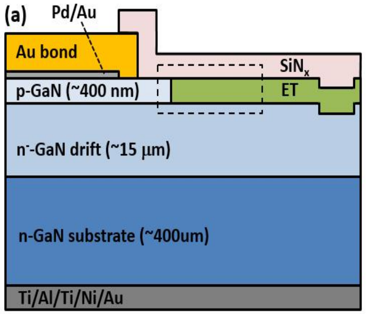
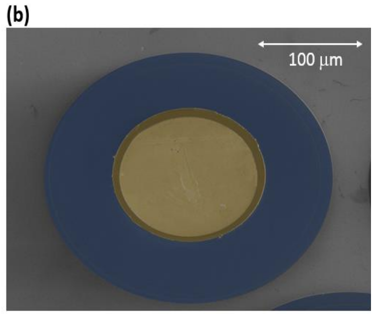
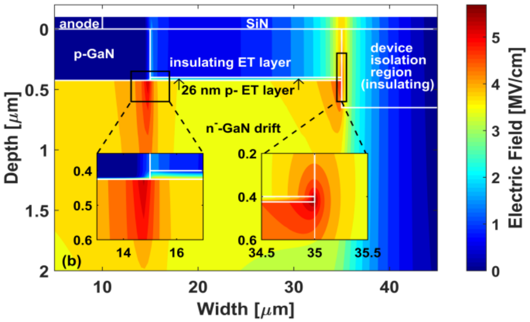
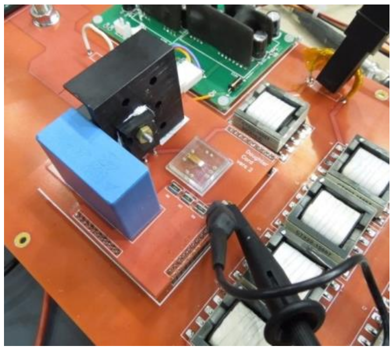
SAND2016-2240C

Exceptional service in the national interest









Generation-After-Next Power Electronics Using Ultra-Wide-Bandgap Semiconductors

R. J. Kaplar, A. A. Allerman, A. M. Armstrong, M. A. Crawford, A. J. Fischer, J. R. Dickerson, M. P. King, A. G. Baca, E. A. Douglas, C. A. Sanchez, and J. C. Neely

Sandia National Laboratories, Albuquerque, NM

Orlando, FL
March 15, 2016

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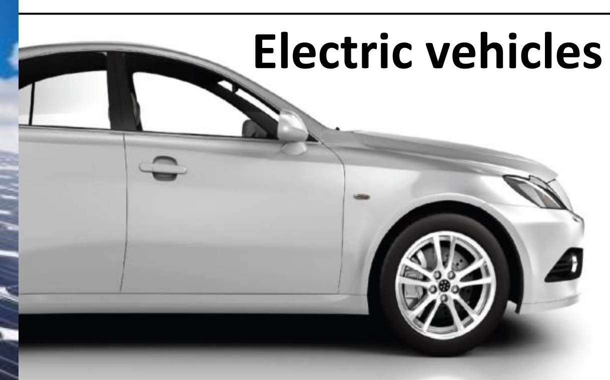
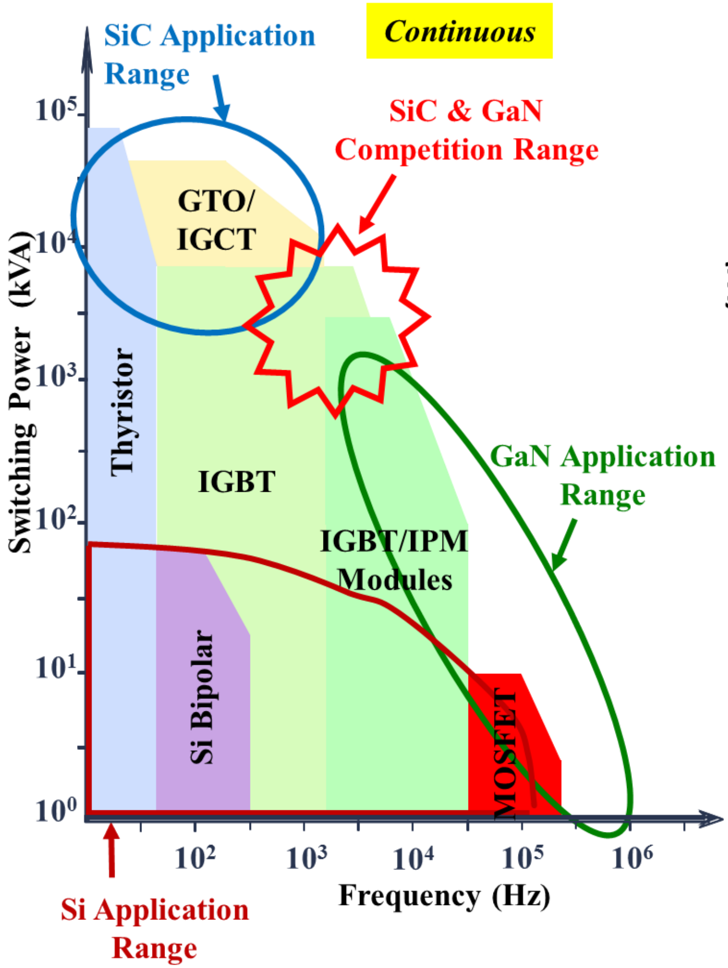
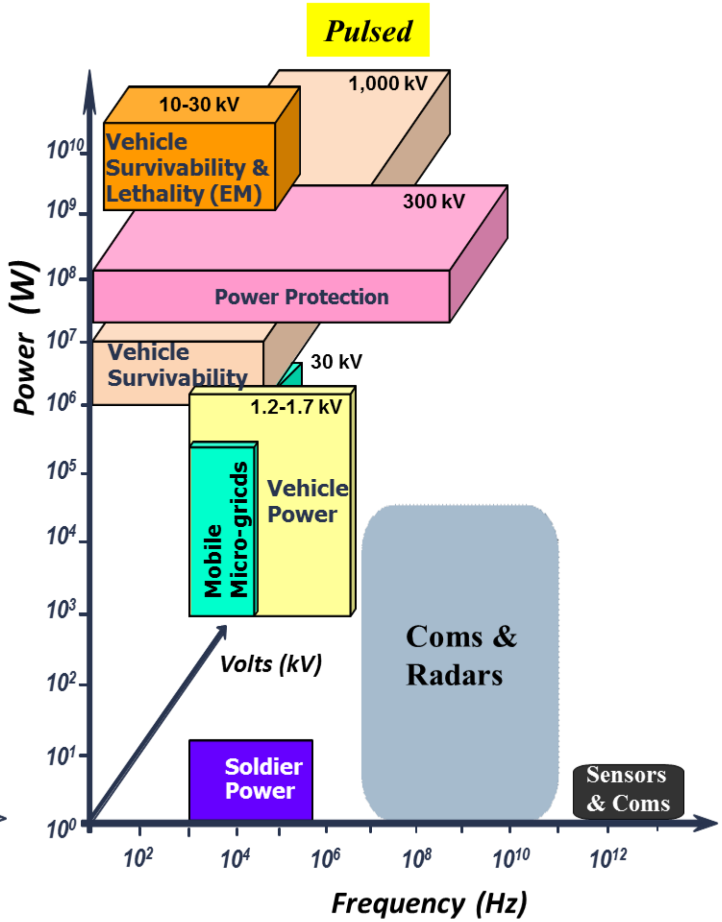
Power Electronics are Ubiquitous



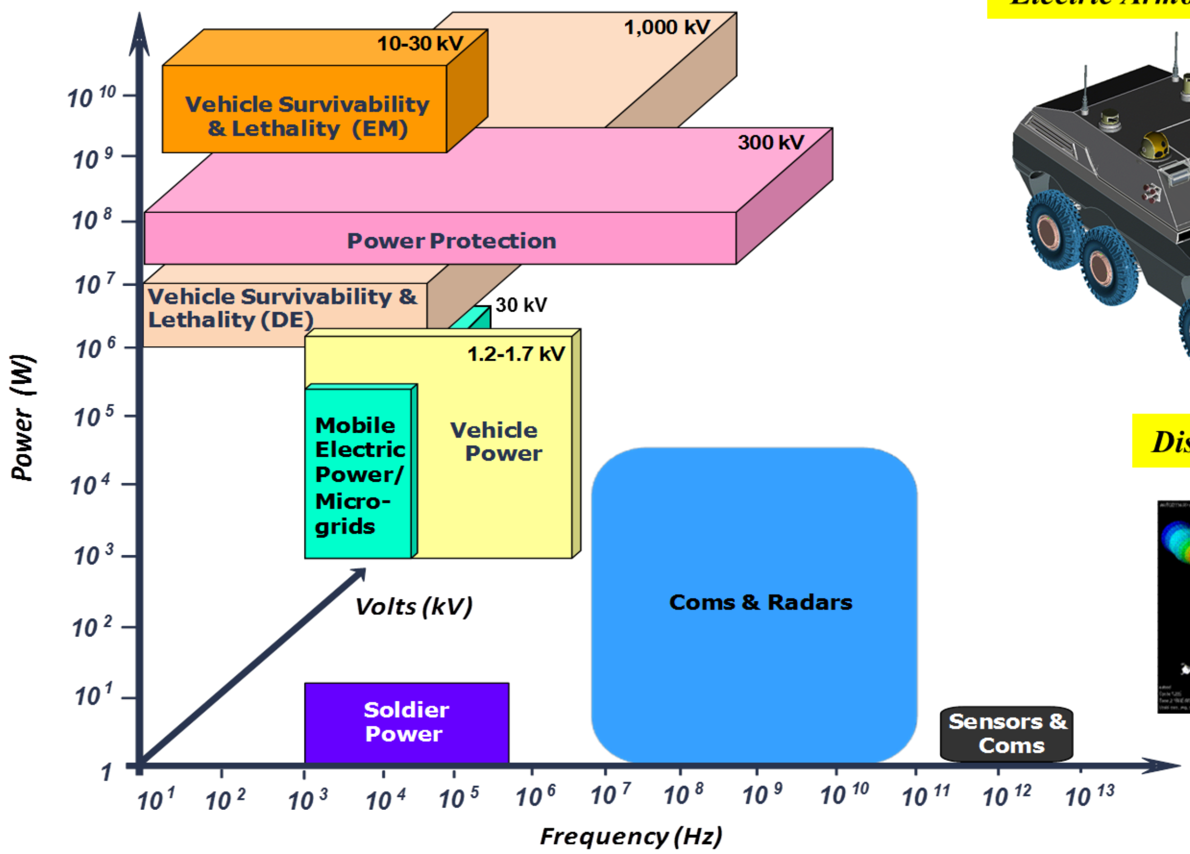
Continuous and Pulsed Power Applications Space



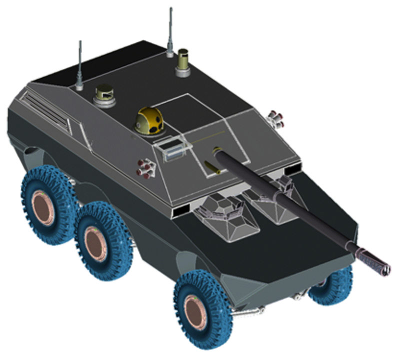


Figures courtesy of Dr. Ken Jones, Army Research Lab

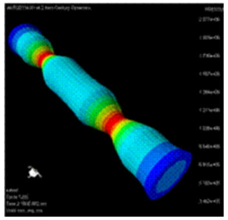
Pulsed Power Applications



Electric Armor for Vehicle

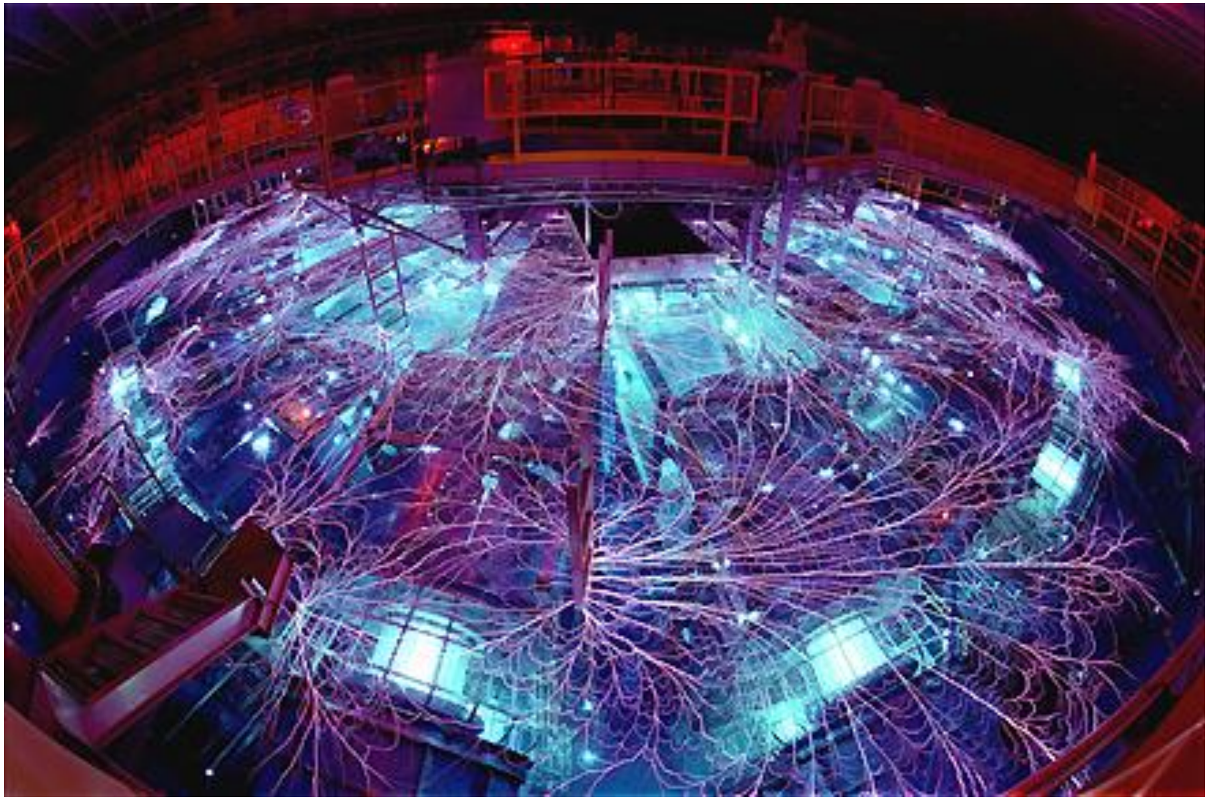


Distort Projectile



Figures courtesy of Dr. Ken Jones, Army Research Lab

Other Pulsed Power Applications

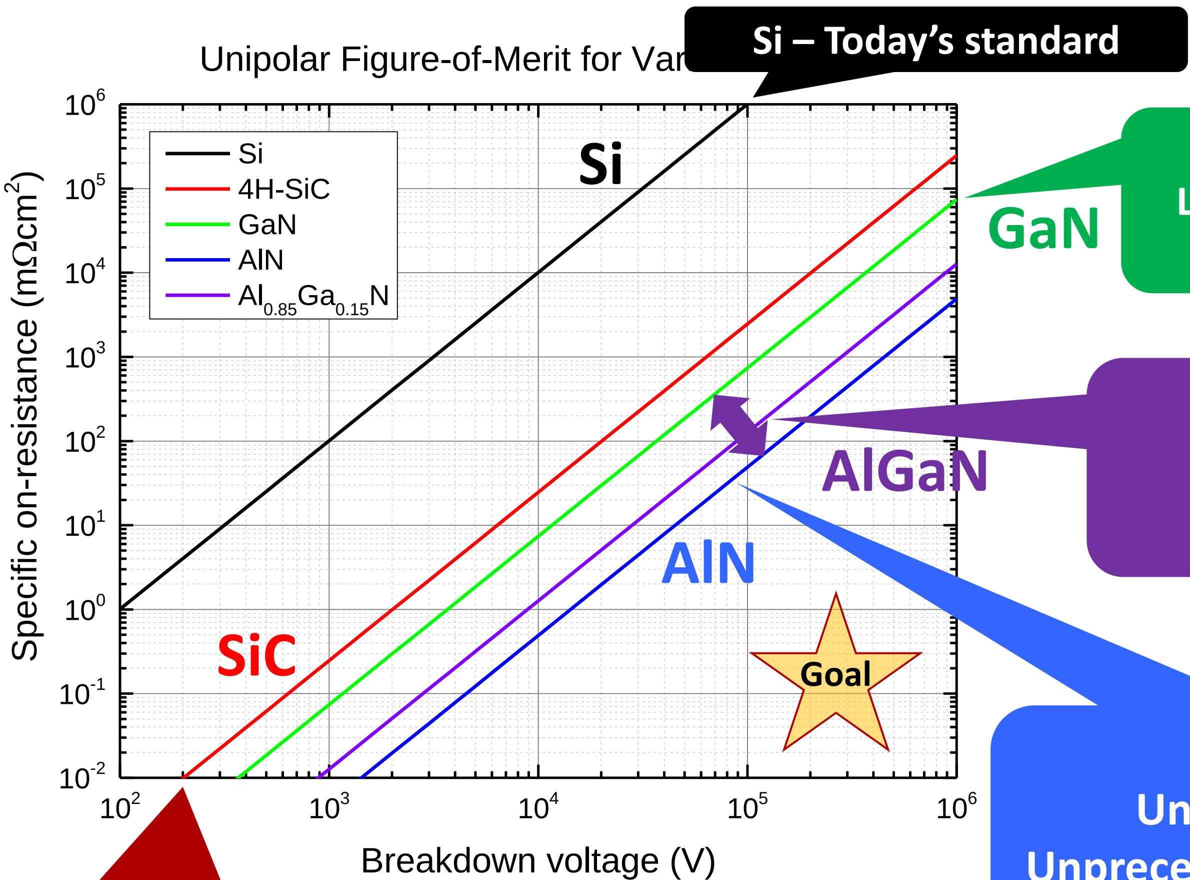


Pulsed power: Sandia Z-machine

(currently uses gas discharge switches)

100 kV switches may eventually be possible using an UWBG material such as AlGaN!

AlGaN Has Potential as the Generation-After-Next Material for Power Electronics



GaN
Lateral devices fairly mature
Vertical devices emerging

AlGaN
Unexplored space
Unprecedented performance
Can dope material

AlN
Unexplored space
Unprecedented performance
Doping is problematic

SiC
Many commercial devices now available

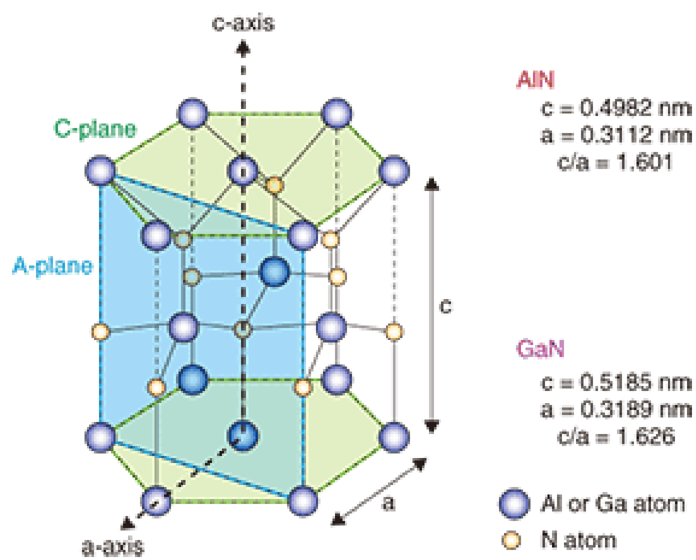
$$FOM = V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$$

III-Nitride Semiconductors Are Ideal 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	6.2
Critical Electric Field (MV/cm)	0.3	0.4	2.0	3.3	15.9
Saturated electron velocity (10^7 cm/s)	1.0	1.0	2.0	2.5	2
Thermal conductivity (W/cm·K)	1.5	0.5	4.5	4.0	3.4

III-N



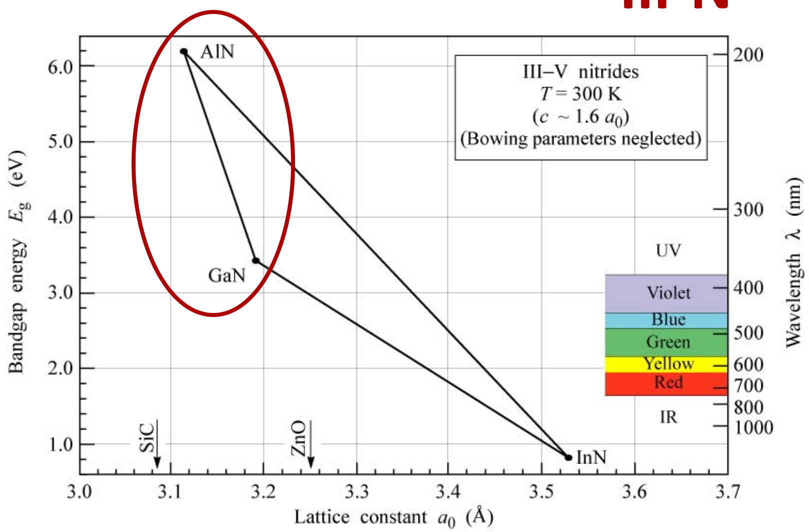
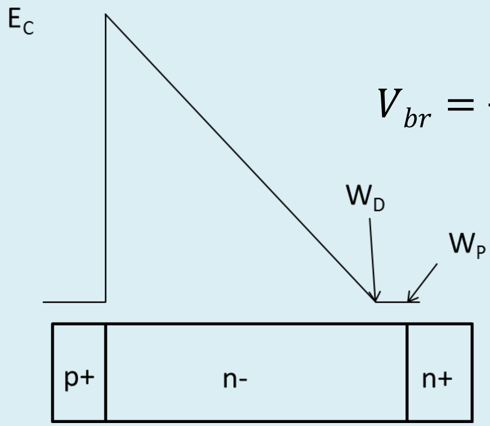


Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

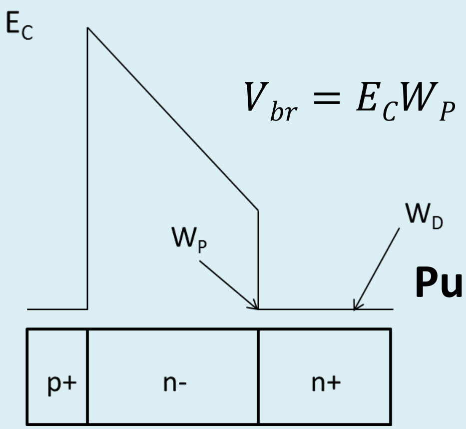
PiN Diode Design: Doping and Drift Region Thickness



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

Non-Punch-Through

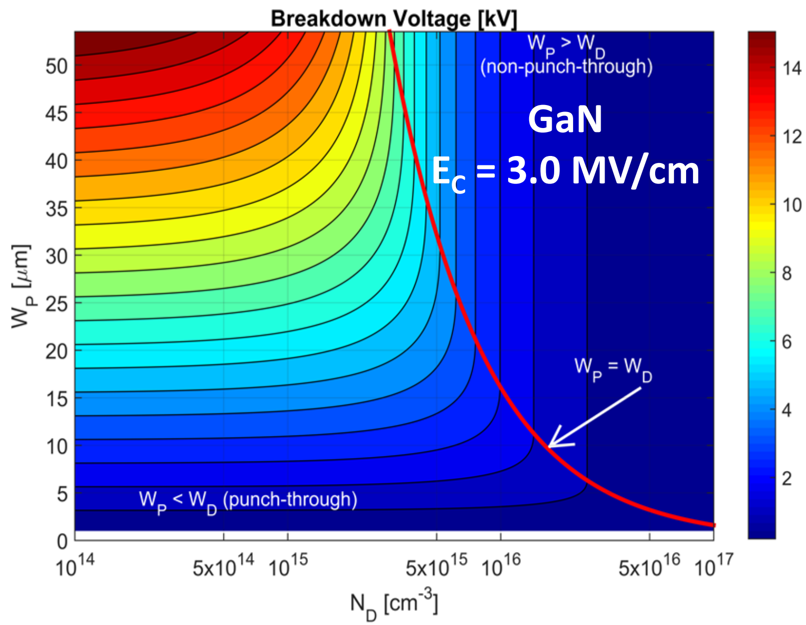
$W_P \geq W_D$



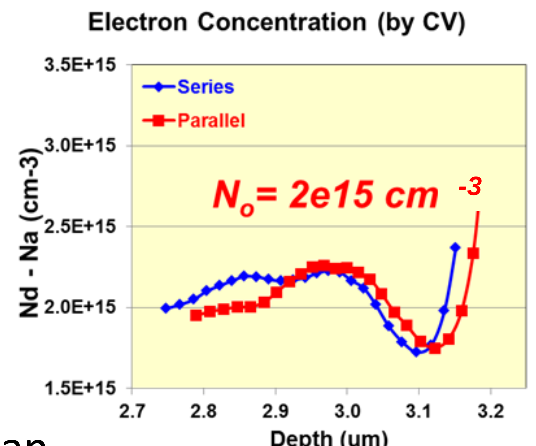
$$V_{br} = E_C W_P - \frac{qN_D W_P^{\,2}}{2\varepsilon}$$

Punch-Through

$W_P < W_D$

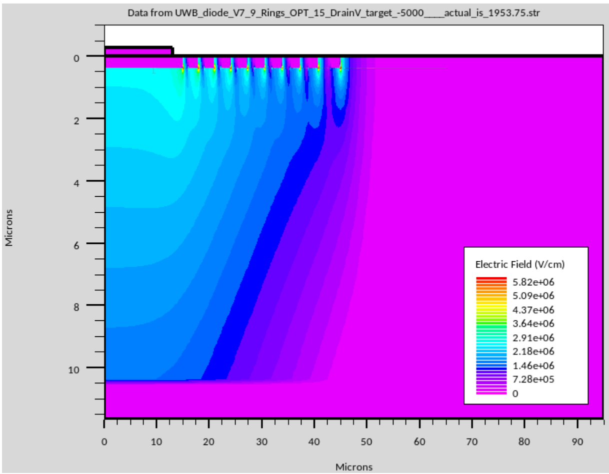


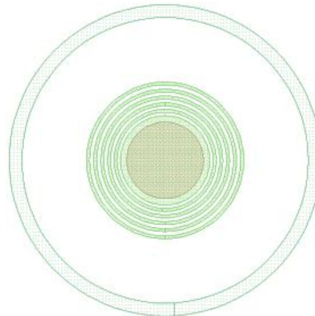
Low doping and thick drift layers are required for high breakdown voltage



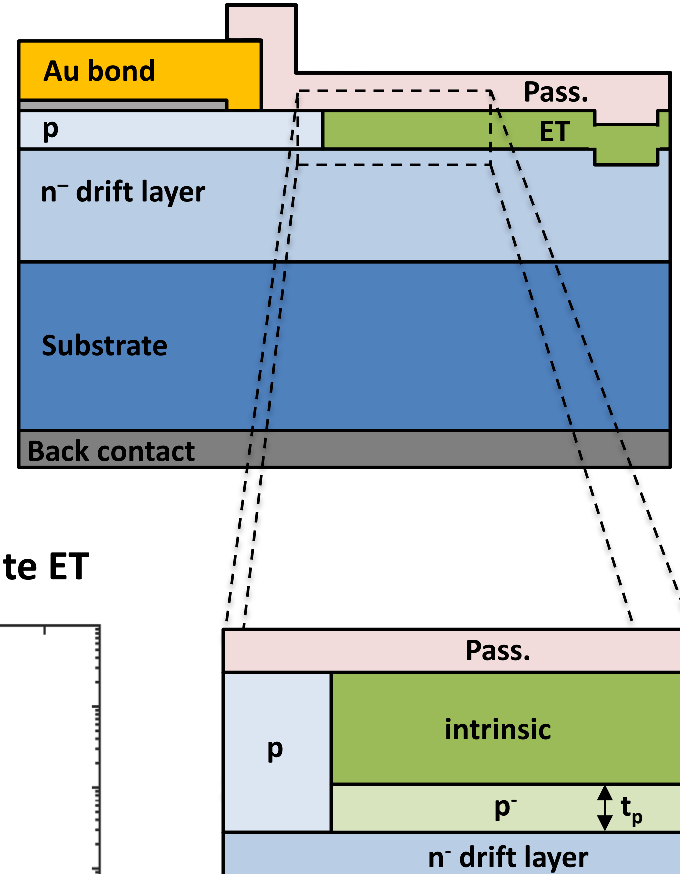
J. Dickerson, A. Allerman

Edge Termination for High Breakdown Voltage



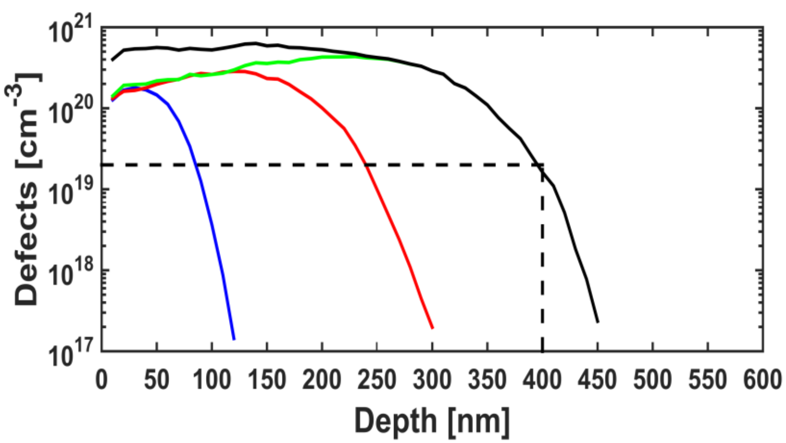


Guard rings



Junction Termination Extension (JTE)

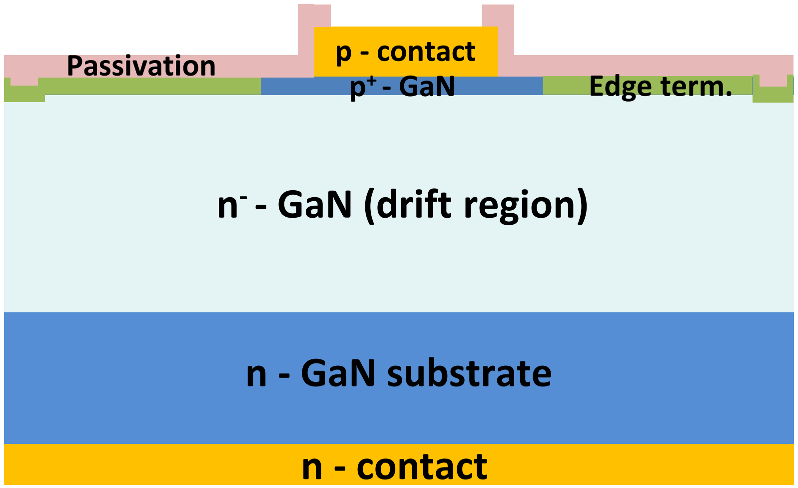
Ion implantation is used to create ET

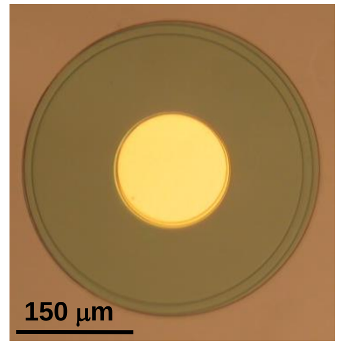


Effective edge termination is required to avoid premature lateral breakdown

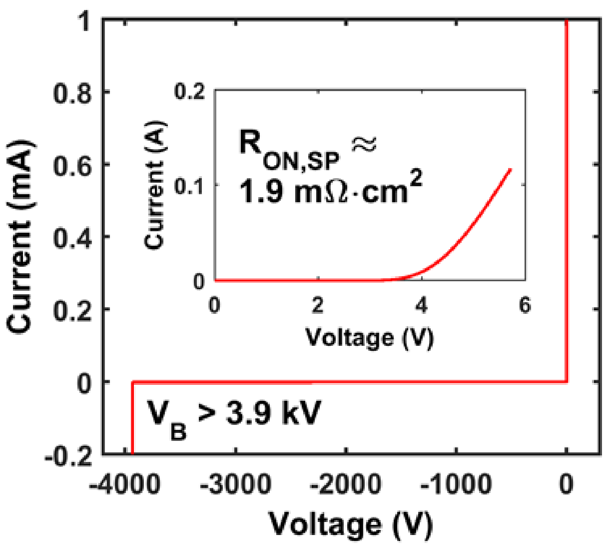
J. Dickerson, M. King

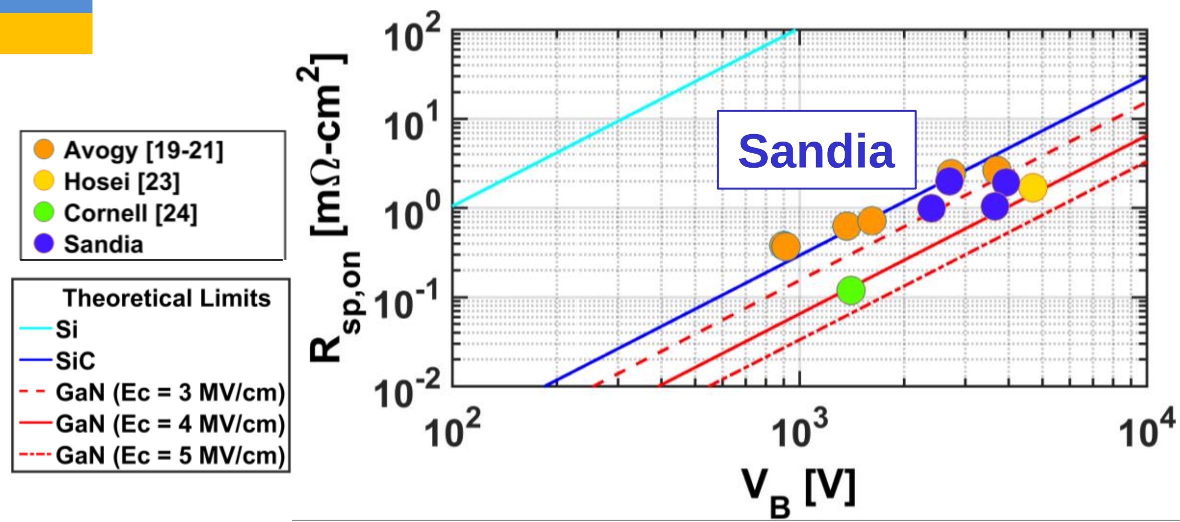
World-Record Sandia-Fabricated GaN PiN Diode Results





- Grown by MOCVD on bulk GaN substrates
- Drift region doping mid-10^{15} cm^{-3}

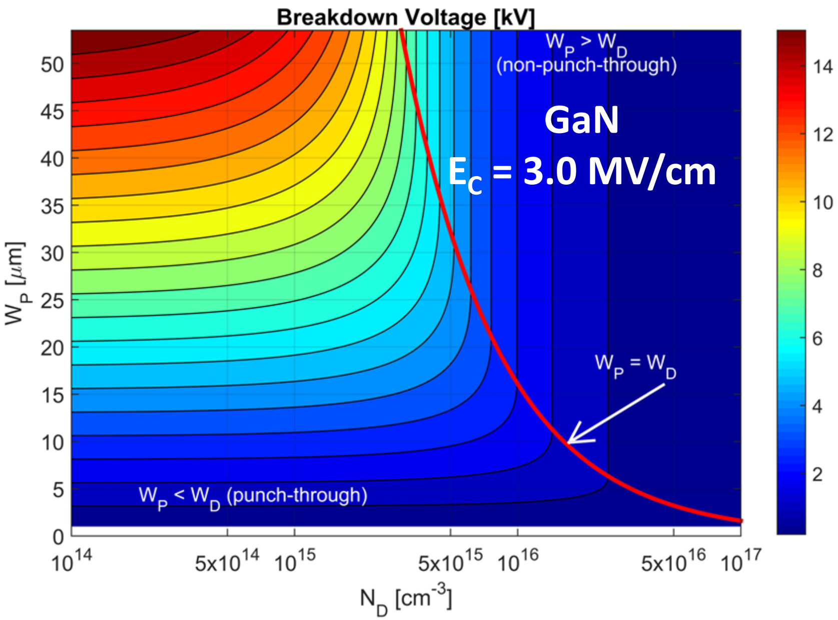


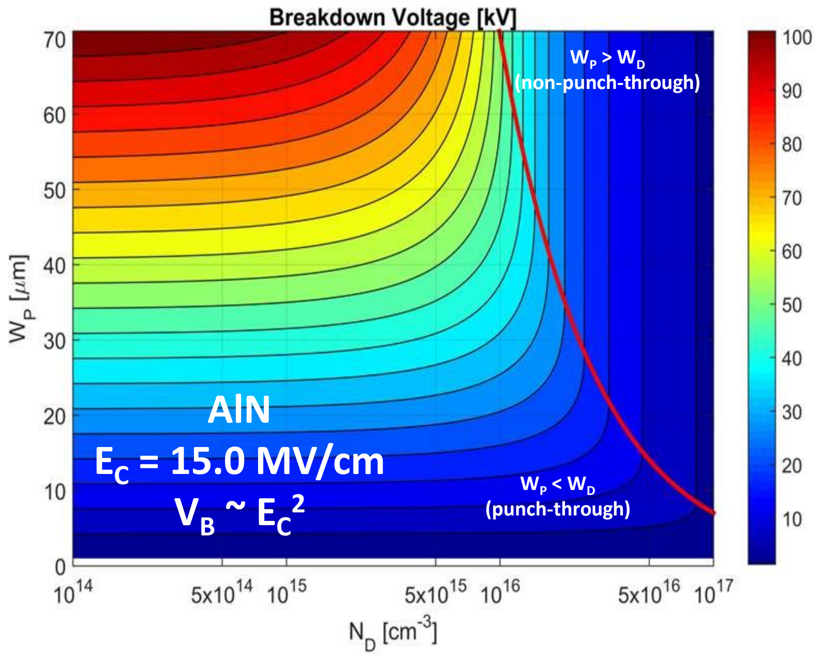


Recently demonstrated world-record $V_B^2/R_{on,sp}$

A. Allerman, A. Armstrong, M. Crawford, A. Fischer, J. Dickerson, M. King, J. Wierer; submitted to electronics letters

GaN to AlGaN



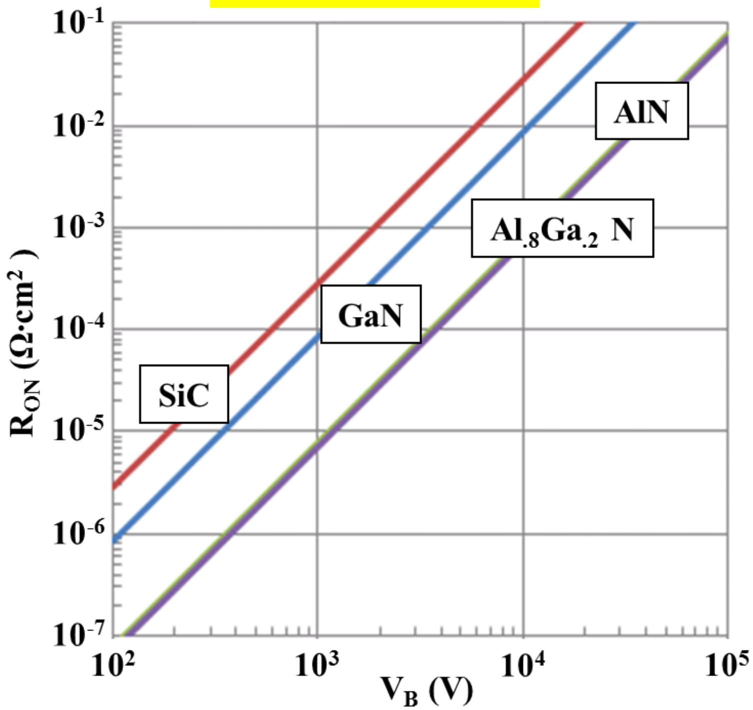


- **Start with 30% AlGaN**
  - **Si is a shallow dopant**
  - **Mg is a deep acceptor (~320 meV), but thermal ionization is still sufficient to achieve p-type conductivity**
- ***Working towards higher Al compositions***

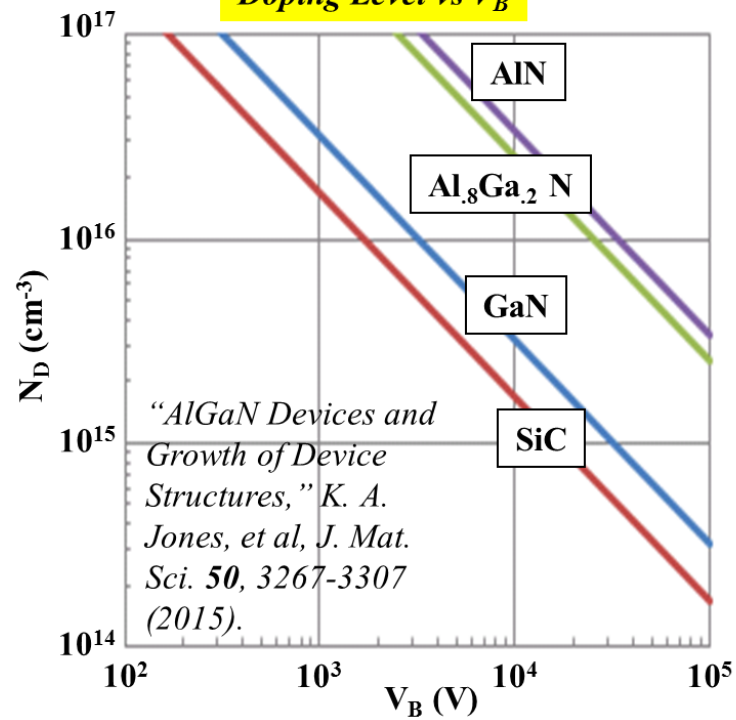
J. Dickerson

AlGaN Device Characteristics

On-Resistance vs V_B



Doping Level vs V_B



$$V_B = \frac{\varepsilon E_C^2}{2qN_D}$$

Parameter Values for $V_B = 10^4$ V

	SiC	GaN	$Al_{.8}Ga_{.2}N$	AlN
• R_{ON} ($m\Omega\cdot cm^2$)	28.9	8.69	.803	.705
• $n_D \times 10^{16}$ (cm^{-3})	.173	.329	2.54	3.37
• RFOM	582	1933	22,000	23,850

Figures courtesy of Dr. Ken Jones, Army Research Lab

Problem: No Lattice-Matched Conducting Substrate!

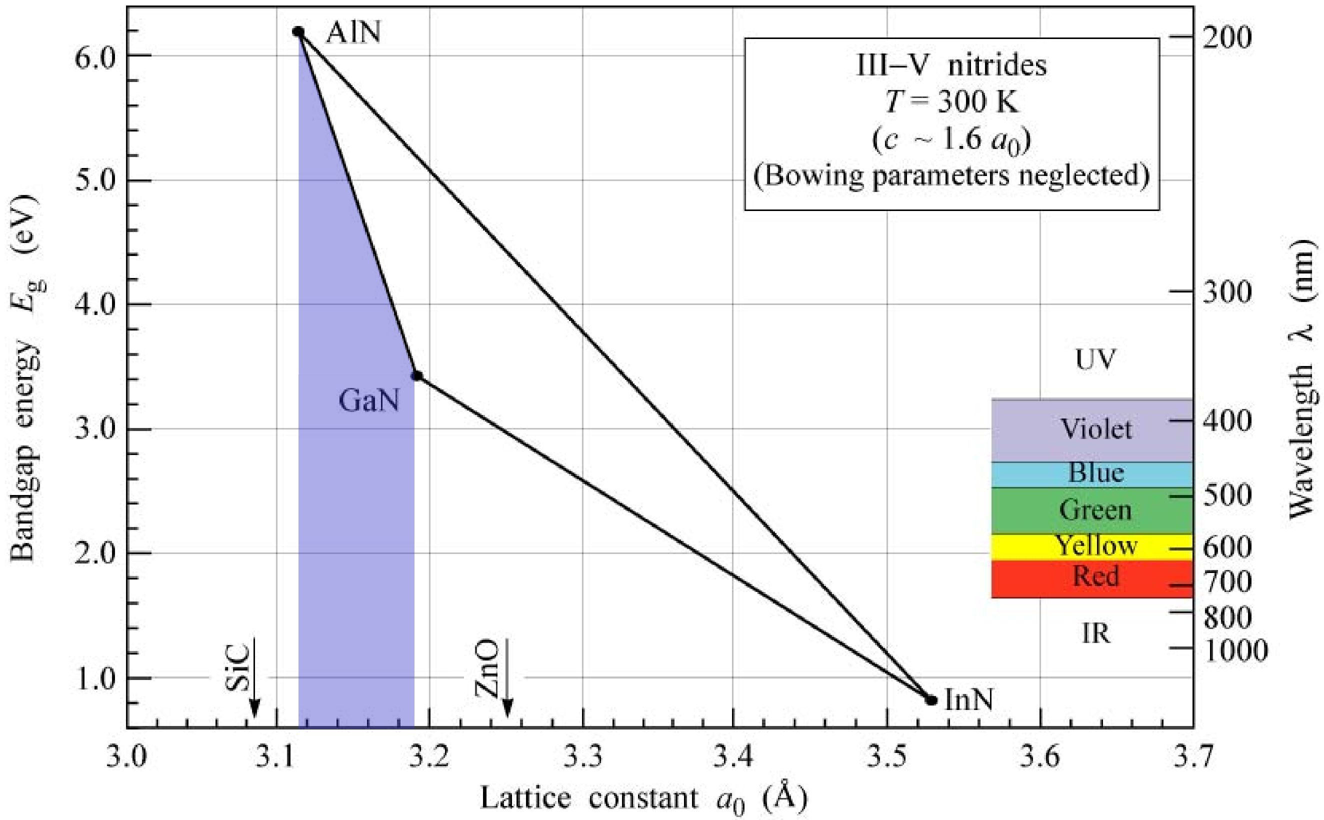


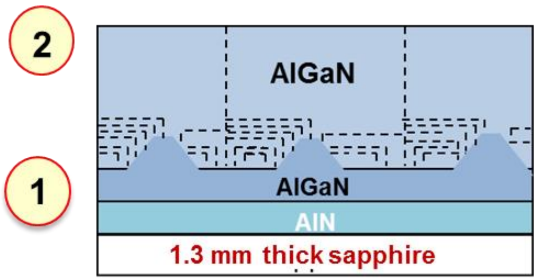
Fig. 12.12. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Substrates: AlGaN Overgrowth of Patterned Templates on Thick Sapphire

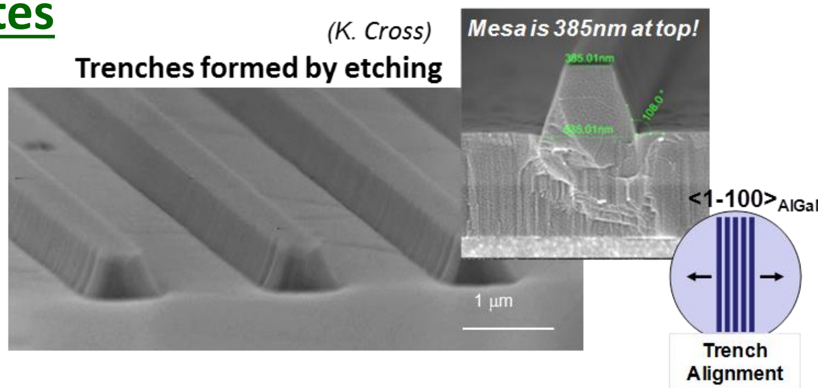
AlGaN Growth on Patterned Templates

AlGaN with reduced dislocations



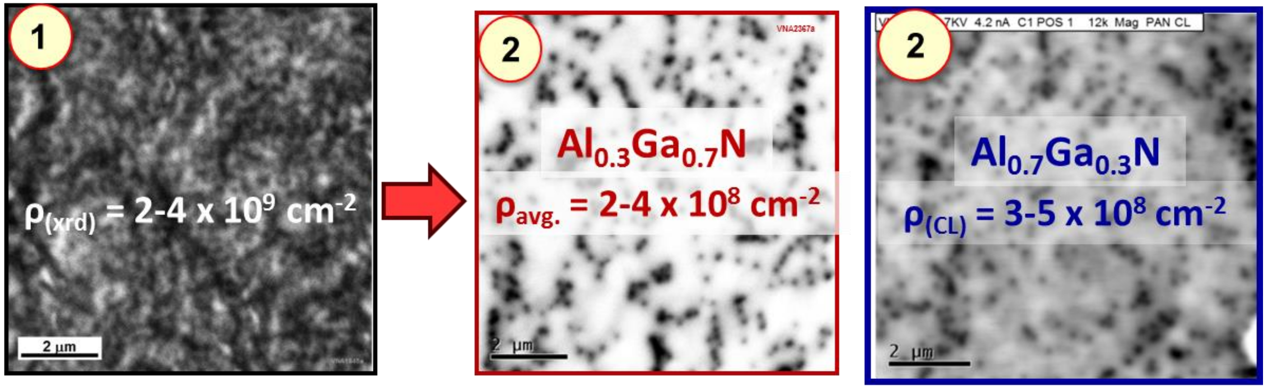
(K. Cross)

Trenches formed by etching



➡ *Sub-micron features are key innovation for uniform reduction of dislocations*

Cathodoluminescence *(L. Alessi)*



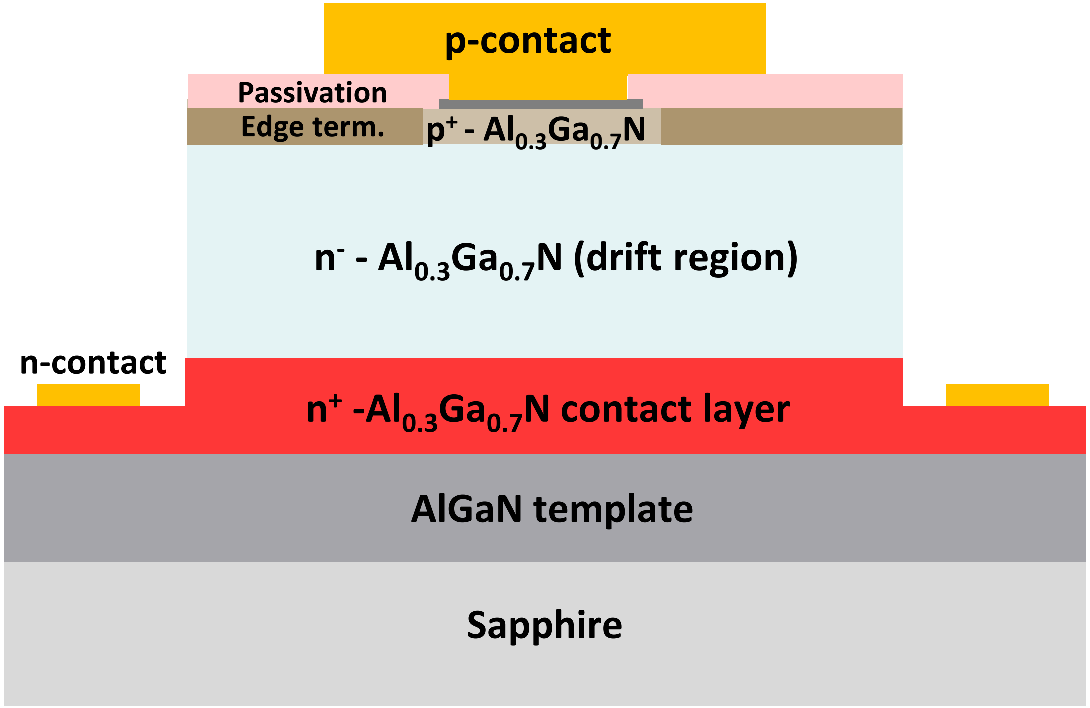
A. Allerman et. al., JCG 2014

10-20x reduction

10-15x reduction

➡ *Method reduces TTD over entire range of AlGaN compositions!*

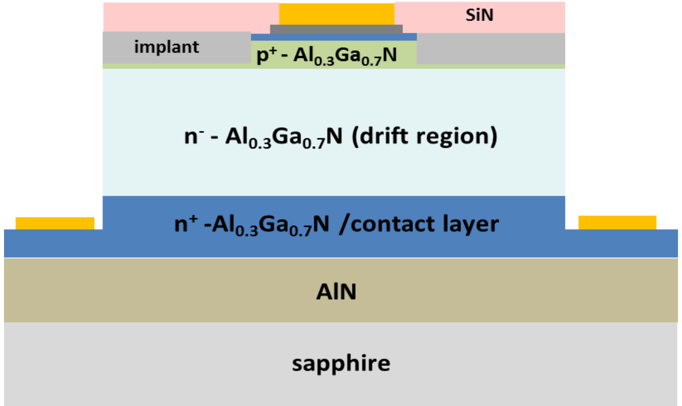
“Quasi-Vertical” $Al_{0.3}Ga_{0.7}N$ PiN Diode

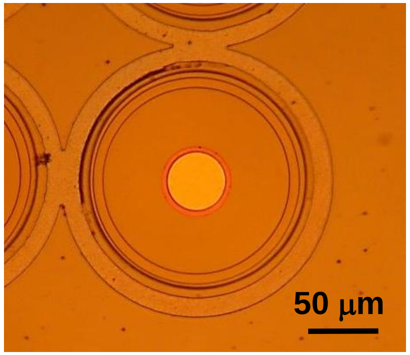


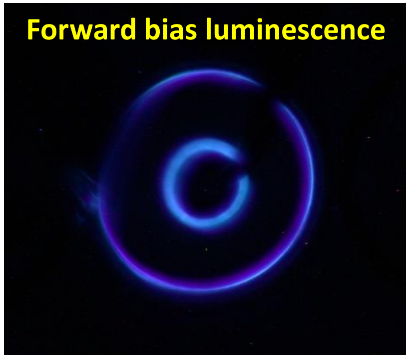
- n-contacts on the front surface of the wafer
- $Al_{0.3}Ga_{0.7}N$ grown by MOCVD on thick sapphire
- Threading dislocation density ~$1\text{-}2\times10^{9}$ cm^{-2}
- Drift region thickness ~4.3 μm
- Drift region doping ~10^{16} cm^{-3}
- Expect spreading resistance due to lateral carrier transport in the n^{+} contact layer

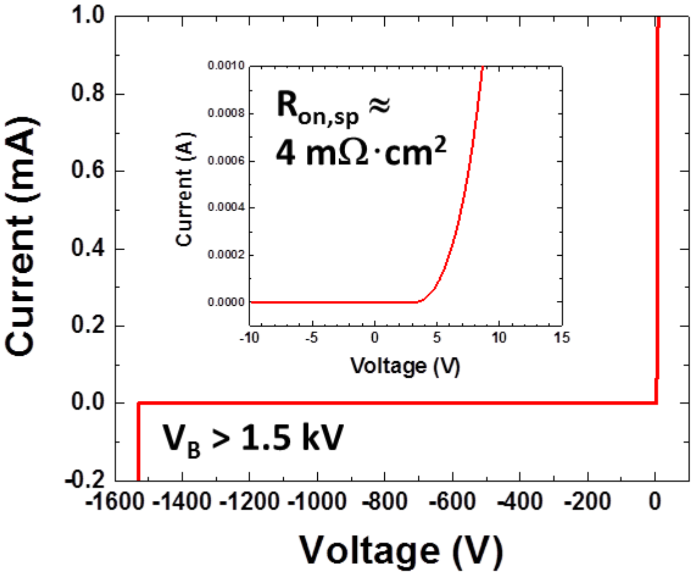
A. Fischer

World's First kV-Class AlGaN PiN Diode









- On resistance is high due to thin current spreading layer
- For $N_D \approx 1\times10^{16}$ cm^{-2}, $W_{Drift} \approx 4.3$ μm, and $V_B \approx$ 1520 V → *E_C > 4.0 MV/cm for $Al_{0.3}Ga_{0.7}N$*

➡ $Al_{0.3}Ga_{0.7}N$ with V_B ~1500 V is near or exceeds theoretical limit for GaN

A. Allerman, M. Crawford, A. Fischer, J. Dickerson, M. King

Target Metrics for 5 kV UWBG HEMT

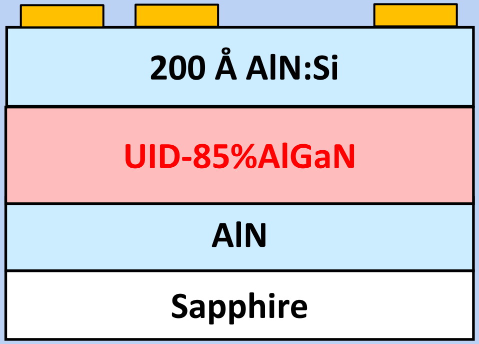
$$R_{on,sp} = \frac{1}{q\mu n_s}\left(L_{sd} + 2\sqrt{q\mu n_s \rho_c}\right)^2$$

$R_{sh} = 1/q\mu n_s$

$$V_B = E_{Bkdn} L_{gd}$$

$$V_{th} = \frac{\phi_B}{q} - \frac{\Delta E_c}{q} - \frac{n_s d}{\epsilon}$$

- $AlN/Al_{0.85}Ga_{0.15}N$ HEMT with L_{gd} = 12.5 μm, L_g = 1 μm, L_{sg} = 1 μm
- $R_{on,sp}$ = 5 mΩ·cm^2
  - μ = 250 cm^2/V·s
  - n_s = 10^{13} cm^{-2}
  - ρ_c = 10^{-5} Ω·cm^2
- V_B = 5000 V
  - $E_{Breakdown}$ = 4 MV/cm (effective value)
- V_T > +3 V
  - ϕ_B = 4 eV

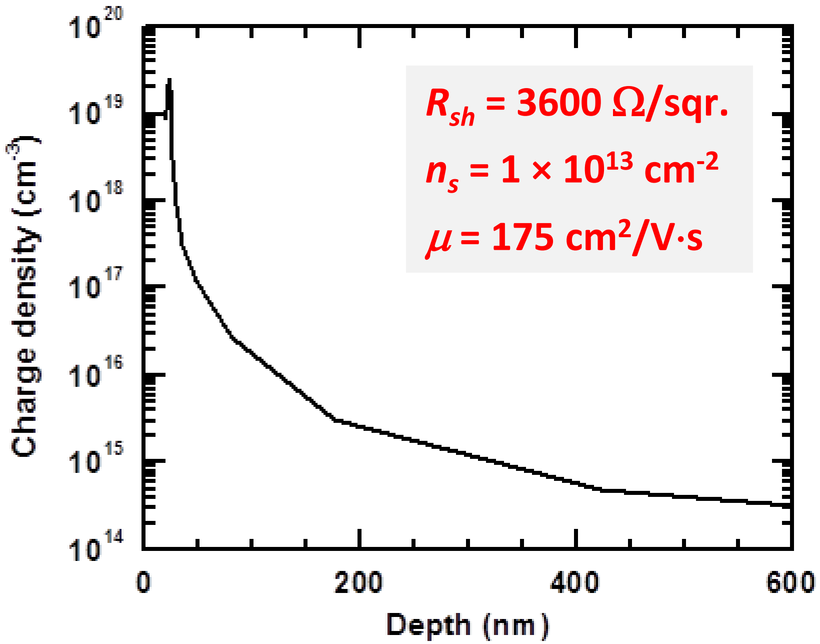


These targets surpass the performance of SiC

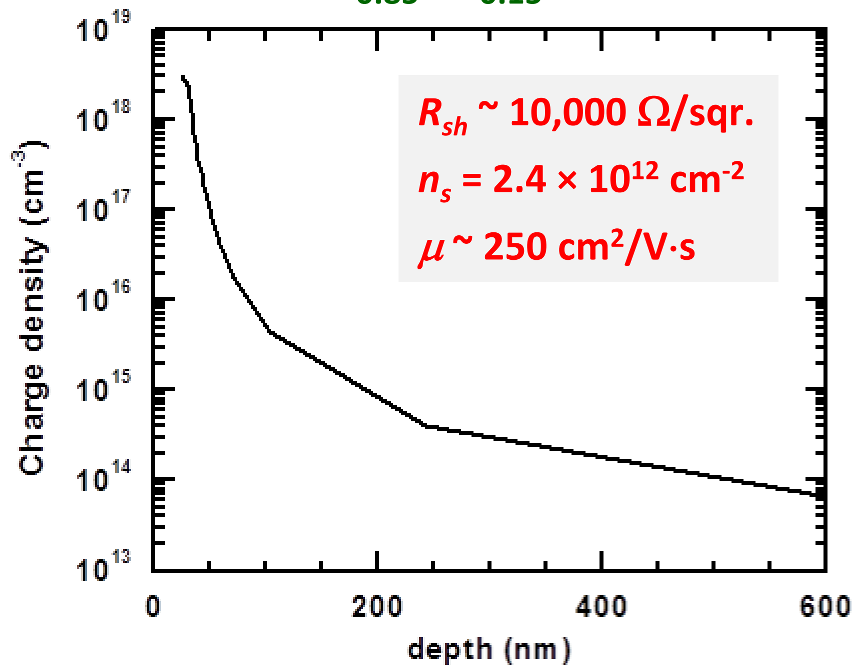
A. Armstrong

Progress Towards World's First HEMT with Channel Al Composition > 70%

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



$AlN/Al_{0.85}Ga_{0.15}N$ MODFET



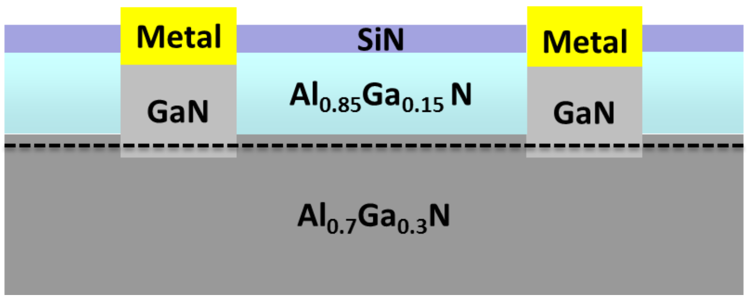
- To our knowledge, this is the first demonstration of a 2DEG in $Al_yGa_{1-y}N/Al_xGa_{1-x}N$ heterostructure for $y > x > 0.7$

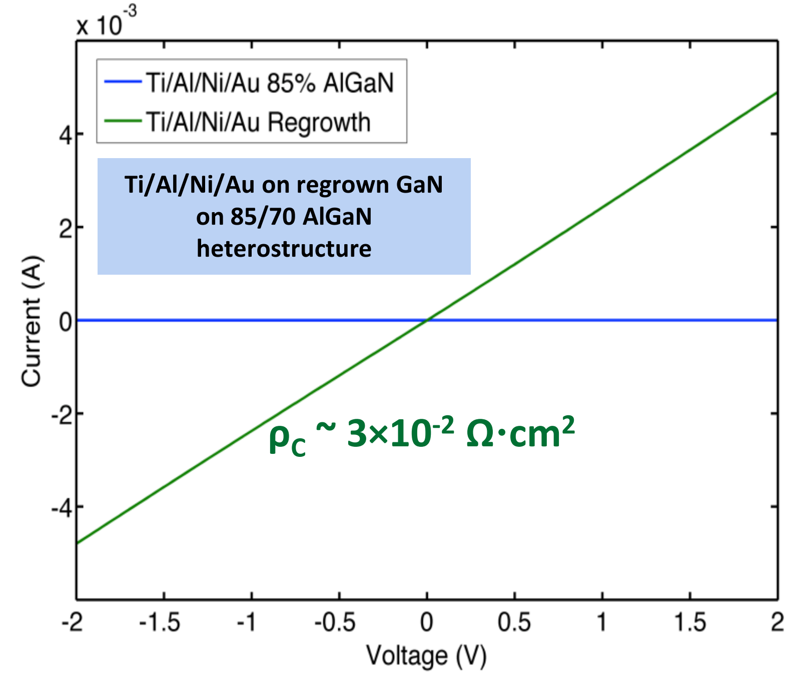
A. Allerman, A. Armstrong

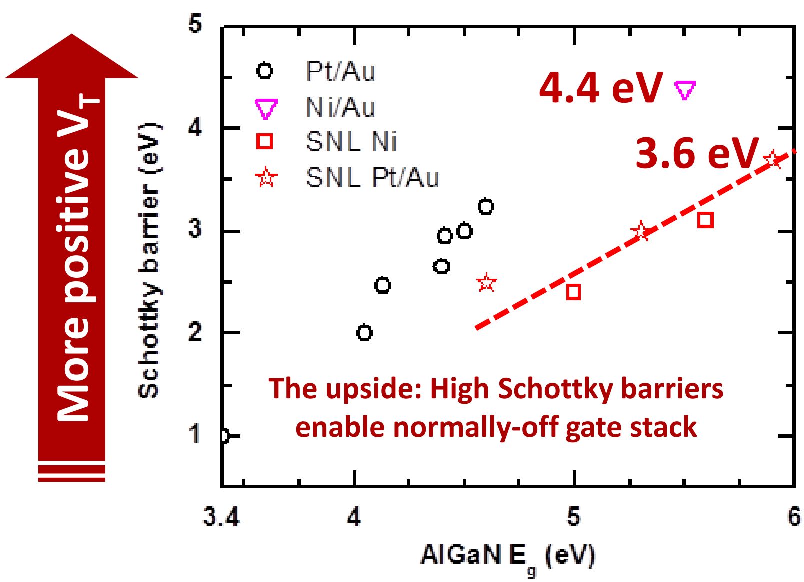
Ohmic and Schottky Contacts

Challenge: Ohmic contacts

Focus on re-grown contacts







Using re-grown contacts, a working AlN/$Al_{0.85}Ga_{0.15}N$ HEMT has been demonstrated!

E. Douglas, C. Sanchez, A. Baca, A. Allerman, D. Koleske, A. Armstrong

Summary

- UWBG materials such as AlGaN have potential to push the state-of-the-art in power electronics for specialized DoD applications
- Demonstrated world-record GaN PiN diodes ($V_B^2/R_{on,sp}$ ~ 18 GW/cm^2)
- Demonstrated $Al_{0.30}Ga_{0.70}N$ PiN diodes with V_B ~ 1.5 kV
- First demonstration of 2DEG in $Al_yGa_{1-y}N/Al_xGa_{1-x}N$ heterostructure for $y > x > 0.7$
- Successful demonstration of working $AlN/Al_{0.85}Ga_{0.15}N$ HEMT

The contributions of the entire Sandia Ultra-Wide-Bandgap Grand Challenge team and the support of Sandia's LDRD program are gratefully acknowledged