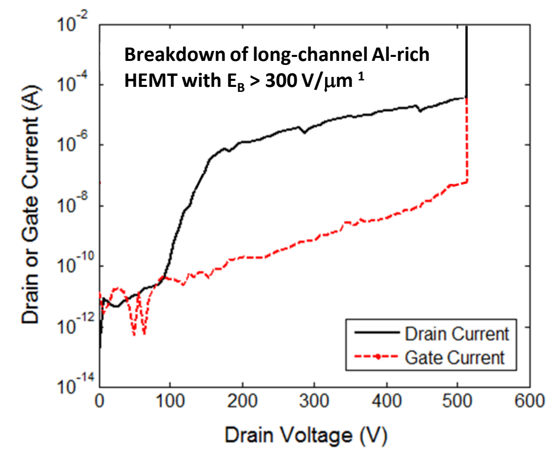


Al-rich AlGaN yields better JFOM than GaN due to higher E_C and comparable v_{sat}

Predicted 8× Power Density Increase for Al-Rich HEMTs Compared to GaN-Channel HEMTs

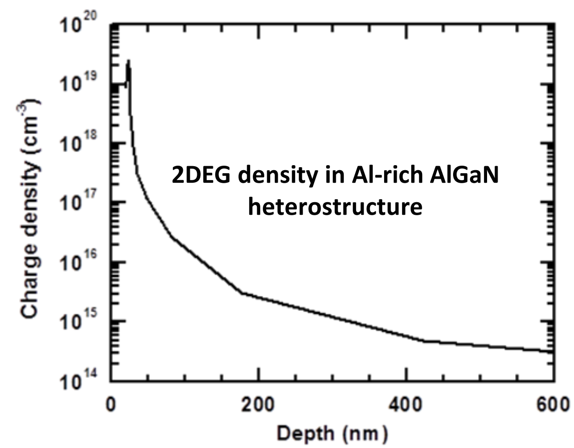
- **Maximum power density $P_{max} = J_{max}V_{max}/8$ with $J_{max} = qv_{sat}n_s$**

- **Three factors plausibly lead to 8× power density for Al-rich AlGaN HEMTs compared to GaN-channel HEMTs (GaN: ~4 W/mm → AlGaN: >30 W/mm)**
  - **4× greater breakdown voltage for same dimensions (V_{max})**
  - **2× sheet carrier density (J_{max})**
  - **Parity in electron saturation velocity (J_{max})**



- **Breakdown electric field is typically ~4× lower than theoretical**
  - **~400 V/μm expected for Al-rich $Al_xGa_{1-x}N$ with x close to 1**
  - **>300 V/μm observed experimentally for $x = 0.7$**
  - **Compared to ~100 V/μm for GaN**

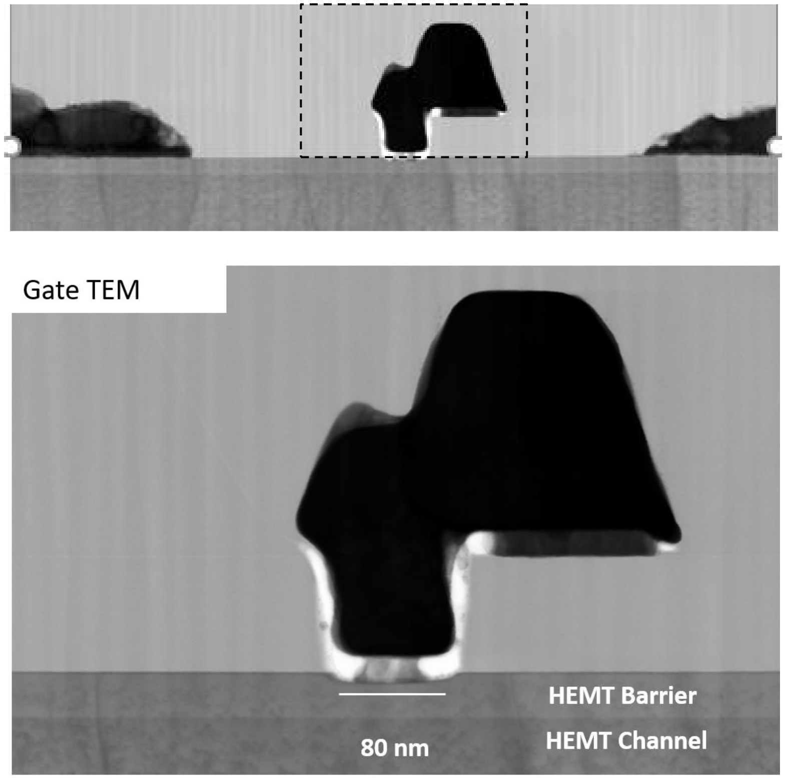
- **2DEG sheet density $n_s > 2\times10^{13}$ cm^{-2}**
  - **Potentially higher bandgap offset**
  - **Larger polarization charge for higher x**
  - **Potential to grow thick, compressively strained barrier layer on AlN substrates**



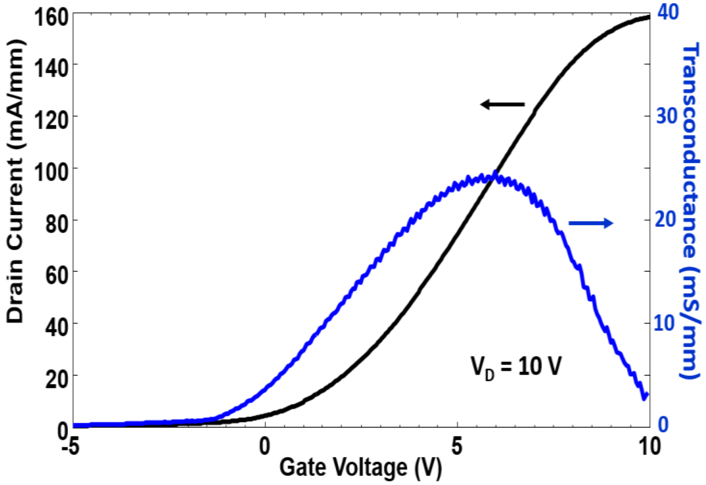
- **v_s ~ 4×10^6 cm/s measured in $Al_{0.7}Ga_{0.3}N$ (~35% that of GaN) [2]**

1 – A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017); 2 – B. A. Klein et al., J. Elec. Mat. (2018)

Sandia $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ HEMT with 80 nm Gate

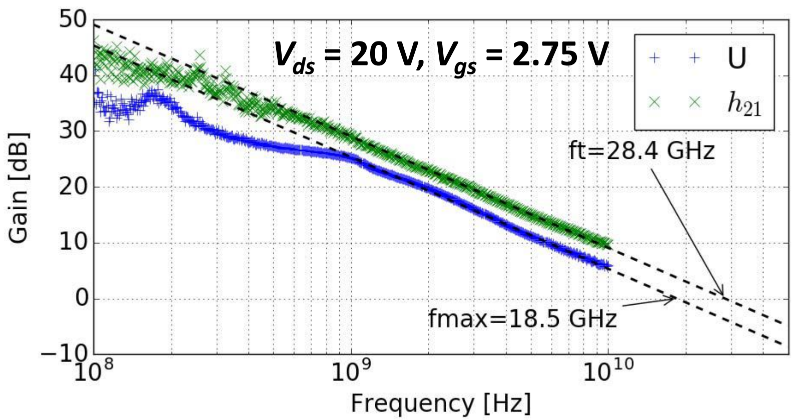


- 30 nm thick $Al_{0.85}Ga_{0.15}N$ barrier and 400 nm thick $Al_{0.70}Ga_{0.30}N$ channel and buffer
  - MOCVD growth on sapphire substrate
  - AlN nucleation and graded transition layers
- Barrier doped with 3.5×18 cm^{-3} Si
- 2DEG resistivity ~2200 Ω/sq → $\mu_{ch} \approx 390\ cm^2/Vs$, $n_s \approx 7.2\times10^{12}\ cm^{-2}$
- Nb/Ti/Al/Mo/Au source and drain contacts
- Ni/Au gate with field plate on SiN_x
- Maximum DC current density ≈ 160 mA/mm at V_{ds} = 10 V, V_{gs} = 10 V

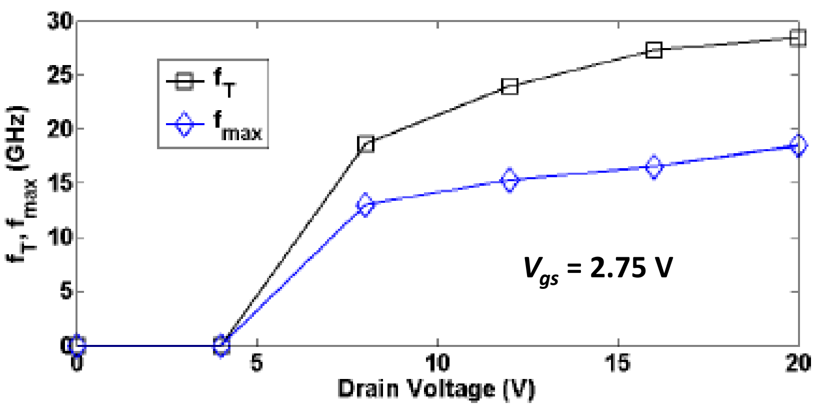


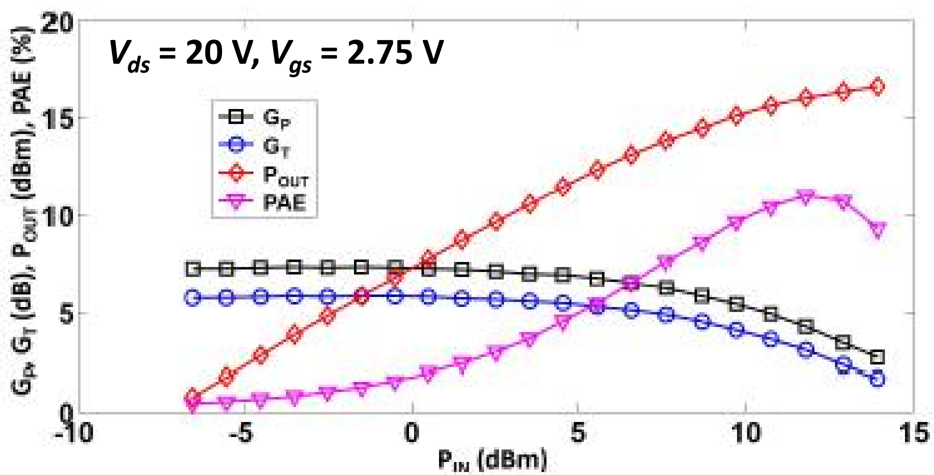
A. G. Baca et al., EDL 40(1), 17 (2019)

RF Characteristics of $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ HEMT



- f_T and f_{max} extracted from s-parameter measurements at V_{ds} = 20 V, V_{gs} = 2.75 V
  - f_T ≈ 28.4 GHz, f_{max} ≈ 18.5 GHz
  - Reversal in order may be due to large gate resistance and/or channel conductance
- Power sweep at 3 GHz, V_{ds} = 20 V, V_{gs} = 2.75 V
  - Output power ≈ 0.38 W/mm (15.8 dBm) at maximum PAE of 11%
  - Maximum power gain G_P ≈ 7.3 dB
- Well below theoretical and simulated values
  - Comparable to other emerging UWBG RF technologies
  - Better Ohmic contacts may help



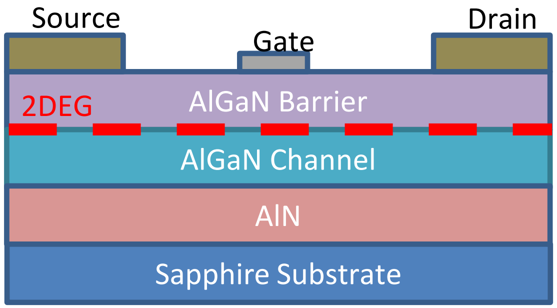


A. G. Baca et al., EDL 40(1), 17 (2019)

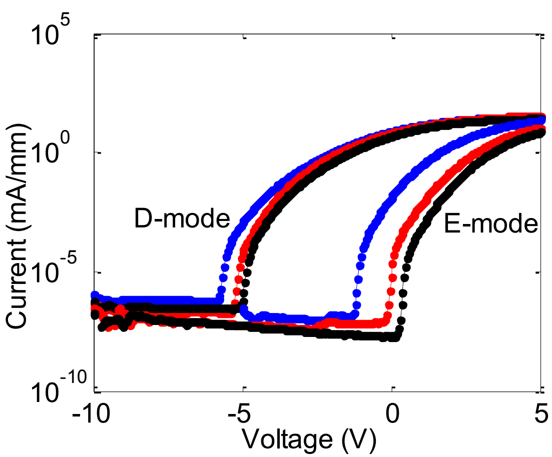
Outline

- Motivation: Applications of UWBGs
- UWBG Properties
- **Sandia AlGaN Devices:**
  - Power Electronics
  - Radio Frequency
  - **High-T Logic**
  - Optoelectronics
- UWBG Community Activities

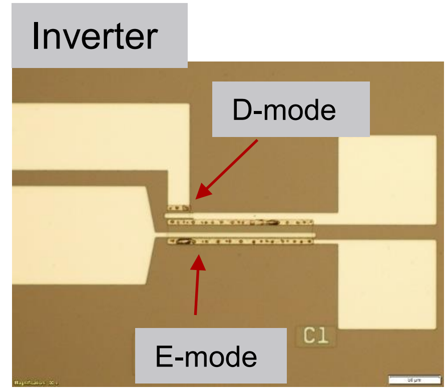
Enhancement and Depletion Mode HEMTs for Digital Logic



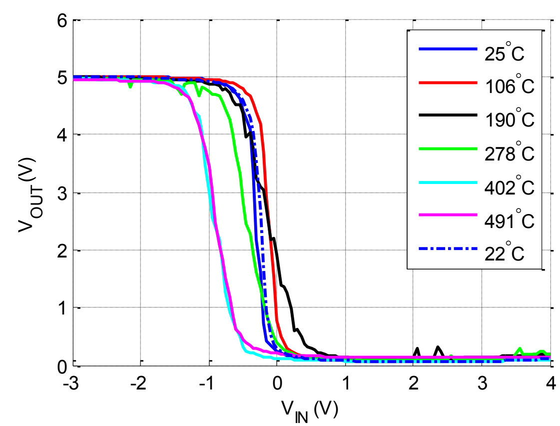
Side view of transistor structure: AlGaN High Electron Mobility Transistor (HEMT)



Adjacent enhancement- and depletion-mode switches have been developed



Enhancement-mode (positive V_T) and depletion-mode (negative V_T) AlGaN HEMTs are combine to make a logic inverter

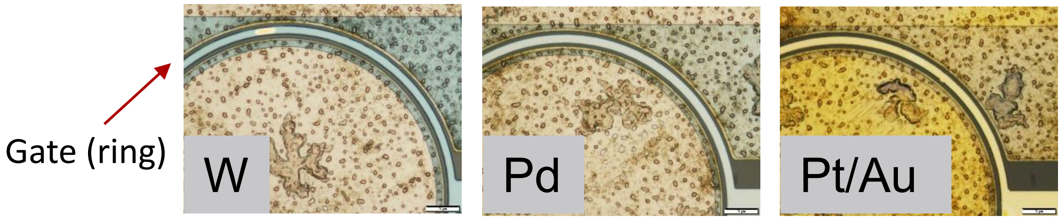


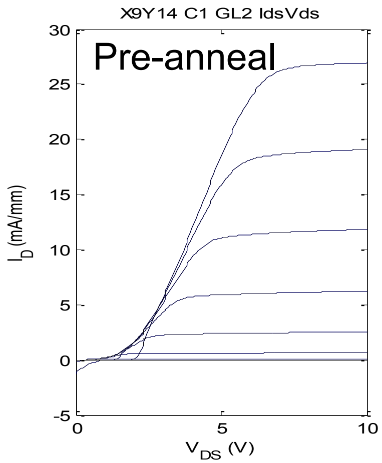
$Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ Inverter operating from 25°C to 491°C

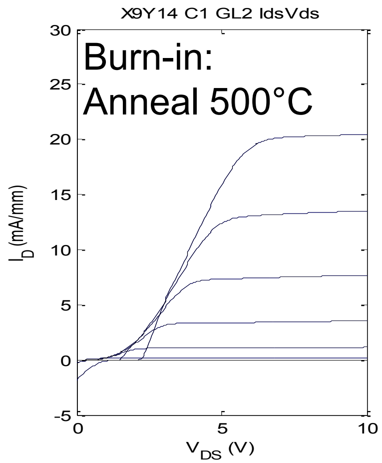
Logic Device Development: Contacts

Develop gate metal for high temperatures

High Temperature Gate Metallurgy: Three Designs





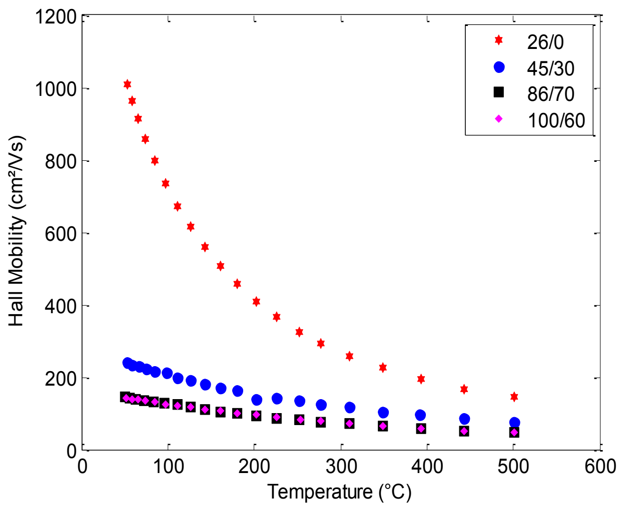


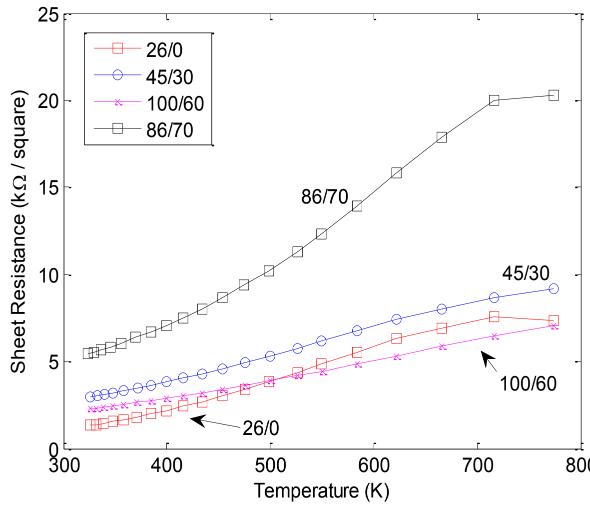
W gate metal (winner)
Least current reduction (25%) after multiple 500°C thermal cycles in N2 atmosphere

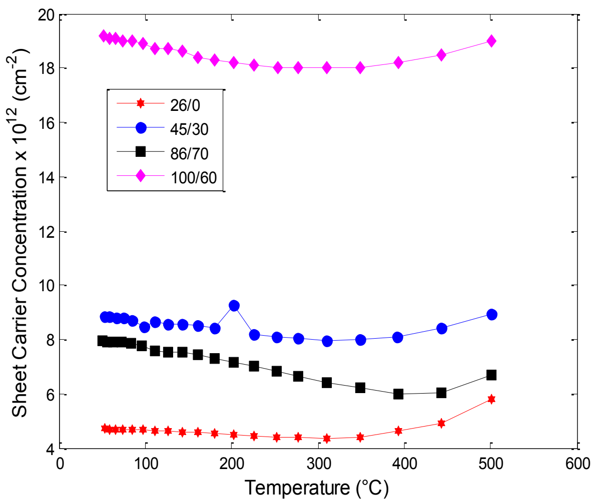
Pd and Pt/Au gate metal
Current reduction of 50% and 70% (thermal cycles); reduced forward-bias gate leakage

Logic Device Development: Transport

Characterize 30-500°C carrier transport for HEMTs of different Al compositions





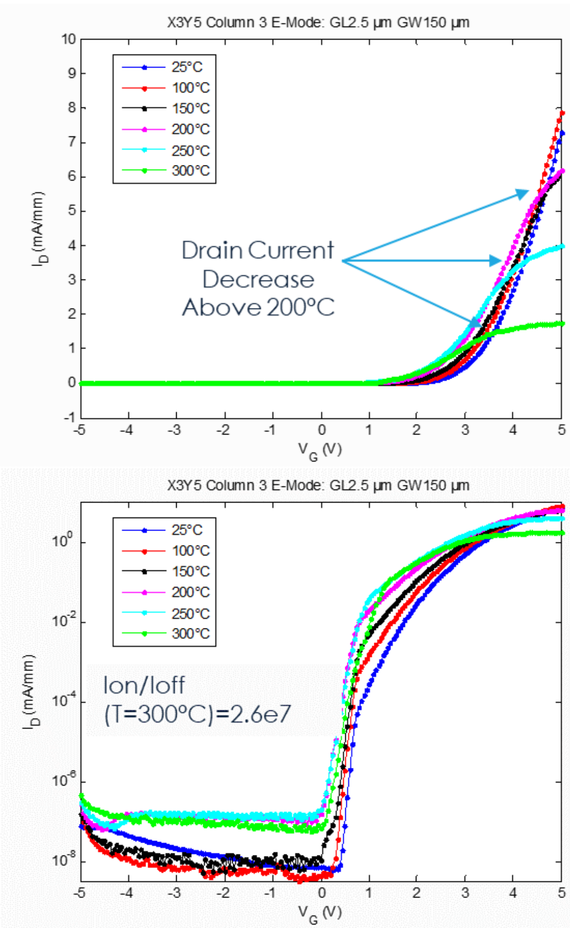


- **AlGaN-channel HEMTs had more stable mobility from 30-500°C than GaN-channel HEMTs**
- **Best results from 100/60 HEMT: High barrier-to-channel aluminum contrast plus less variation in mobility**

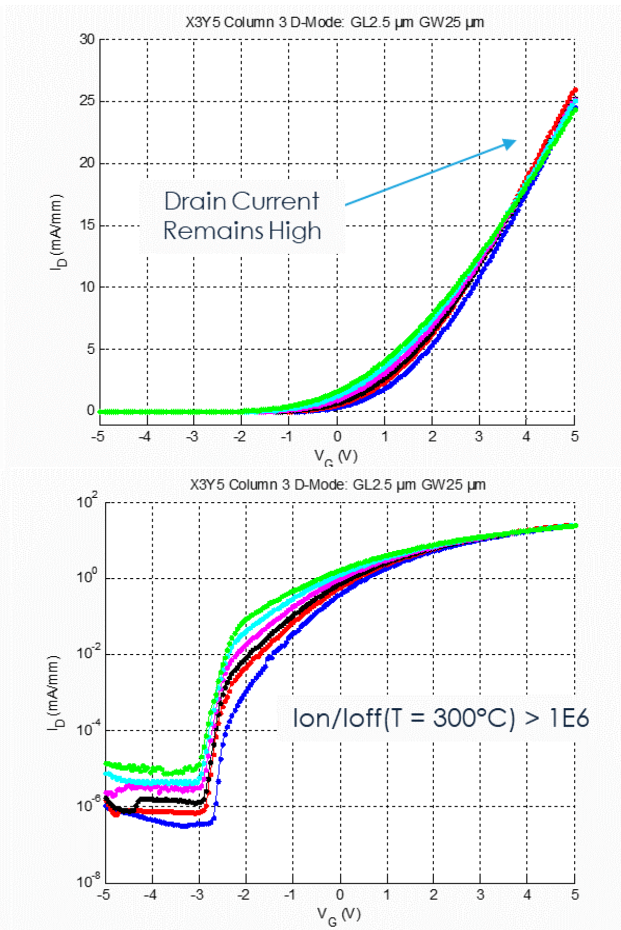
Logic Device Development: Characterization

Characterize devices and inverters over temperature and feed back to design

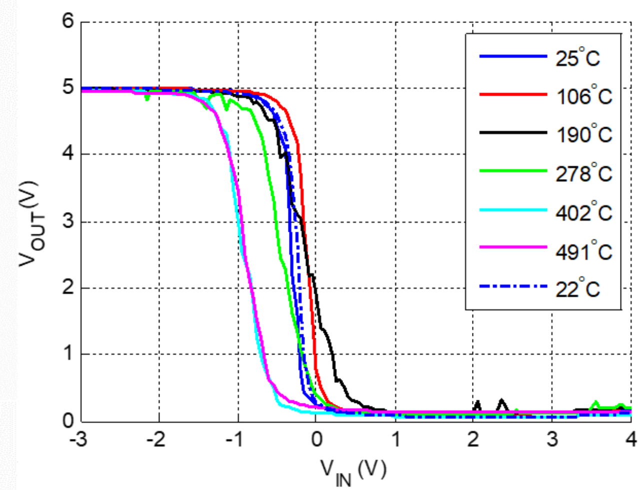
Enhancement Mode



Depletion Mode



Inverter



Best result to date: Inverter operation from room temperature to 491°C

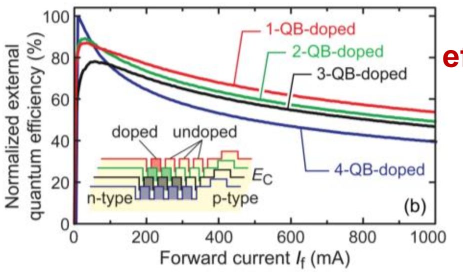
Outline

- Motivation: Applications of UWBGs
- UWBG Properties
- **Sandia AlGaN Devices:**
  - Power Electronics
  - Radio Frequency
  - High-T Logic
  - **Optoelectronics**
- UWBG Community Activities

History of III-Nitride Optoelectronics at Sandia

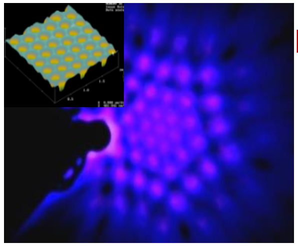
InGaN: Visible LEDs for Solid-State Lighting

Sandia GC LDRD 2000-2004; DOE EERE 2005-2013, DOE BES EFRC 2009-2014



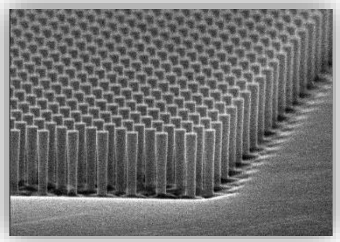
LED efficiency droop

Schubet (RPI), Crawford, Koleske



Enhancing light extraction with photonic lattice LEDs

J. Wierer (Lumileds), Wendt, Simmons

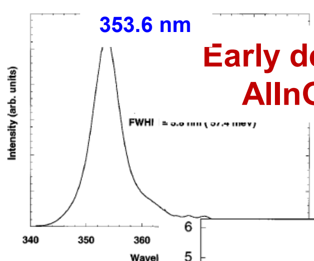


Exploring advanced light-emitter concepts: nanowire LEDs and lasers

G. Wang, Q. Li, J. Wright, I. Brener

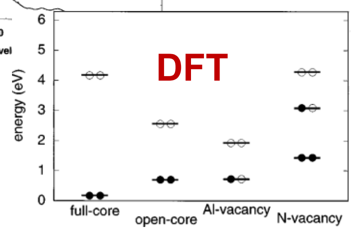
AlGaN: UV LEDs, Laser Diodes

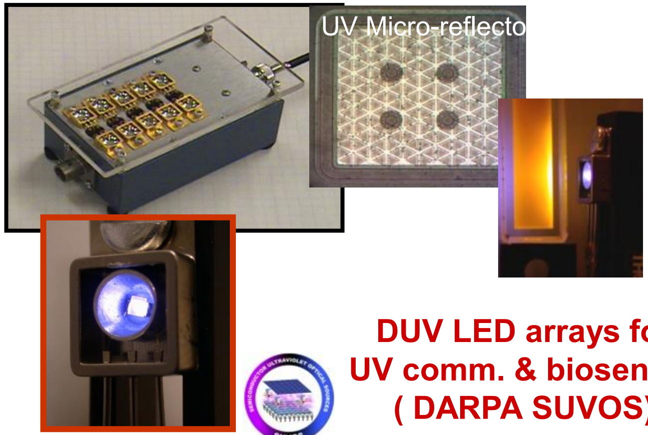
Sandia LDRD (1996-2000), DARPA SUVOS and SAIL programs (2003-2009), Sandia LDRD and Mission (2009-2017)



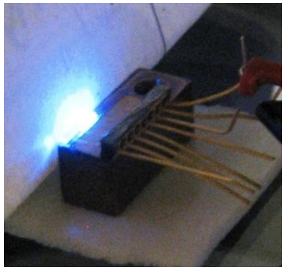
Early demonstrator of AlInGaN UV LED

J. Han, M. Crawford





DUV LED arrays for UV comm. & biosensor (DARPA SUVOS)



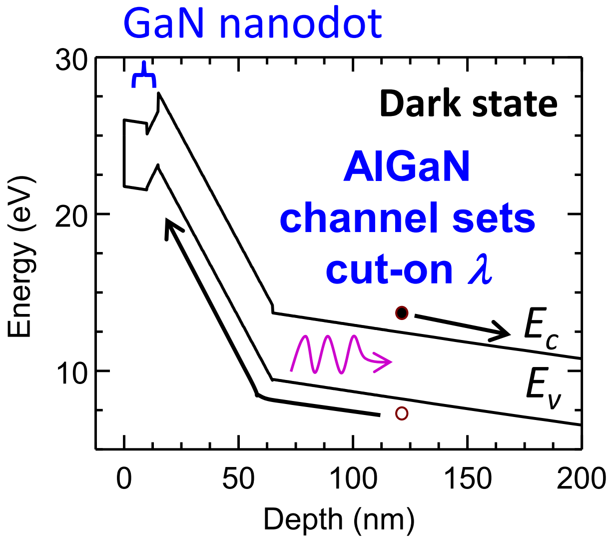
UV Laser Diode (~350 nm)

A. Allerman, A. Fischer, M. Crawford, J. Wierer, K. Bogart

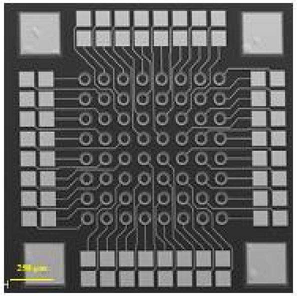
AlGaN Photo-HEMT Fills UV-C Detector Technology Gaps

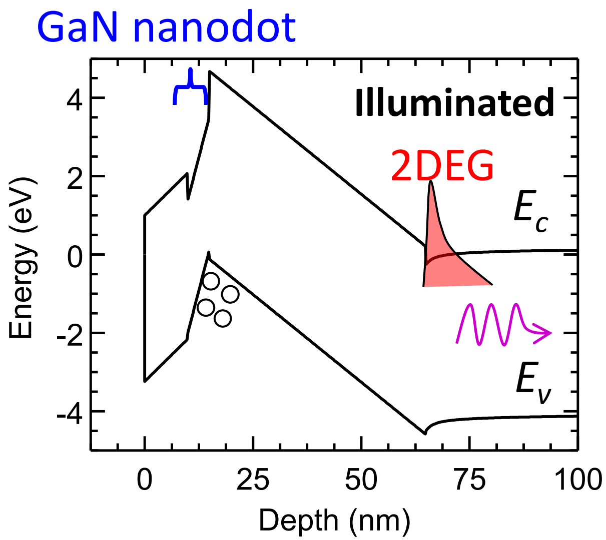
AlGaN quantum dot floating gate HEMT[1]

- Small (low voltage)
- Robust (solid-state)
- Room and high temp. (large ΔE_V)
- Filter-free (large E_g)
- High sensitivity (Large g_m)
- Low dark count (non-avalanche)
- Rad-hard (large E_g)



Man-portable → **Micro-opto-electronic**

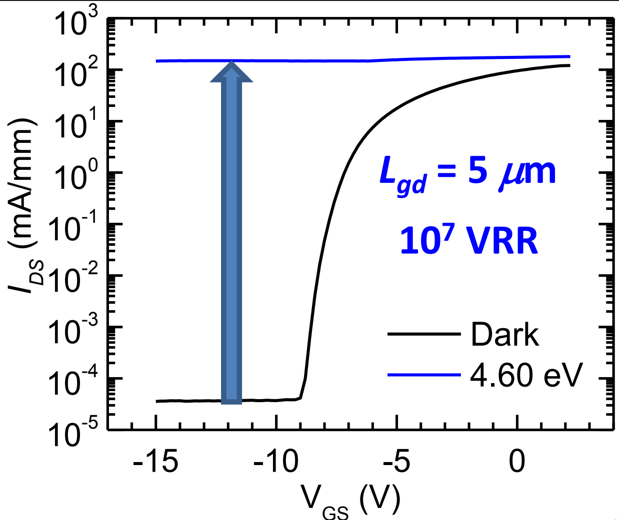


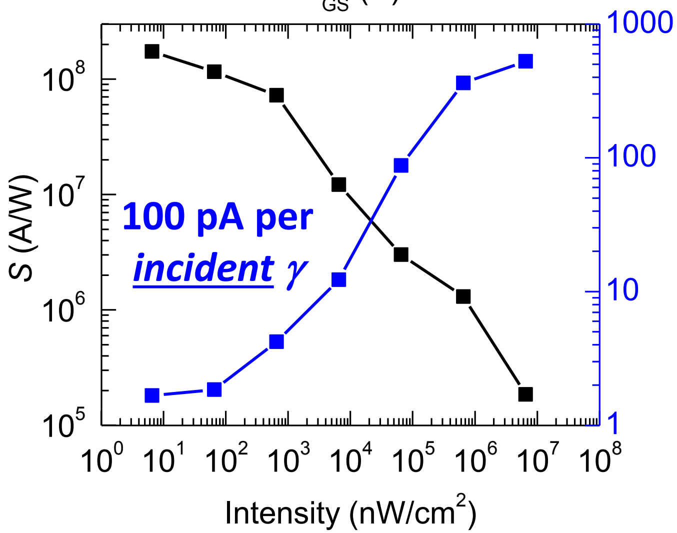


1. Gansen *et al.*, IEEE JSTQE 13, 967 (2007)

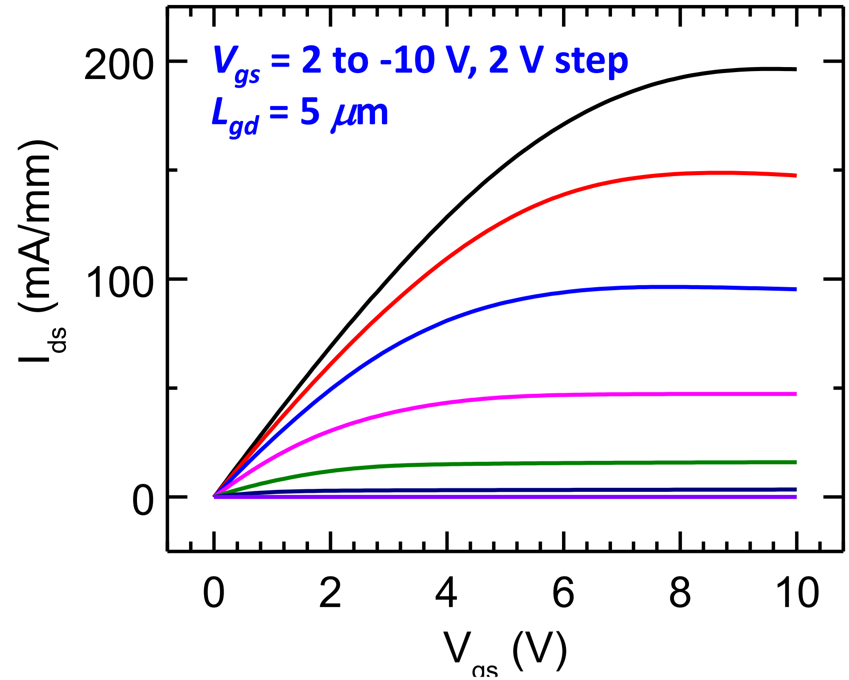
Vis-Blind Demonstrated and Solar-Blind Now Possible

Vis-blind $Al_{0.5}Ga_{0.5}N/Al_{0.3}Ga_{0.7}N$ photo-HEMT





$Al_{0.85}Ga_{0.15}N/Al_{0.5}Ga_{0.5}N$ HEMT



Advance to solar-blind technology

- Established ohmics for $Al_{0.5}Ga_{0.5}N$ channel (270 nm)
- Move to sub-micron L_{gd} for nA/photon sensitivity
- Move from GaN quantum dot to GaN quantum well for easier epitaxy and fabrication

Armstrong *et al.*, Photon. Res. 7 B24 (2019)

Outline

- Motivation: Applications of UWBGs
- UWBG Properties
- Sandia AlGaN Devices:
  - Power Electronics
  - Radio Frequency
  - High-T Logic
  - Optoelectronics
- **UWBG Community Activities**

UWBG Working Group Study

- Three workshops held (Oct. 2015 / April 2016 / May 2019)
  - ~75 initial participants (government, academia, industry, national labs)
  - Subset formed a working group
    - Study on material parameters, growth, physics, applications, extreme environments, and processing/packaging
- Goals
  - Establish (refresh) best materials parameters and physics
  - Evaluate applications and projected performance spaces
    - Power switching, RF power/switching, optoelectronics, quantum information sciences, extreme environments
  - Articulate Research Challenges and Opportunities
- Out-brief at GOMAC 2017 special session
- Published article in *Advanced Electronic Materials*
  - J. Y. Tsao et al., *Adv. Elec. Mat.* 4, 1600501 (2018)
  - 54 pages, 353 references, best materials parameters listed
  - Handbook for roadmap development

April 2016 UWBG Workshop in Arlington, VA

Technical Exchange on UWBG Semiconductors: Research Opportunities and Directions

Basic Research Innovation and Collaboration Center | Arlington, VA

UWBG Working Group Study: Twenty-Six Research Opportunities Identified

Four topical areas:

1. **Materials:** Bulk and epitaxial growth, point and extended defects, doping, materials characterization, fundamental theory and DFT
2. **Physics:** Electronic transport at low and high fields, optical properties, phonon transport, electrical breakdown, carrier confinement
3. **Devices:** Device architectures, fundamental limits to device performance, device fabrication and processing techniques, co-design for thermal packaging
4. **Applications:** New applications enabled by UWBG devices, device performance targets, power switching needs, RF needs, UV emitter & detectors, quantum information

J. Y. Tsao et al., *Adv. Elec. Mat.* 4, 1600501 (2018)

REVIEW
Semiconductors
ADVANCED ELECTRONIC MATERIALS
www.advelectronicmat.de

Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges

J. Y. Tsao, S. Chowdhury, M. A. Hollis,* D. Jena, N. M. Johnson, K. A. Jones, R. J. Kaplar,* S. Rajan, C. G. Van de Walle, E. Bellotti, C. L. Chua, R. Collazo, M. E. Coltrin, J. A. Cooper, K. R. Evans, S. Graham, T. A. Grotjohn, E. R. Heller, M. Higashiwaki, M. S. Islam, P. W. Juodawlkis, M. A. Khan, A. D. Koehler, J. H. Leach, U. K. Mishra, R. J. Nemanich, R. C. N. Pilawa-Podgurski, J. B. Shealy, Z. Sitar, M. J. Tadjer, A. F. Witulski, M. Wraback, and J. A. Simmons*

Ultrawide-bandgap (UWBG) semiconductors, with bandgaps significantly wider than the 3.4 eV of GaN, represent an exciting and challenging new area of research in semiconductor materials, physics, devices, and applications. Because many figures-of-merit for device performance scale nonlinearly with bandgap, these semiconductors have long been known to have compelling potential advantages over their narrower-bandgap cousins in high-power and RF electronics, as well as in deep-UV optoelectronics, quantum information, and extreme-environment applications. Only recently, however, have the UWBG semiconductor materials, such as high Al-content AlGaN, diamond and Ga_2O_3, advanced in maturity to the point where realizing some of their tantalizing advantages is a relatively near-term possibility. In this article, the materials, physics, device and application research opportunities and challenges for advancing their state of the art are surveyed.

Dr. J. Y. Tsao
Material, Physical, and Chemical Sciences Center
Sandia National Laboratories
PO Box 5800, Albuquerque, NM 87185-1421, USA
E-mail: jytsao@sandia.gov
Prof. S. Chowdhury
Electrical and Computer Engineering Department
University of California Davis
3133 Kemper Hall, Davis, CA 95616, USA
Dr. M. A. Hollis
Advanced Technology Division
MIT Lincoln Laboratory
244 Wood Street, Lexington, MA 02421-6426, USA
E-mail: hollis@ll.mit.edu
Prof. D. Jena
Electrical and Computer Engineering and Materials Science and Engineering Departments
Cornell University
326 Bard Hall, Ithaca, NY 14853, USA
Dr. N. M. Johnson, Dr. C. L. Chua
Electronic Materials and Devices Laboratory
PARC
3333 Coyote Hill Road, Palo Alto, CA 94303, USA
Dr. K. A. Jones
Sensors and Electron Devices Directorate
U.S. Army Research Laboratory
2800 Powder Mill Road, Delphi, MD 20783, USA
Dr. R. J. Kaplar
Material, Physical, and Chemical Sciences Center
Sandia National Laboratories
PO Box 5800, Albuquerque, NM 87185-1086, USA
E-mail: rjkapla@sandia.gov
Prof. S. Rajan
Electrical and Computer Engineering and Materials Science and Engineering Departments
Ohio State University
2015 Neil Avenue, 205 Dreese Laboratory, Columbus, OH 43210, USA
Prof. C. G. Van de Walle
Materials Department
University of California Santa Barbara
2510 Engineering II, Santa Barbara, CA 93106-5050, USA
Prof. E. Bellotti
Electrical and Computer Engineering Department
Boston University
8 St. Mary's Street Room 533, Boston, MA 02215, USA
Prof. R. Collazo
Materials Science and Engineering Department
North Carolina State University
911 Partners Way (EBI 219), Raleigh, NC 27695, USA
Dr. M. E. Coltrin
Material, Physical, and Chemical Sciences Center
Sandia National Laboratories
PO Box 5800, Albuquerque, NM 87185, USA
Prof. J. A. Cooper
Electrical and Computer Engineering Department
Purdue University
1205 West State Street, West Lafayette, IN 47906, USA
Dr. K. R. Evans, Dr. J. H. Leach
Kyma Technologies, Inc.
8829 Midway West Rd, Raleigh, NC 27617, USA
Prof. S. Graham
Mechanical Engineering Department
Georgia Institute of Technology
771 Ferst Drive, Atlanta, GA 30332, USA

DOI: 10.1002/aelm.201600501

Adv. Electron. Mater. **2017**, 1600501 — **1600501 (1 of 49)**

Combined topics in report; 26 research challenges identified

NYCREATES

UWBG Working Group Material Parameter Refresh

Sandia National Laboratories

Material-Properties Table for Electronic Applications

Parameter at 27°C	GaN (for reference)	$Al_xGa_{1-x}N$	AlN	Example AlN/GaN HEMT [1]	β-Ga_2O_3	Cubic BN	Diamond	Diamond MOS
Bandgap (eV)	3.4 [3]	Interpolation [37]	6.0 [4]	multiple	4.9 [5]	6.4 [6]	5.5 [7]	multiple
Proj. bulk E_C (MV/cm at doping = 10^{16} cm^{-3})	4.95 [8] (measured baseline)	Varies non-uniformly by composition [41]	15.4 [after 9]	2.6 (reported)	10.3 [after 9]	17.5 [after 9]	13.0 [after 9]	Depends on insulator
n_s (cm^{-2})	Various (see Doping below)	Various (see Doping below)	Low at 300 K	1.2×10^{13}	1.5×10^{13} / TBD 2012 [38] / --	Various (see Doping below)	Various (see Doping below)	4×10^{13} / 1.7×10^{14} 2012 [48] / 2013 [49]
e- drift mobility (cm^2/V•s)	1000 [3,32,52,53]	Interpolation	426 / 300 2006 [63] / 1994 [52]	1200 (Hall mobility)	153 / 225 (Hall mobility) 2015 [11] / 2017 [65]	825 / TBD (Hall mobility) 2003 [19] / --	4500 / 7300 2002 [26] / 2014 [27]	TBD
hole drift mobility (cm^2/V•s)	11 [64] (Hall mobility)	Various	--	--	--	500 / TBD (Hall mobility) 1998 [20] / --	3800 / 5300 2002 [26] / 2014 [27]	340-47 / TBD (over 2×10^{17} – 6×10^{19} cm^{-3} hole density) 2016 [50] / --
v_{sat} (10^7 cm/s): e- & holes	1.4 (e-) [16]	Various	1.3 (e-) [16]	2.8 (e-); velocity overshoot due to short gate [16]	-- / 1.1 @ 10^{18} cm^{-3} (e-) -- / 2015 [13]	--	1.9 / 2.3 (e-) 2006 [33] / 1975 [28] 1.4 / 1.1 (holes) 2006 [33] / 1981 [29]	TBD / TBD (e-) ~ 0.94 / TBD (holes) 2008 [51] / --
Relative permittivity	10.4 for E//c axis; 9.5 for E perp. c axis [30,31]	Interpolation	9.76, E//c axis [18]; NR perp. to c axis	--	10 [12]	7.1 [21]	5.7 [7]	Depends on insulator
$\sigma_{thermal}$ (W/m•K)	253 [66]	Interpolation	285 / 319 both 1987 [34]	< 370 [3] (on 4H-SiC)	11-27 / 16-22 2015 [14] / 2015 [15]	768 / 940 (natural isotopic ratio) -- / 2145 (isotopically pure) 1983 [22] / 2013 [23]	2270 / 2290 (natural isotopic ratio) 3300 / 3450 (pure ^{12}C) 1992-3 [24, 25] / 2013 [23]	2270 / 2290 (natural isotopic ratio) 3300 / 3450 (pure ^{12}C) 1992-3 [24, 25] / 2013 [23]
Maturity assessment:	Mature for GaN HEMTs; Immature for vert. GaN devices	Immature	Immature	Mature	Immature	Immature	Immature	Immature
- Doping (p & n); or polarization-induced; or surface-transfer	Both n & p (Si & Mg) [3,37]	n (Si) below 70% Al; p (Mg deep) [35,37]	Possible S donor [35]; no good acceptor	Polarization-induced 2DEG	n type (Sn donor) [38]	n type (S donor); deep acceptors [40]	Light to medium p type for N_A < mid-10^{19} cm^{-3}; Heavy for N_D, N_A > mid-10^{19} cm^{-3} [42-44]	Surface-transfer doping [48 - 51]
- Dual-use/ low-cost or low-volume/ high-cost	Dual use / low cost	Dual use / low cost?	Low volume/ high cost?	Mid to low volume/ Mid to high cost?	Dual use / low cost?	Low volume/ high cost?	Low volume/ high cost?	Low volume/ high cost?
- Substrate size/ availability	50-mm GaN substrates; GaN layers on 150-mm SiC & 200-mm Si	Uses common substrates for GaN	2016: 25 mm 2017: 50 mm [36]	On 75-mm SiC	2016: 50 mm 2017: 100 mm [39]	Few-mm size HPHT crystals	2016: 15 & 25 mm [45,46]. 7x20 mm; Larger diamond on Si [47,58]. 2018: 38 mm [46].	2016: 15 & 25 mm [45,46]. 7x20 mm; Larger diamond on Si [47,58]. 2018: 38 mm [46].
			Data format often is: Measured number / Theoretical number Year [ref.] / Year [ref.]					

- **Working group study reviewed the literature and determined best-known parameters for WBG and UWBG materials**
- **Materials included are:**
  - **GaN (reference)**
  - **AlGaN**
  - **AlN**
  - **AlGaN/GaN HEMT**
  - **β-Ga_2O_3**
  - **c-BN**
  - **Diamond**
  - **Diamond MOS**

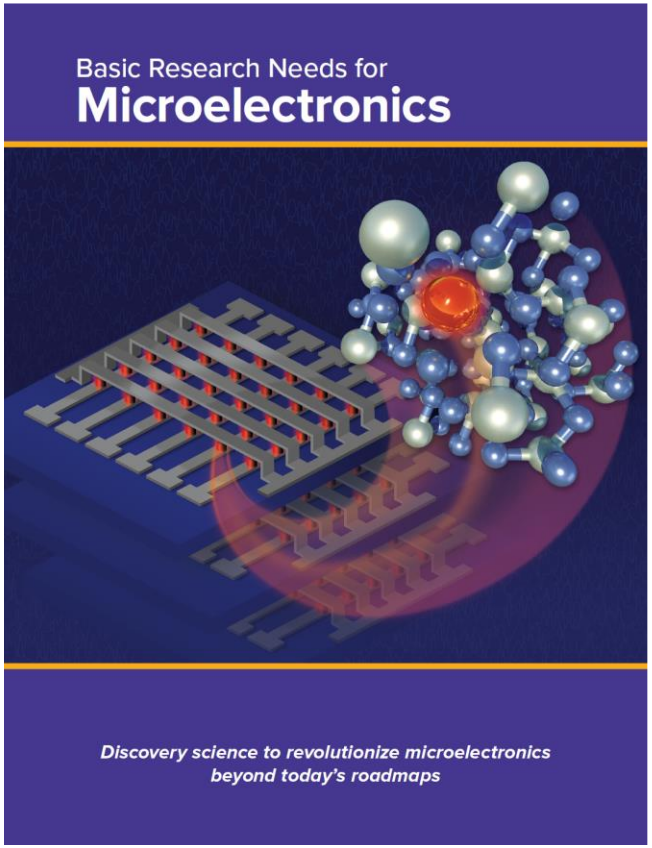
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Report on Third UWBG Workshop Recently Completed

- Most recent UWBG workshop held May 14-16 at ARL in Adelphi, MD
- Workshop report just published by ARL, covering updates in the following areas:
  - Ga_2O_3
  - AlGaN
  - Diamond
  - Supporting technologies (thermal materials, magnetics, dielectrics)
  - Applications (high power electronics, optoelectronics, sensors)

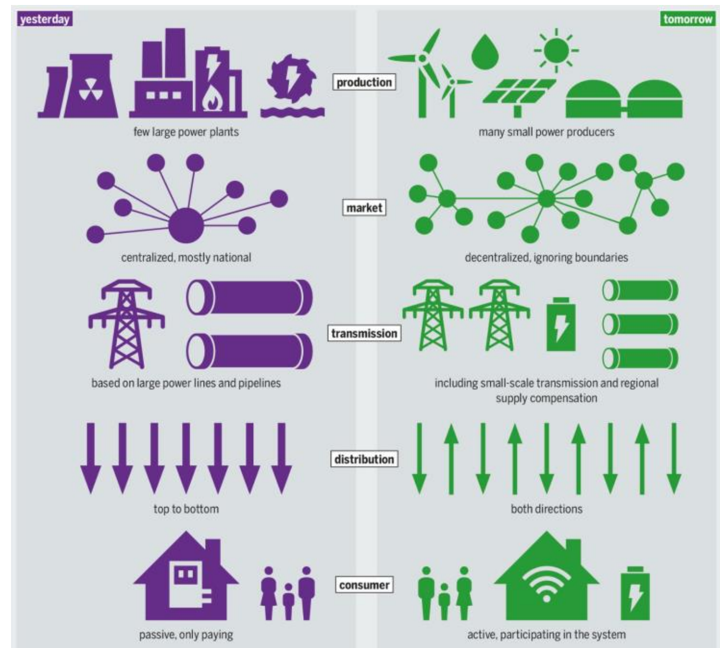
DOE Office of Science Microelectronics Workshop and Report



DOE Office of Science Workshop on Basic Research Needs for Microelectronics (October 23-25, 2018)

https://science.osti.gov/-/media/bes/pdf/reports/2019/BRN_Microelectronics_rpt.pdf

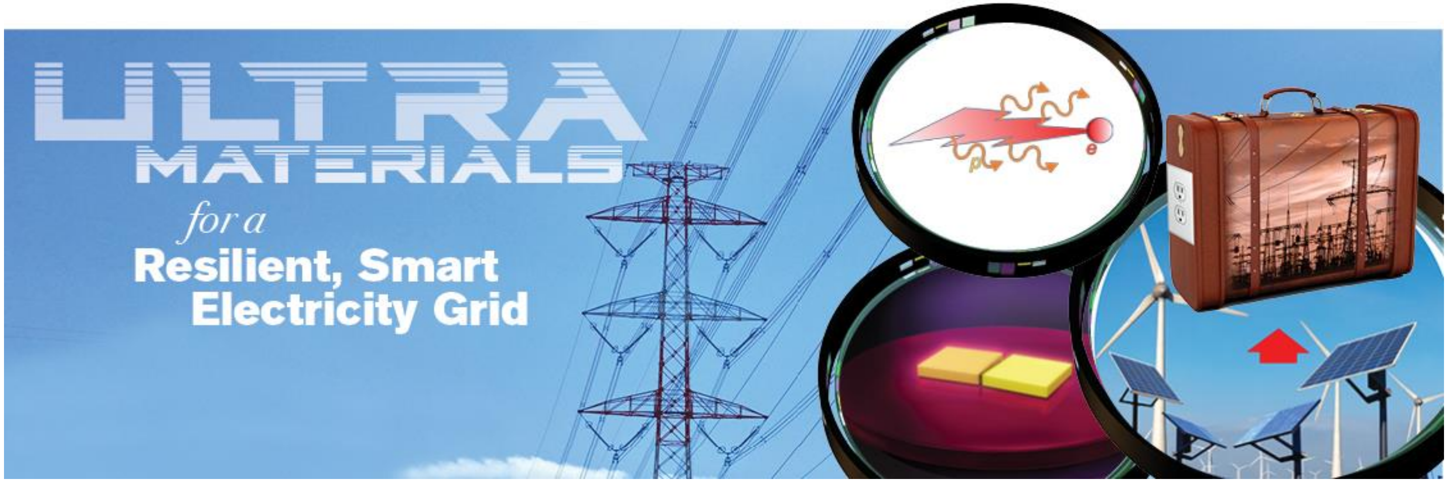
Priority Research Direction 5: Reinvent the electricity grid through new materials, devices, and architectures



"A new generation of ultra-wide-bandgap (UWBG) semiconductors for power electronics is required to enable power conversion systems that are higher power, more efficient, smaller, and cheaper. These, in turn, will enable a smart grid that is higher performing and more resilient than what exists today."

Ultra Materials for a Resilient, Smart Electricity Grid (ULTRA)

Director: Robert Nemanich, Deputy Director: Stephen Goodnick,
Research Collaborations Director: Srabanti Chowdhury



U.S. DEPARTMENT OF ENERGY | Office of Science

https://science.osti.gov/bes/efrc/Centers/ULTRA
https://ultracenter.asu.edu/

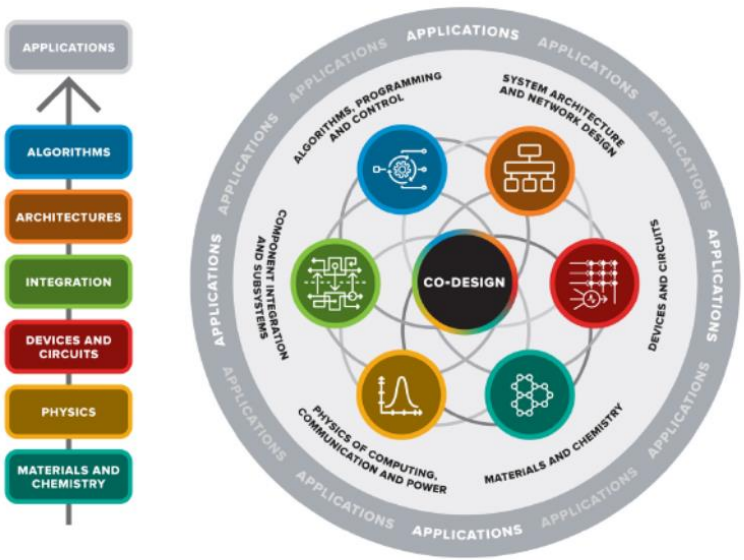
Arizona State University · UAB The University of Alabama at Birmingham · UC Riverside · Cornell University · Michigan State University · Sandia National Laboratories · Stanford University · University of Bristol

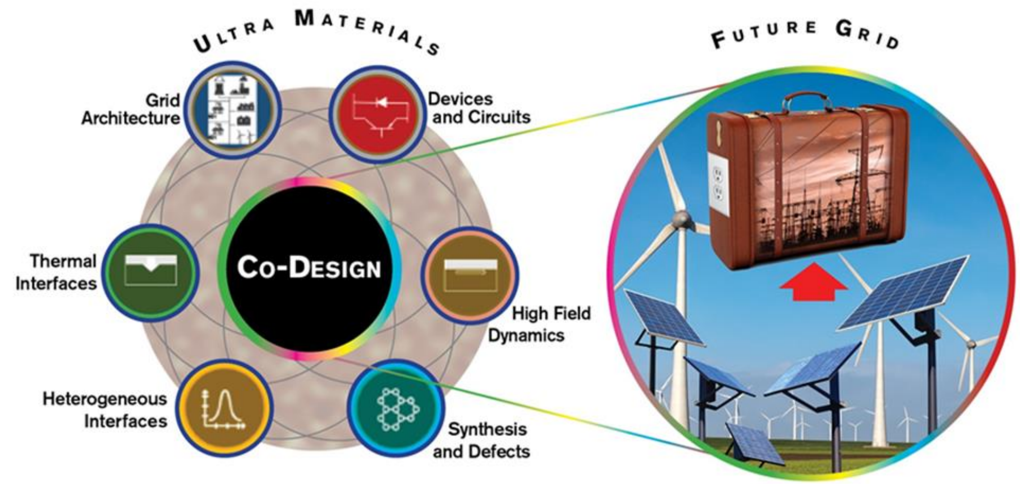
Office of Science Co-Design Concept Adapted for UWBGs and the Grid

U.S. DEPARTMENT OF ENERGY | Office of Science

Computing: Co-design of software and hardware

UWBGs:
- **Integration of bulk/interfacial and electronic/thermal properties**
- **Ultimate impact of material properties on the grid (material ↔ device ↔ circuit ↔ grid)**





"Substation in a suitcase"

Arizona State University | THE UNIVERSITY OF ALABAMA AT BIRMINGHAM | UC RIVERSIDE | Cornell University | MICHIGAN STATE UNIVERSITY | Sandia National Laboratories | Stanford University | University of BRISTOL

Questions?

- Motivation: Applications of UWBGs
- UWBG Properties
- Sandia AlGaN Devices:
  - Power Electronics
  - Radio Frequency
  - High-T Logic
  - Optoelectronics
- UWBG Community Activities

Bob Kaplar: rjkapla@sandia.gov