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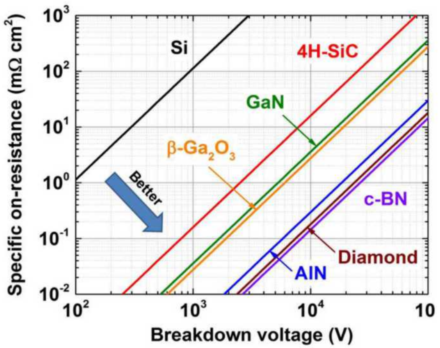
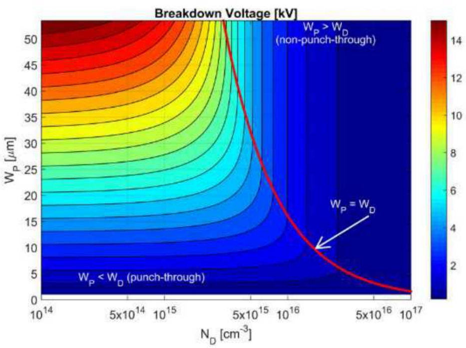
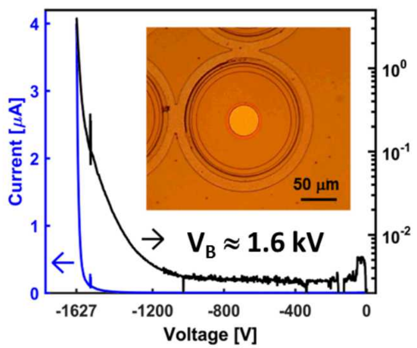
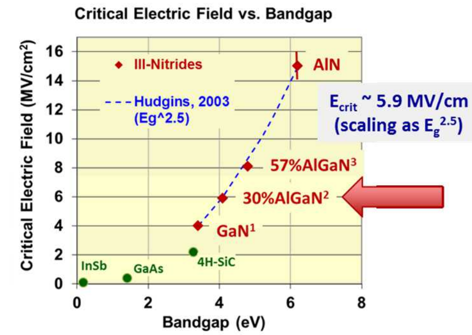
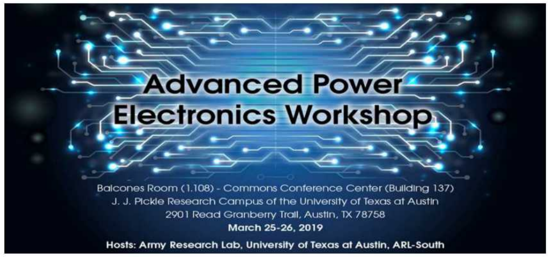








Ultra-Wide-Bandgap Semiconductors for High-Power Electronics: Current Status and Future Opportunities



ARL Advanced Power Electronics Workshop
UT-Austin, March 25, 2019
Robert Kaplar, Sandia National Labs

UWBG Working Group: Mark Hollis (MIT-LL), Noble Johnson (PARC), Ken Jones (ARL)

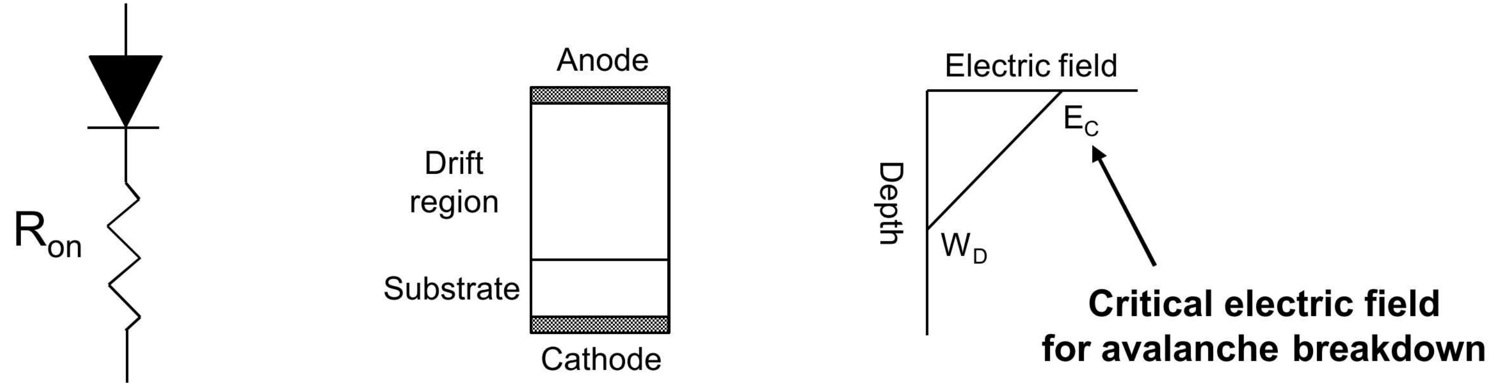
Sandia National Labs: Jerry Simmons, Jeff Tsao, Andy Allerman, Andy Armstrong, Mary Crawford, Greg Pickrell, Jeramy Dickerson, Jack Flicker, Jason Neely, Elizabeth Paisley, Albert Baca, Brianna Klein, Erica Douglas

Supported by the Laboratory Directed Research and Development at Sandia National Laboratories, a multimission 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.

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**

Critical Electric Field and Unipolar Figure-of-Merit



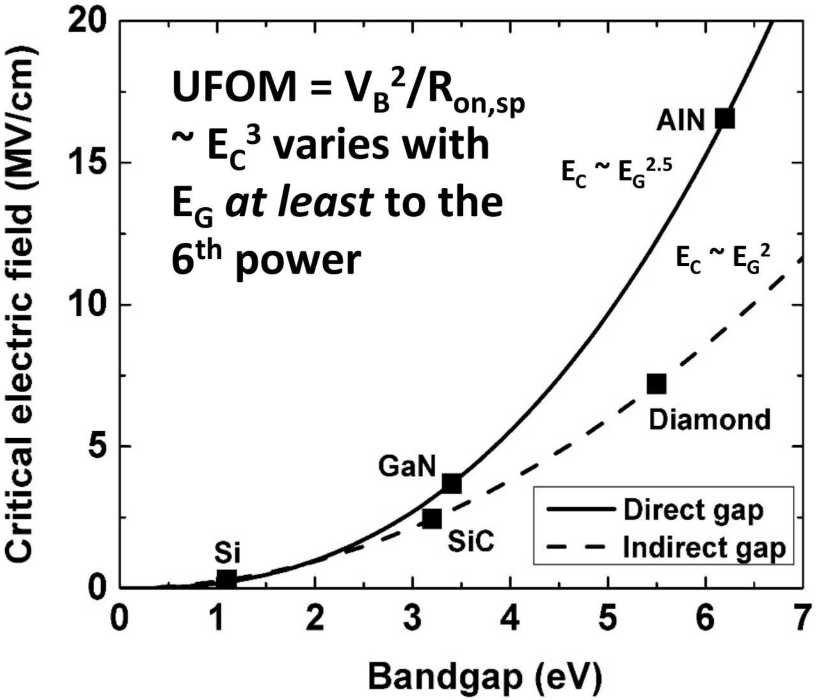
- Off-state: Integrate electric field to get breakdown voltage: $\mathbf{V_B = W_D E_C/2}$ (1)
- Gauss' law: $\boldsymbol{\varepsilon E_C = qN_D W_D}$ (2)
- On-state: Current transport due to carrier drift, resistance $R_{on} = W_D/\sigma A$
  Conductivity $\sigma = q\mu_n n = q\mu_n N_D$ *assuming complete dopant ionization*
  Specific on-resistance $R_{on,sp} = R_{on}A = W_D/\sigma \rightarrow$ $\mathbf{R_{on}A = W_D/\ q\mu_n N_D}$ (3)

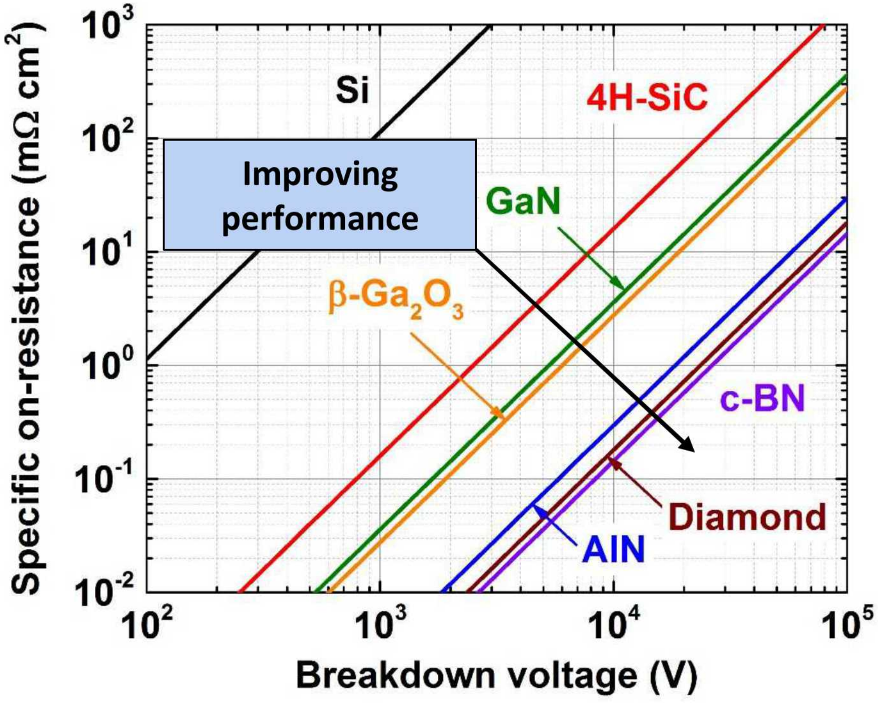
- Combining (1) and (2) gives dependence of V_B on N_D and E_C: $\mathbf{V_B = \varepsilon E_C^2/2qN_D}$

- Combining (1), (2), and (3) one obtains the **unipolar "figure-of-merit"**:
  $R_{on,sp} = 4V_B^2/\varepsilon\mu_n E_C^3 \rightarrow$ $\mathbf{V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4}$

Assumptions: Triangular electric field profile and complete dopant ionization

Critical Electric Field Scales with Bandgap and Determines Unipolar FOM





Dependence of E_C on E_G needs further study

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

Hudgins et al., *IEEE Trans. Pwr. Elec.* 18, 907 (2003); J. Y. Tsao et al., *Adv. Elec. Mat. Adv. Elec. Mat.* 4, 1600501 (2018)

UWBG Working Group Parameter Refresh

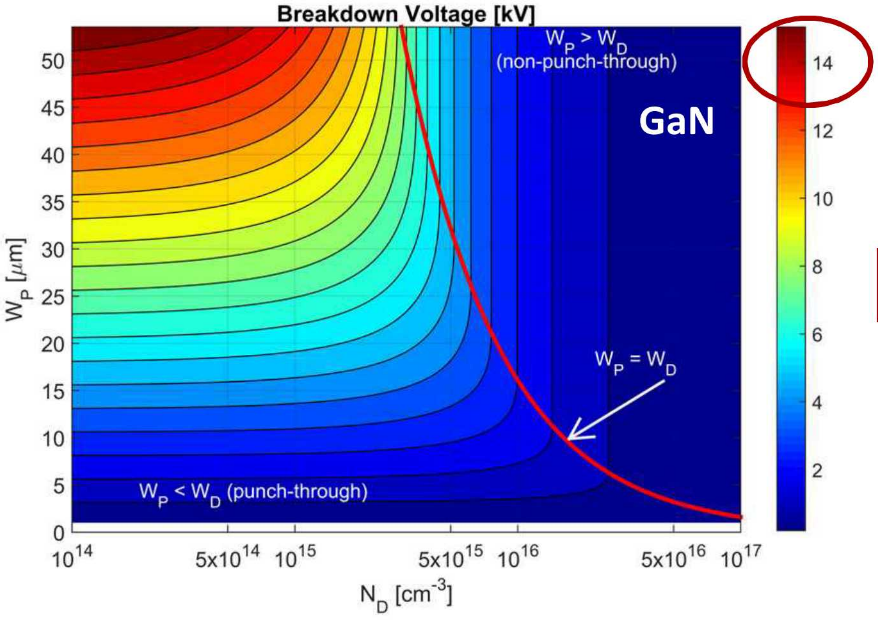
Material-Properties Table for Electronic Applications

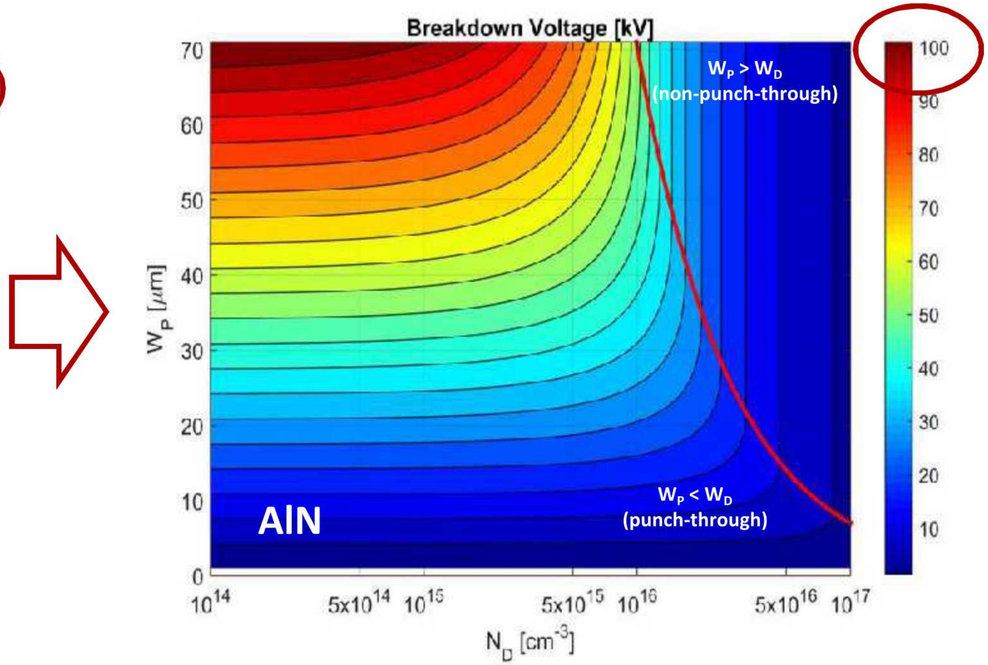
Parameter at 27°C	GaN (for reference)	$Al_xGa_{1-x}N$	AlN	Example AlN/GaN HEMT [1]	β-Ga_2O_3	Cubic BN	Diamond	Diamond MOS
Bandgap (eV)	3.4 [3]	Interpolation [37]	6.0 [4]	multiple	4.9 [5]	6.4 [6]	5.5 [7]	multiple
Proj. bulk E_C (MV/cm at doping = 10^{16} cm^{-3})	4.95 [8] (measured baseline)	Varies non-uniformly 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	$1.2x10^{13}$	$1.5x10^{13}$ / TBD 2012 [38] / --	Various (see Doping below)	Various (see Doping below)	$4x10^{13}$ / $1.7x10^{14}$ 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 $2x10^{17}$ – $6x10^{19}$ 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
- Results reported in J. Y. Tsao et al., *Adv. Elec. Mat.* 4, 1600501 (2018)

Next UWBG workshop coming up May 14-16 at ARL in Adelphi, MD

Impact of Critical Electric Field on Breakdown Voltage

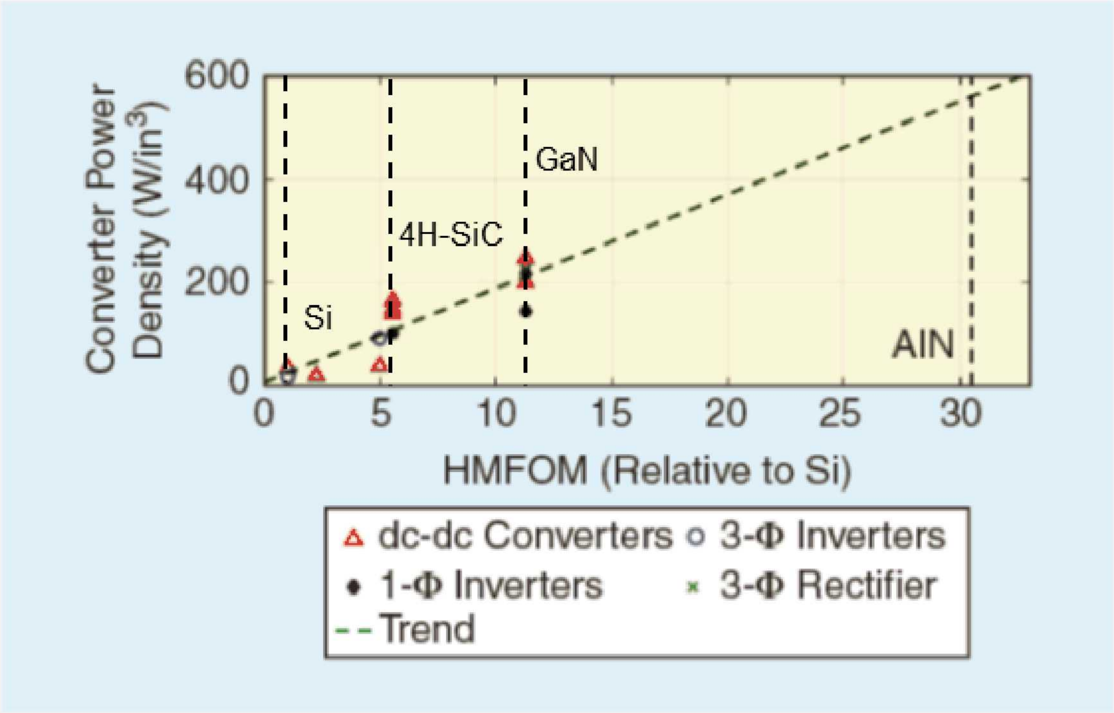


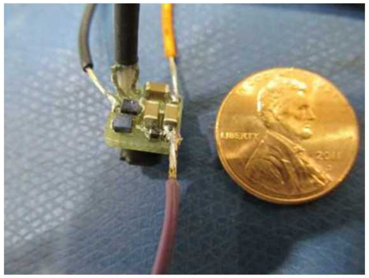


- Increasing E_C may significantly increase V_B
  - 100 kV device may be possible using materials like AlN
  - But low doping and thick drift layers are also required

J. Dickerson, SNL

Power Density Scaling with Semiconductor Material Properties





SNL "Coin Converter"
90 V, 90 mA → 215 W/in^3

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)*

UWBG Working Group Study: Twenty-Six Research Opportunities Identified for Technology Maturation

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
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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.

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DOI: 10.1002/aelm.201600501

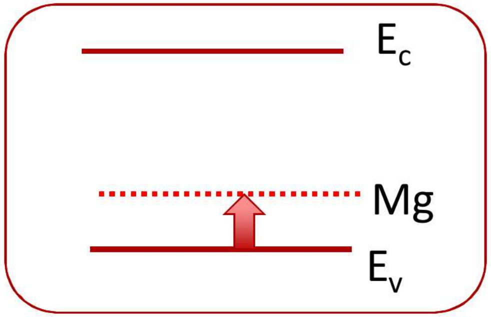
Adv. Electron. Mater. **2017**, 1600501 1600501 (1 of 49)

Combined topics in report; 26 research challenges identified

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

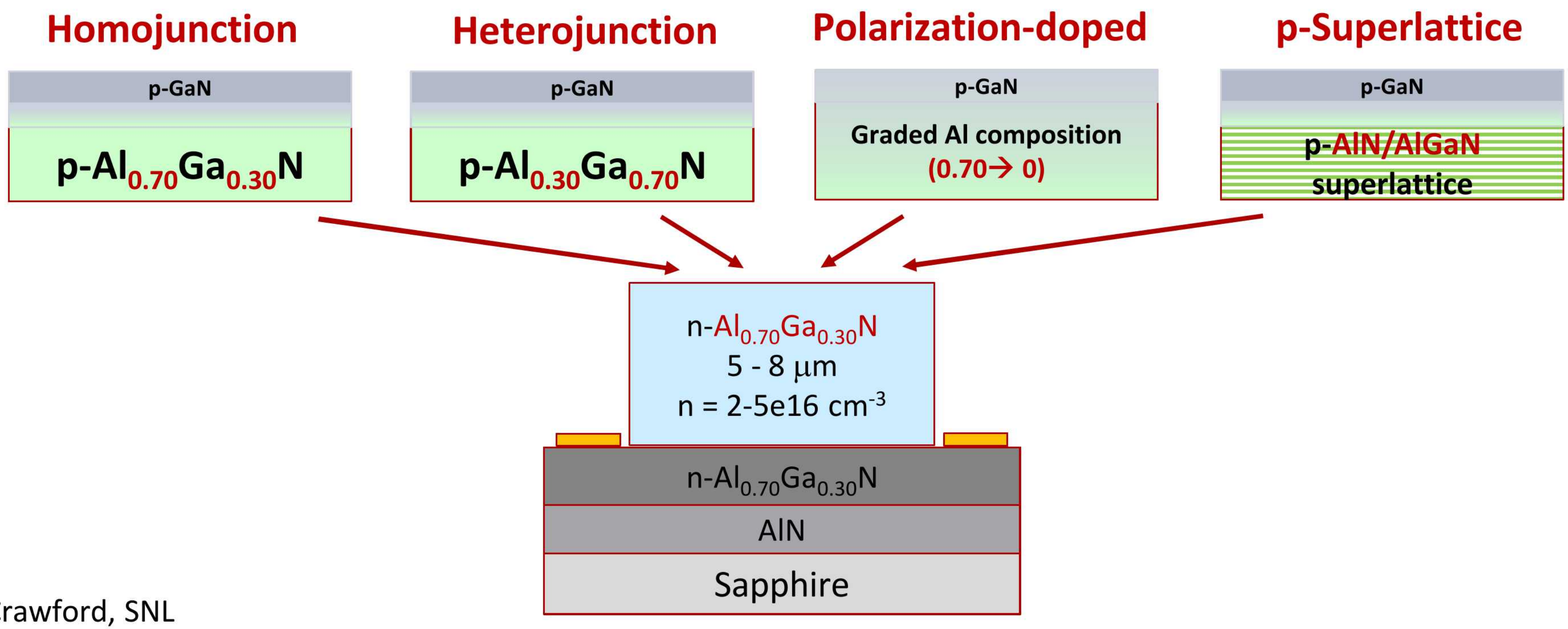
Doping Challenges in UWBG Materials

p-type doping very challenging with increasing Al:
E_a (GaN) ~180 meV
E_a (AlN) ~ 500 meV



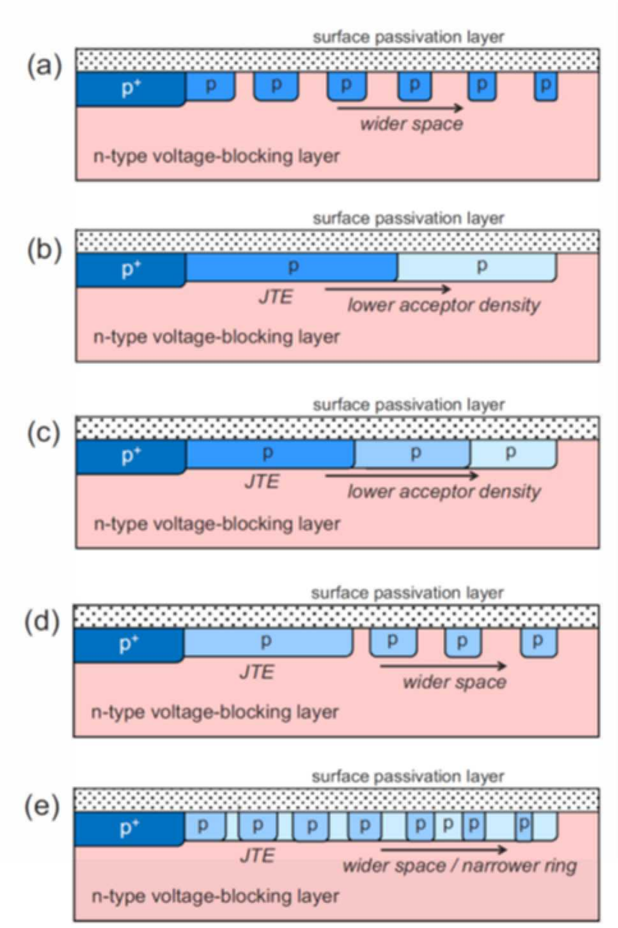
kT ~ 0.026 eV

Thermal activation of holes not viable for high-Al alloys



M. Crawford, SNL

Edge Termination for High Breakdown Voltage

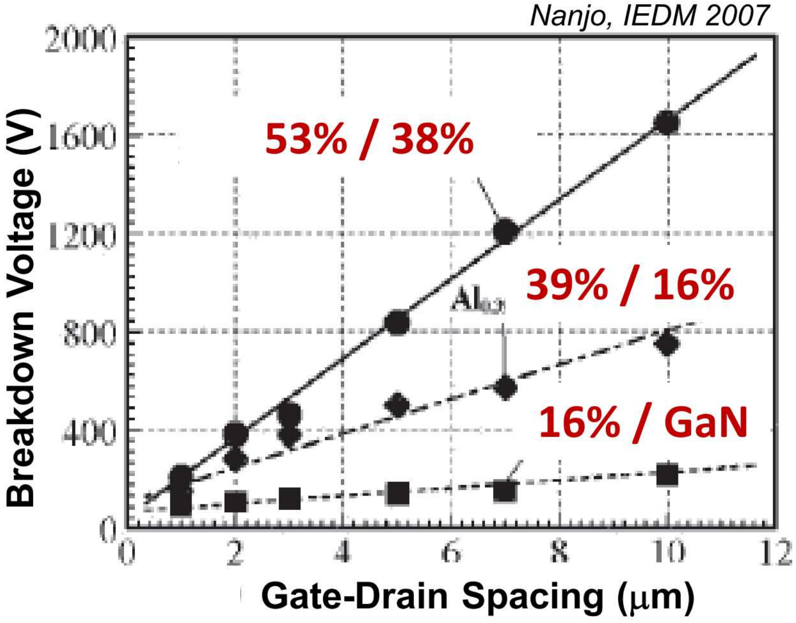


- Edge termination is critical to prevent premature breakdown
  - Breakdown will be well below value predicted by 1D model if no edge termination is not used
  - Due to electric field enhancement at corners, surfaces, etc.
- Variety of edge termination schemes are possible
  - Guard rings, junction termination extension (JTE), field plates, beveling
  - Well-developed for Si and SiC technologies
  - Processing is challenging in UWBG materials

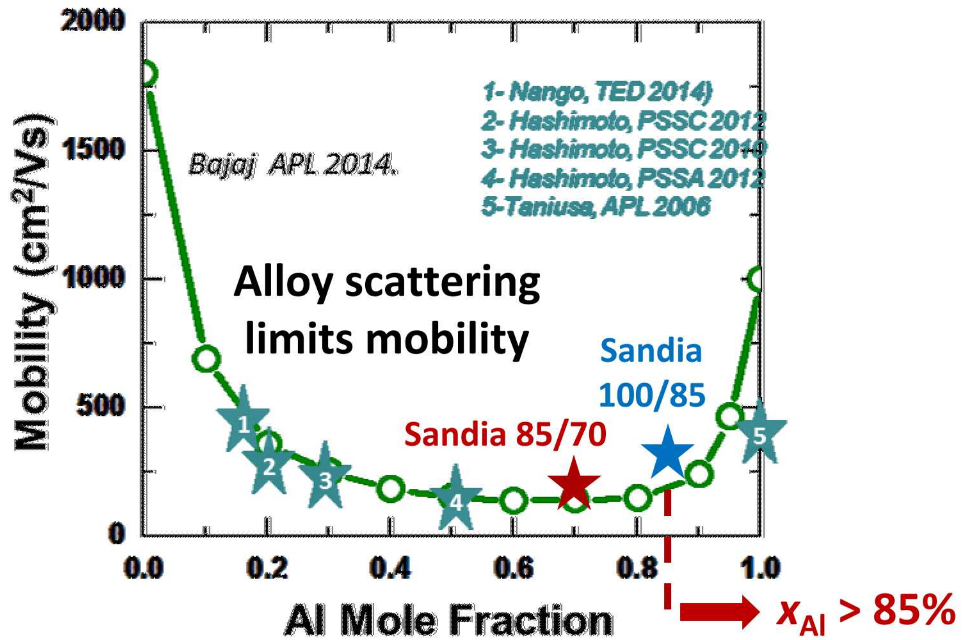
T. Kimoto and Y. Yonezawa, *Mat. Sci. in Semicon. Proc.* 78, 43 (2018)

Tradeoffs Between Higher Critical Field and Reduced Mobility for Alloys

Breakdown voltage of AlGaN HEMTs vs. G-D spacing



Electron mobility vs. AlGaN channel composition



Higher Al compositions:

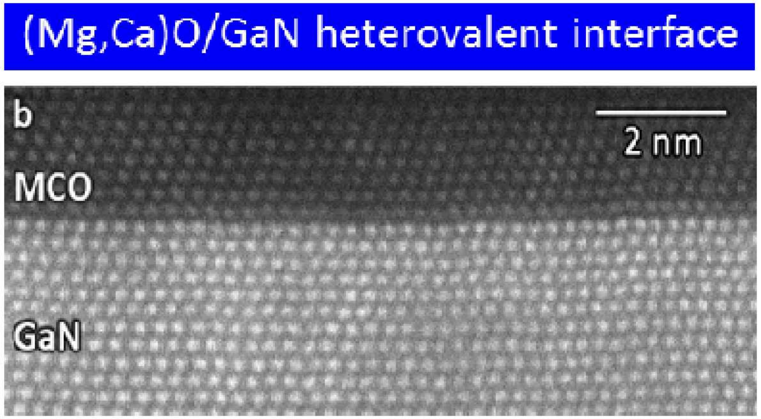
➡ ***Higher breakdown voltages***

Highest Al compositions:

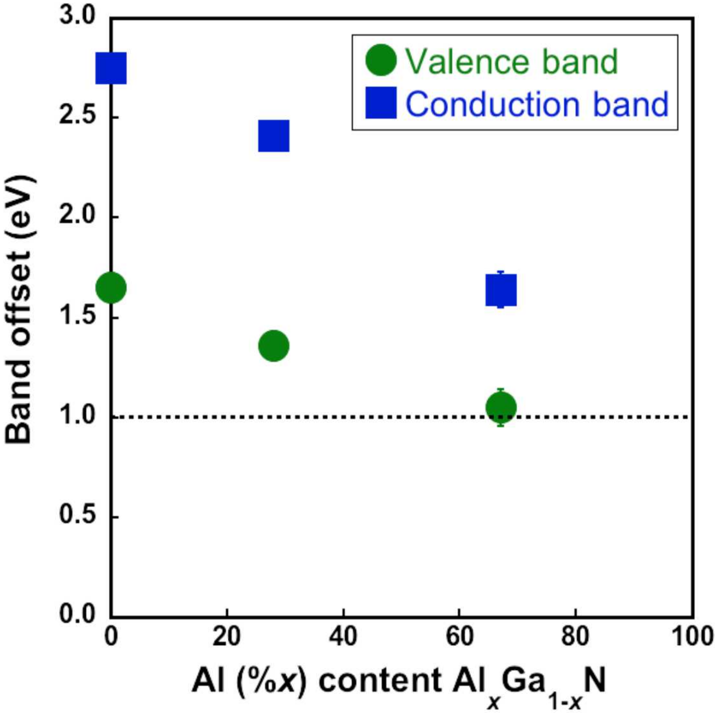
➡ ***Higher mobility is predicted***

Thermal conductivity has similar issue

Gate Dielectrics for UWBG Materials



Band Offsets

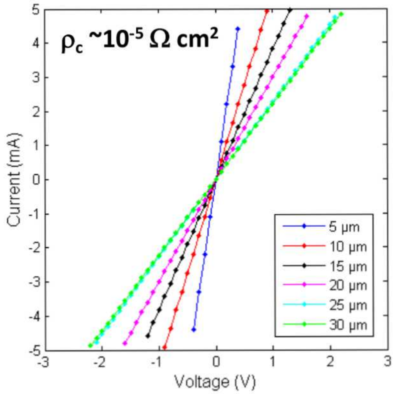


Difficult to find gate dielectrics on UWBG materials that have:

- **Sufficient band offsets**
- **Low interfacial defect density**

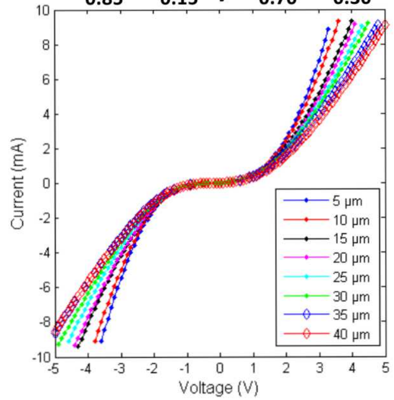
E. A. Paisley et al., Appl. Phys. Lett. 107, 102101 (2015)

Ohmic Contact Development

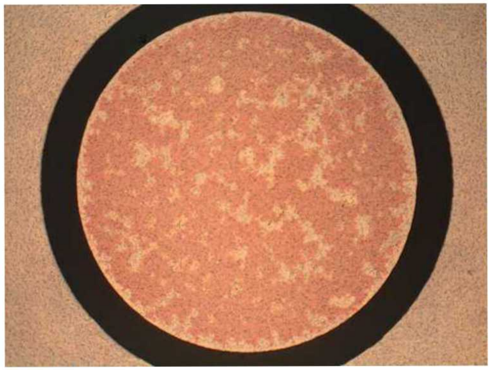


50 nm $Al_{0.45}Ga_{0.55}N$
4.15 mm $Al_{0.3}Ga_{0.7}N$
1.6 mm AlN
Sapphire Substrate

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

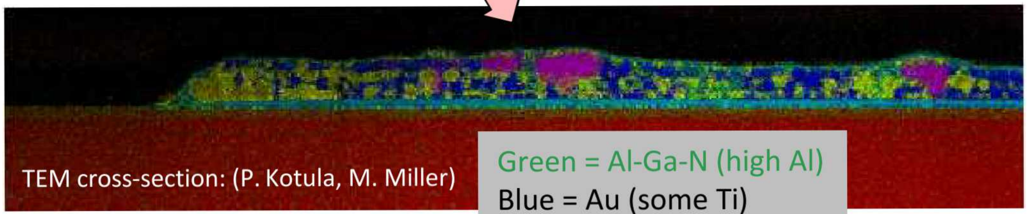


25 nm $Al_{0.85}Ga_{0.15}N$
400 nm $Al_{0.7}Ga_{0.3}N$
Graded Layer 50 nm
2.9 mm AlN
Sapphire Substrate



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

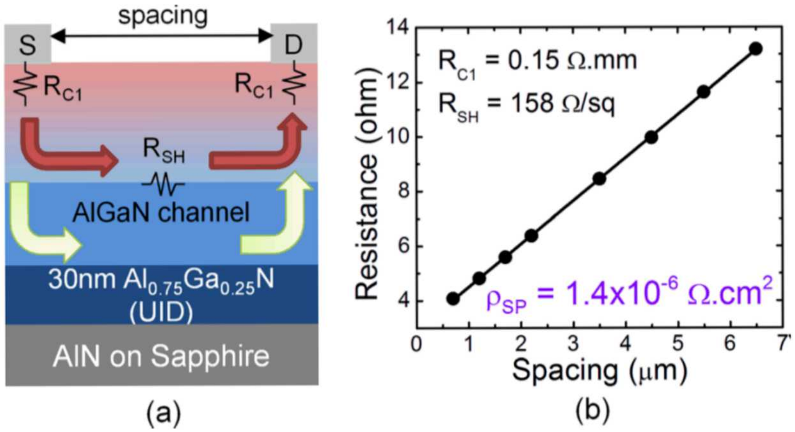
900°C anneal



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)

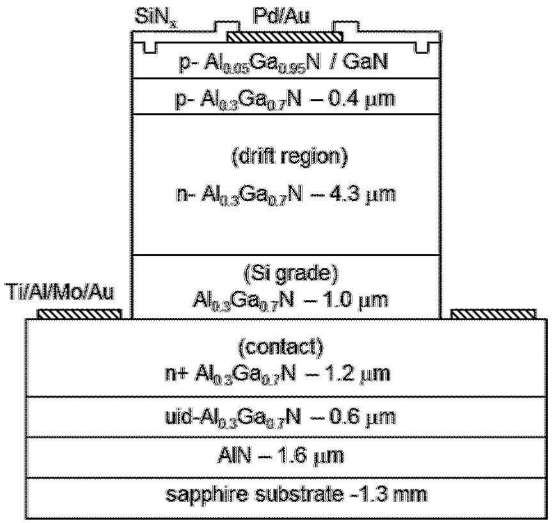
Graded heterostructure approach



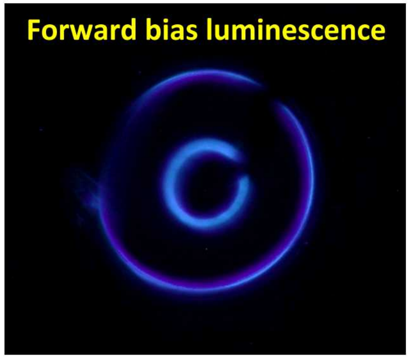
S. Bajaj et al., Appl. Phys. Lett. 133508 (2016)

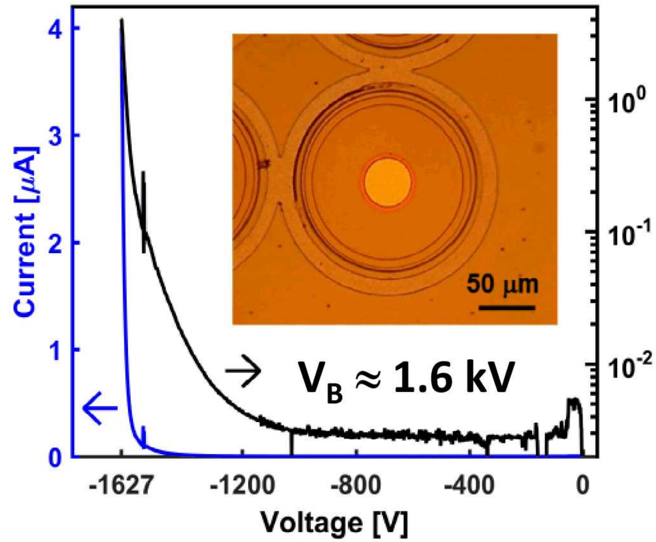
B. Klein, SNL

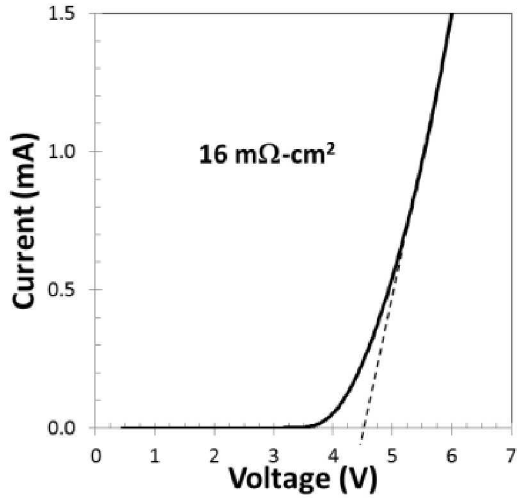
Example UWBG Device: Vertical $Al_{0.3}Ga_{0.7}N$ PiN Diode



- Drift region doping mid-10^{16} cm^{-3} n-type
- Record $V_B^2/R_{on,sp}$ = 150 MW/cm^2 for AlGaN
- Drift region thickness = 4.3 µm
- Current density up to 3.5 kA/cm^2 measured



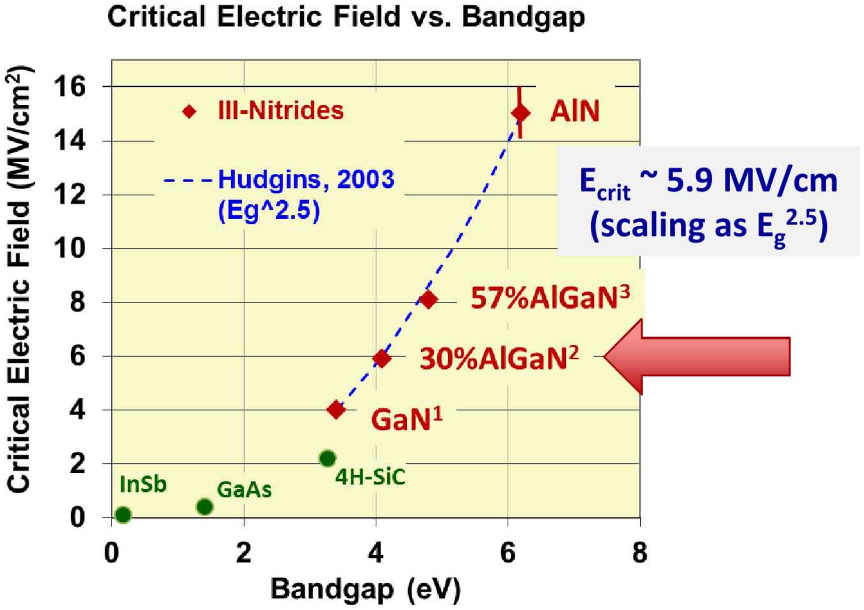




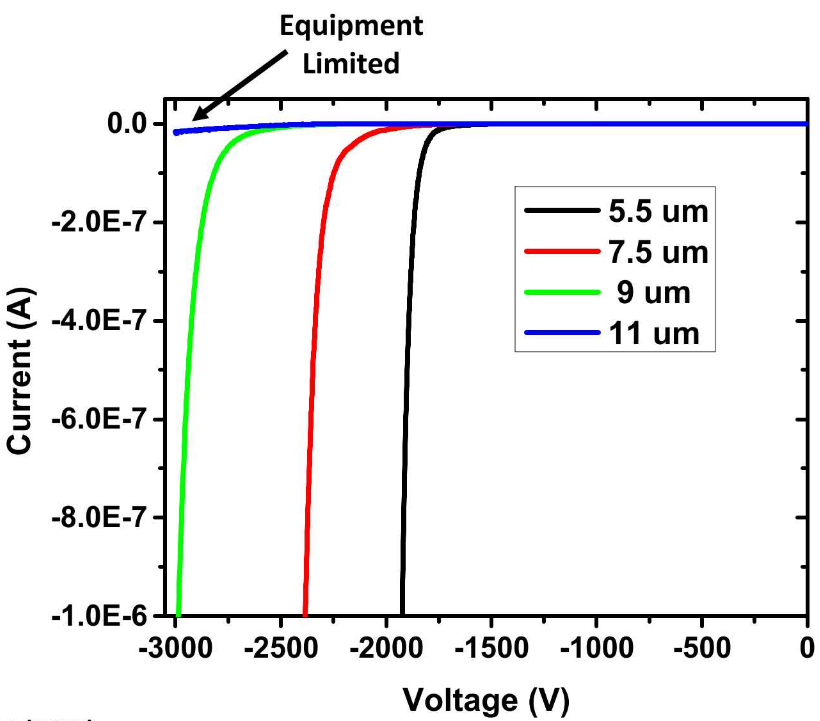
On-resistance likely limited by quasi-vertical design

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

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

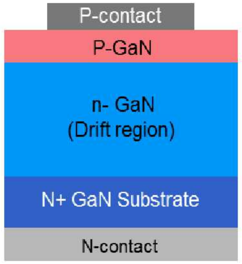


Devices grown using thicker drift regions show higher breakdown voltage

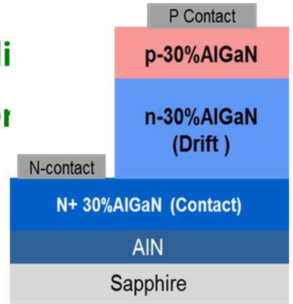
1 – Armstrong EL 2016; 2 – Allerman EL 2016; 3 – Nishikawa et al. JJAP 46 (4B), 2316 (2007)

Comparison of Breakdown Voltages Reported for III-N PiN Diodes

GaN diode (Vertical)



AlGaN di (Quasi-ver



Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7 / 5.0	2-16e15	33	GaN	Hosei Univ.	EDL 36 p1180 (2015) / Jpn J Appl. P. 57 (2018)
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)

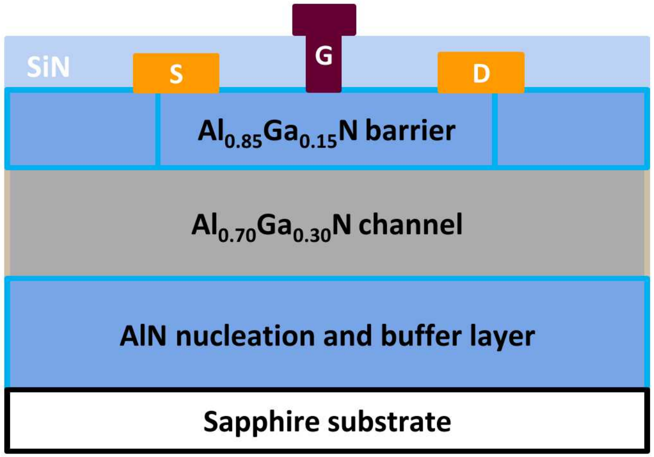
Advantages of Ultra-Wide-Bandgap AlGaN

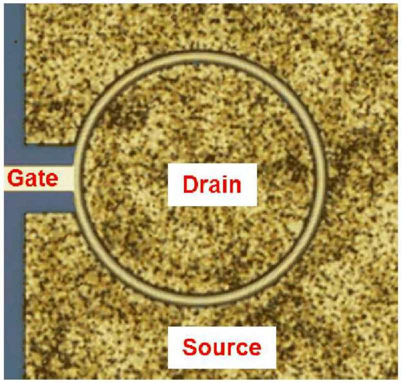
	GaN	$Al_{0.3}Ga_{0.7}N$	
N_o (cm^{-3})	low 10^{15}	low 10^{16}	⇐ Larger E_C & E_G
Drift (μm)	20-30	~10	
TDD (cm^{-2})	≤ 10^6	low 10^9	⇐ Impact?

A. Allerman, SNL

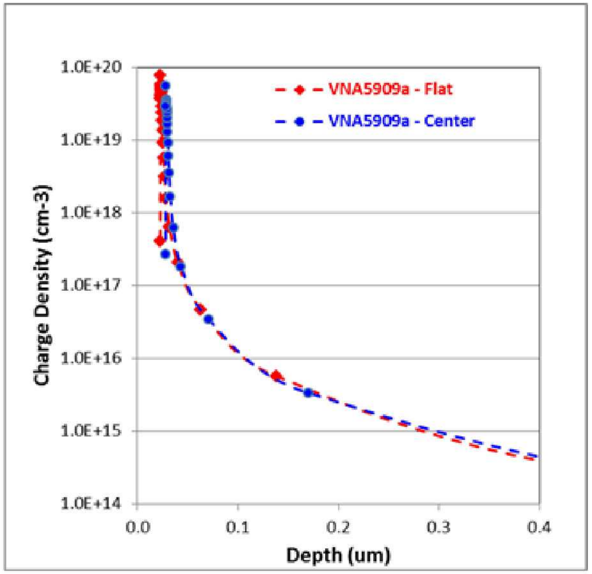
U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

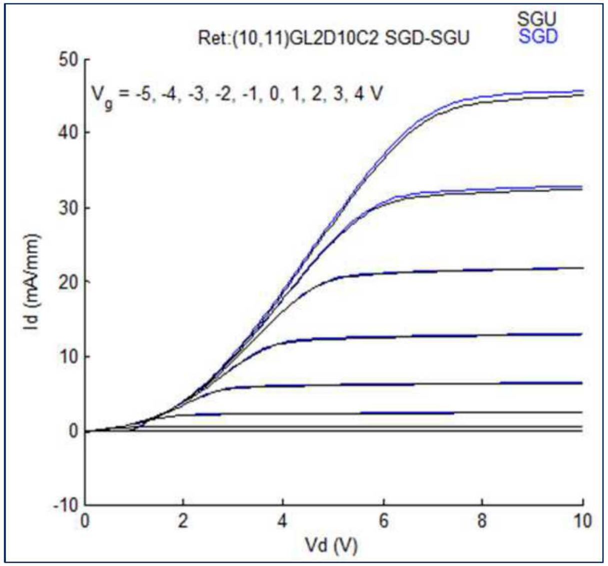
Al-Rich Heterostructure-Based Transistors





Electrical Characteristics

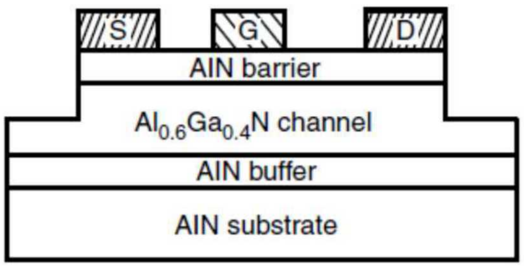


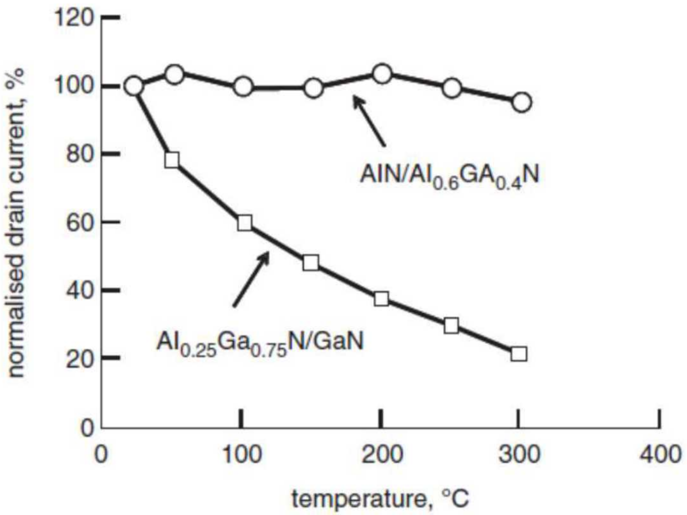


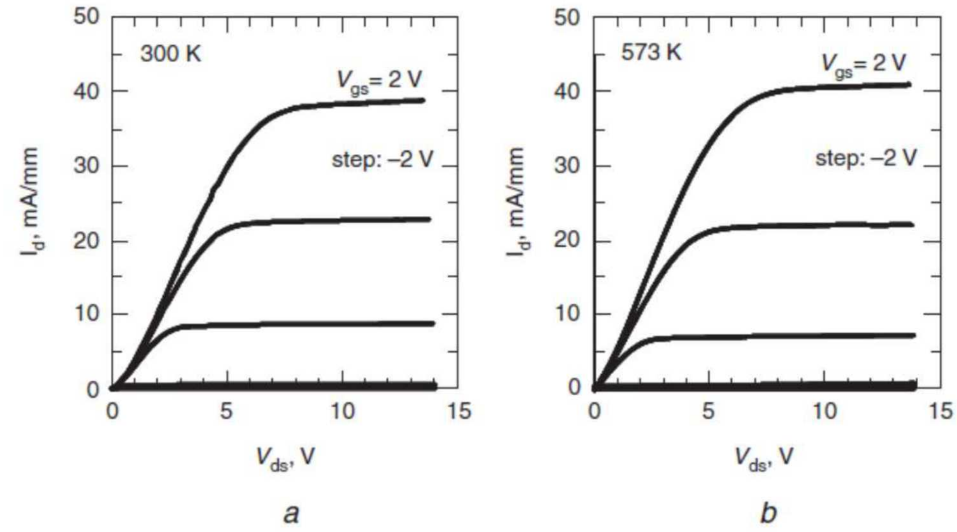
- Sheet resistance: 2200 Ω/□
- Pinch-off voltage: -4.5 V
- Sheet charge density: 6×10^{12} cm^{-2}
- Inferred mobility: 250 cm^2/Vs
- Breakdown field exceeds that of GaN HEMTs

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

Extreme Temperature Operation of AlGaN Transistors





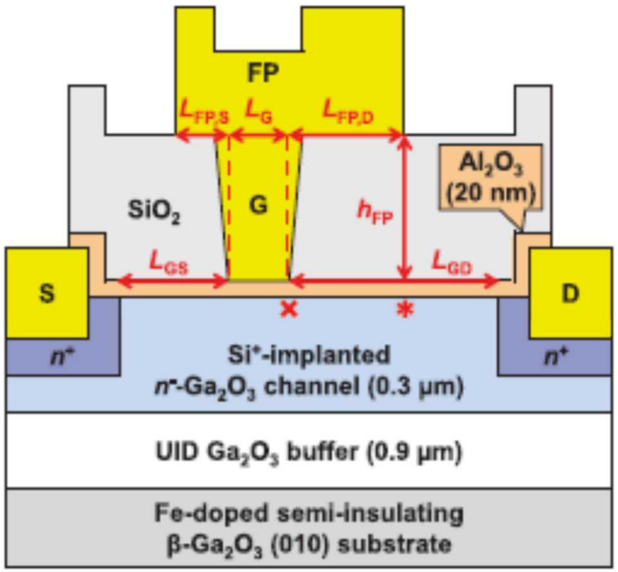


Drain current is insensitive to temperature up to 300°C

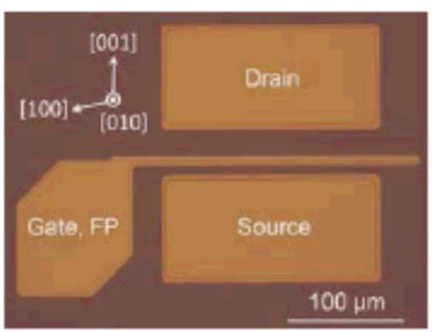
- **Likely due to dominance of alloy scattering in $Al_{0.6}Ga_{0.4}N$ channel**
- **Good Ohmic contacts**

N. Yafune et al., Elec. Lett. 50 (3), 211 (2014)

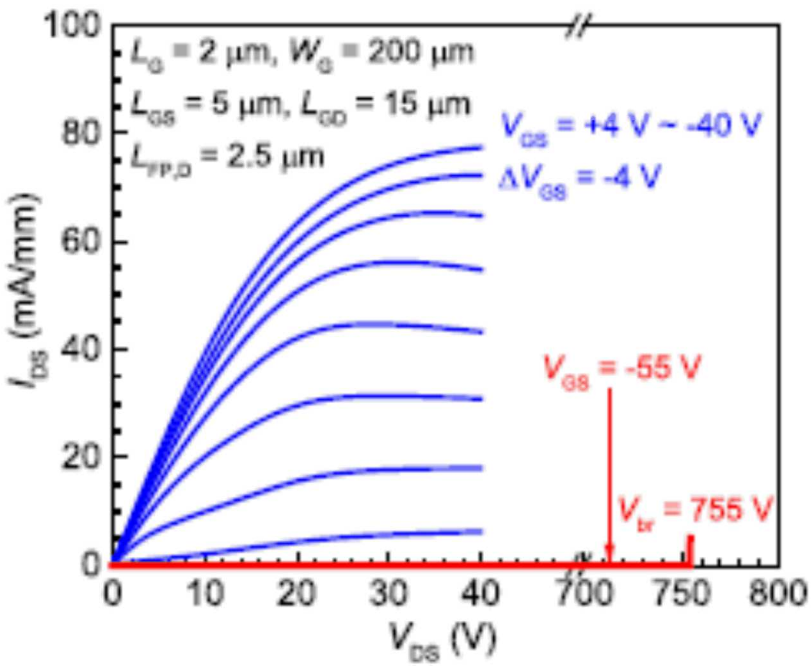
Ga_2O_3 Transistors



(a)



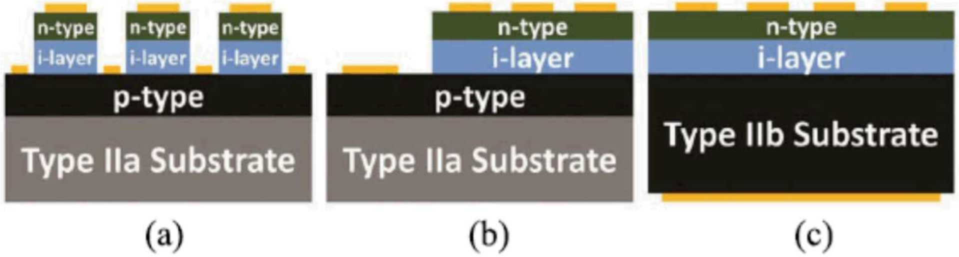
(b)

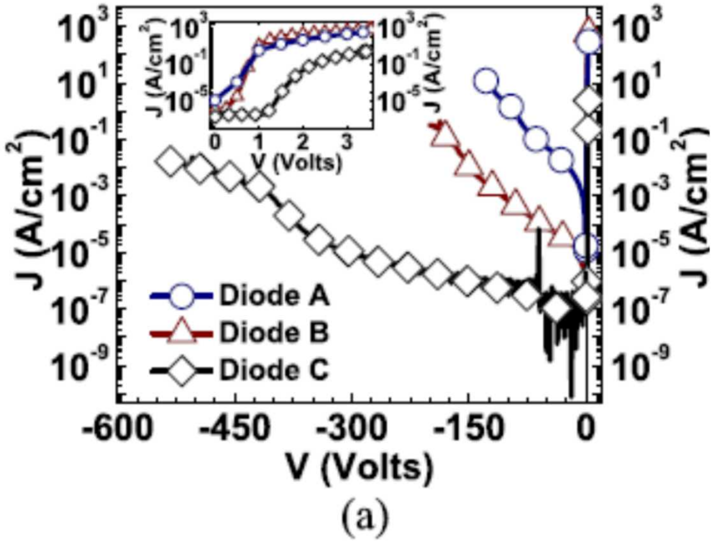


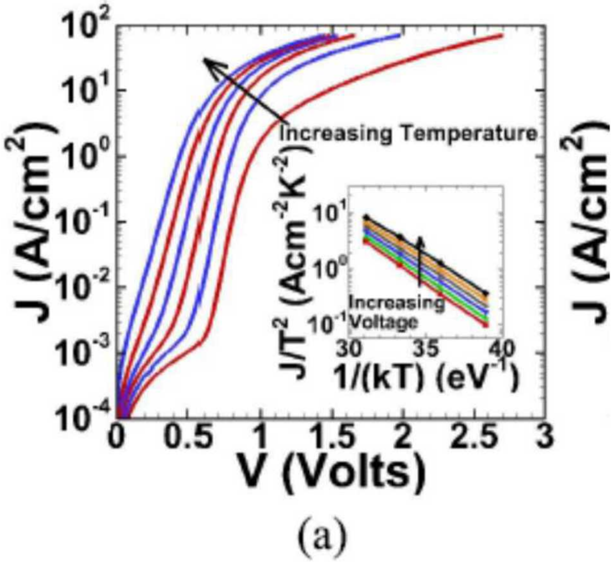
(a)

M. H. Wong et al., Elec. Dev. Lett. 37 (2), 212 (2016)

Diamond PiN Diodes







M. Dutta et al., Elec. Dev. Lett. 37 (9), 1170 (2016)

Summary

- UWBG semiconductors represent the next generation of semiconductors for high-power electronics
- Material properties directly impact device performance (e.g. critical electric field)
- But many material properties are not well known, and many material growth and device processing challenges exist
- Much research is ongoing, and the literature on UWBG materials and devices is growing rapidly