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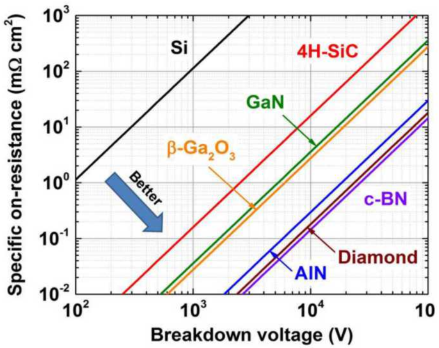

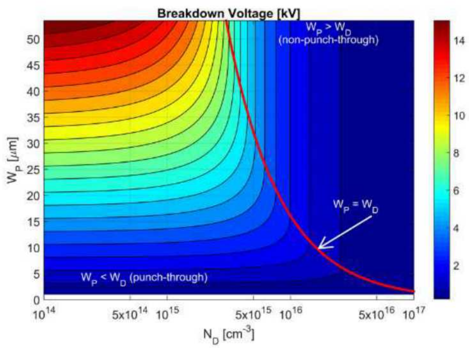

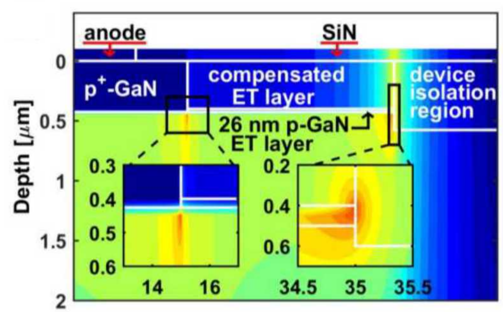

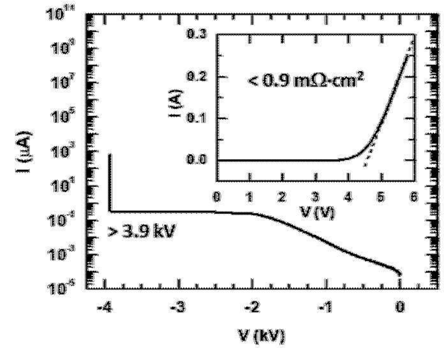

Ultra-Wide-Bandgap Semiconductors: Materials, Devices, and Applications

Bob Kaplar, Sandia National Labs

UNM ECE Graduate Seminar

February 15, 2019

Acknowledgements:

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

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Outline

- Applications Motivating the Development of UWBG Semiconductors
- Impact of UWBG Semiconductor Properties on Devices
- UWBG Device Design, Fabrication and Operation Considerations
- Examples of UWBG Devices

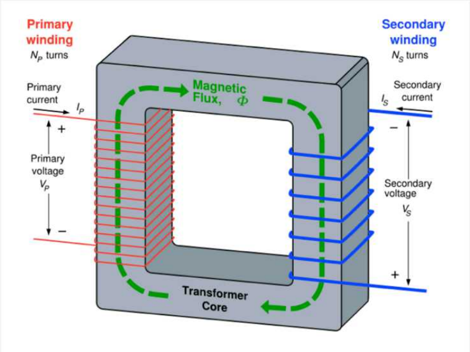
Outline

- ➢ **Applications Motivating the Development of UWBG Semiconductors**
- ➢ Impact of UWBG Semiconductor Properties on Devices
- ➢ UWBG Device Design, Fabrication, and Operation Considerations
- ➢ Examples of UWBG Devices

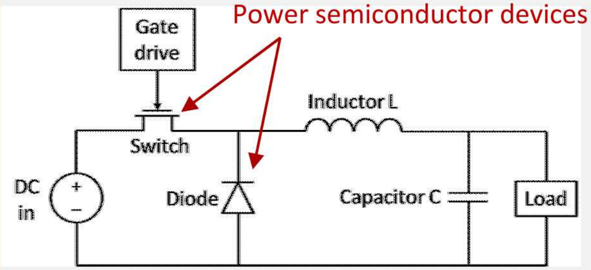
Power Electronics

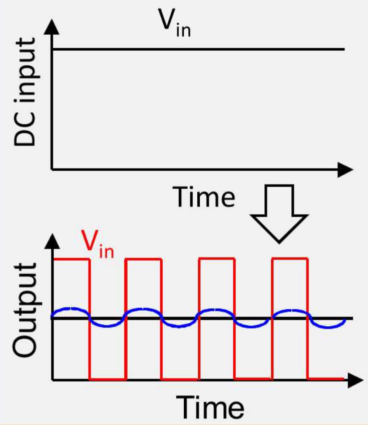
***Power electronics*: Application of solid-state electronics for routing, control, and conversion of electrical power**

Passive transformers (dumb)



Power Electronics – active switching (smart)





- **Current power electronics are limited by the properties of Silicon semiconductor devices**
- **New system capabilities are enabled by:**
  - **Higher switching frequency (enables better SWaP)**
  - **Lower power loss**
  - **Higher temperature operation**

➢ ***Motivation for WBG/UWBG semiconductors***

Energy-Efficiency Applications

Lateral GaN

Si

SiC

Ultra WBG

Vertical GaN

Operating Voltage: 600 V | 1200 V | 10s of kV | MV

600 V

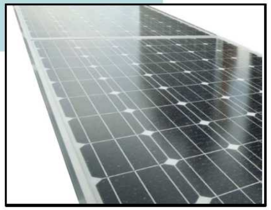
Motor drives
Electric vehicles
Airplanes

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

1200 V

PV inverters

- Higher voltages, lower resistive losses



10s of kV

Electric grid
Electric rail
Grid-level energy storage

- AC subsystems to 13.8 kV

MV

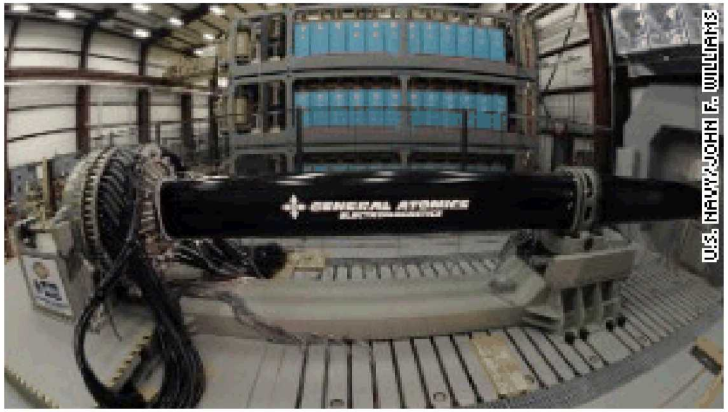
HV-DC transmission and fault protection

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

Military Applications

USS Zumwalt

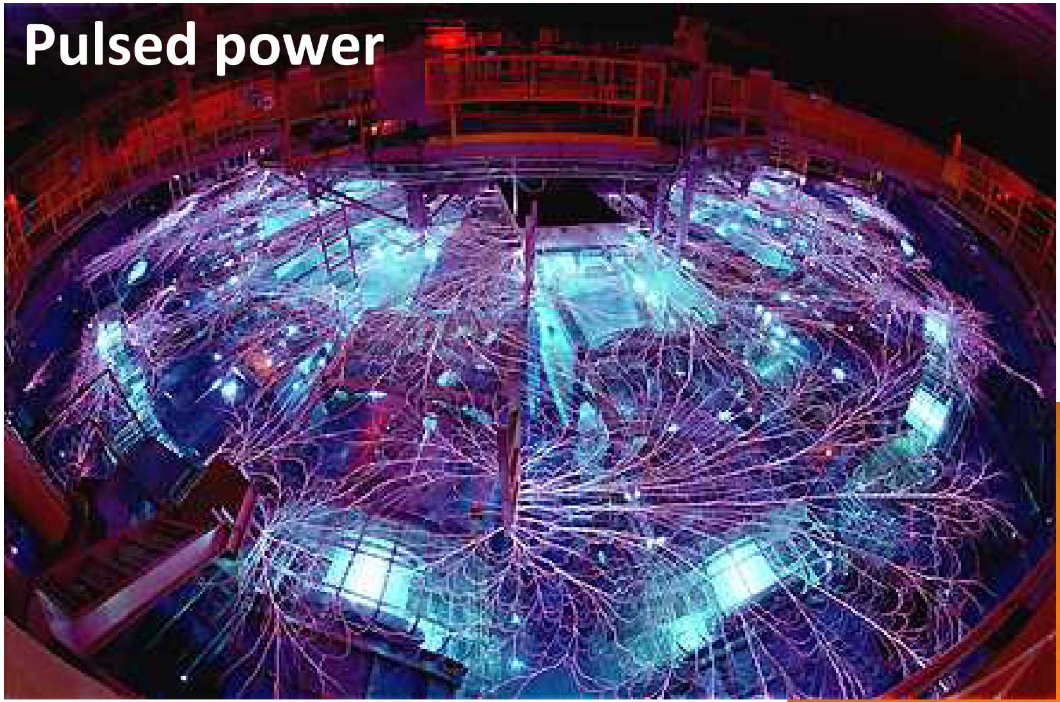
Electromagnetic Railgun



Higher degree of electrification desired in a SWaP-constrained environment

USS Gerald R. Ford

Ultra-High-Voltage Applications



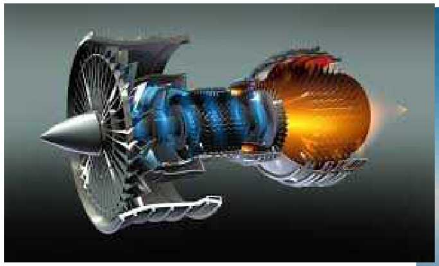
Conservative but critically important power device markets

100 kV switches may be possible using UWBG semiconductors!

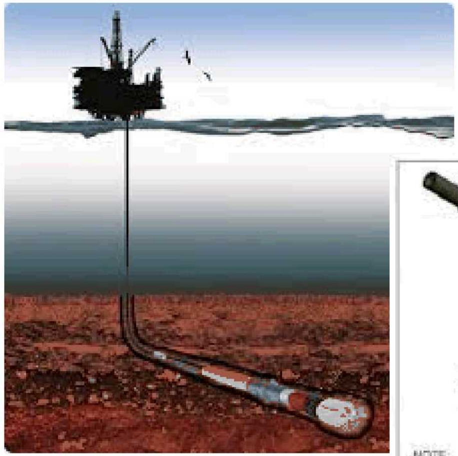
Power Electronics for Extreme Environments

Relevant extreme environments for power electronics:

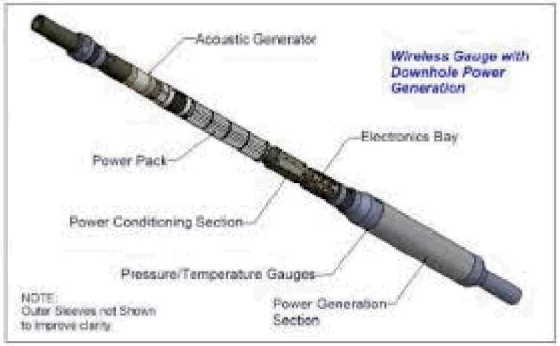
- Temperature extremes
- Vibration
- Radiation

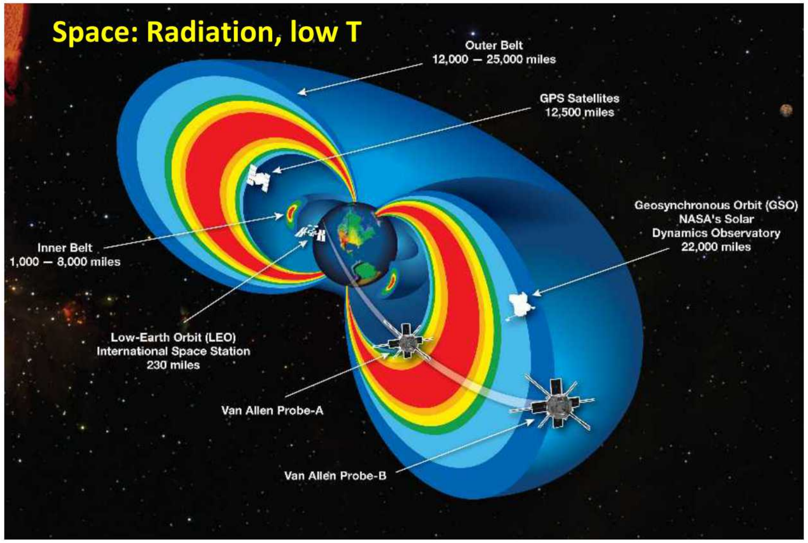


Aviation: High T, vibration



Down-hole: High T, vibration



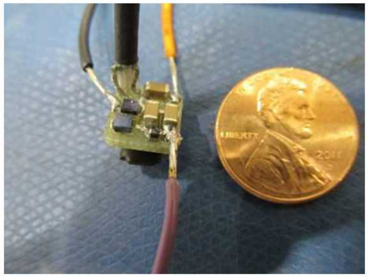


Avalanche ruggedness is important for numerous power conversion circuits

WBG and UWBG Enable Orders-of-Magnitude Reduction in Power Converter Volume

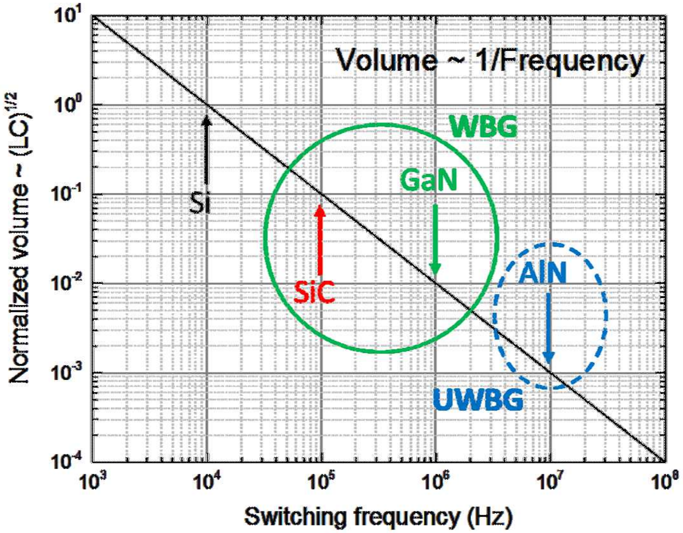
SiC converter is 10% the volume and weight of Si for equivalent capability (10 kV, 100 A)

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



UWBG materials and devices may enable *another order-of-magnitude reduction* in power converter size and weight!

UWBG

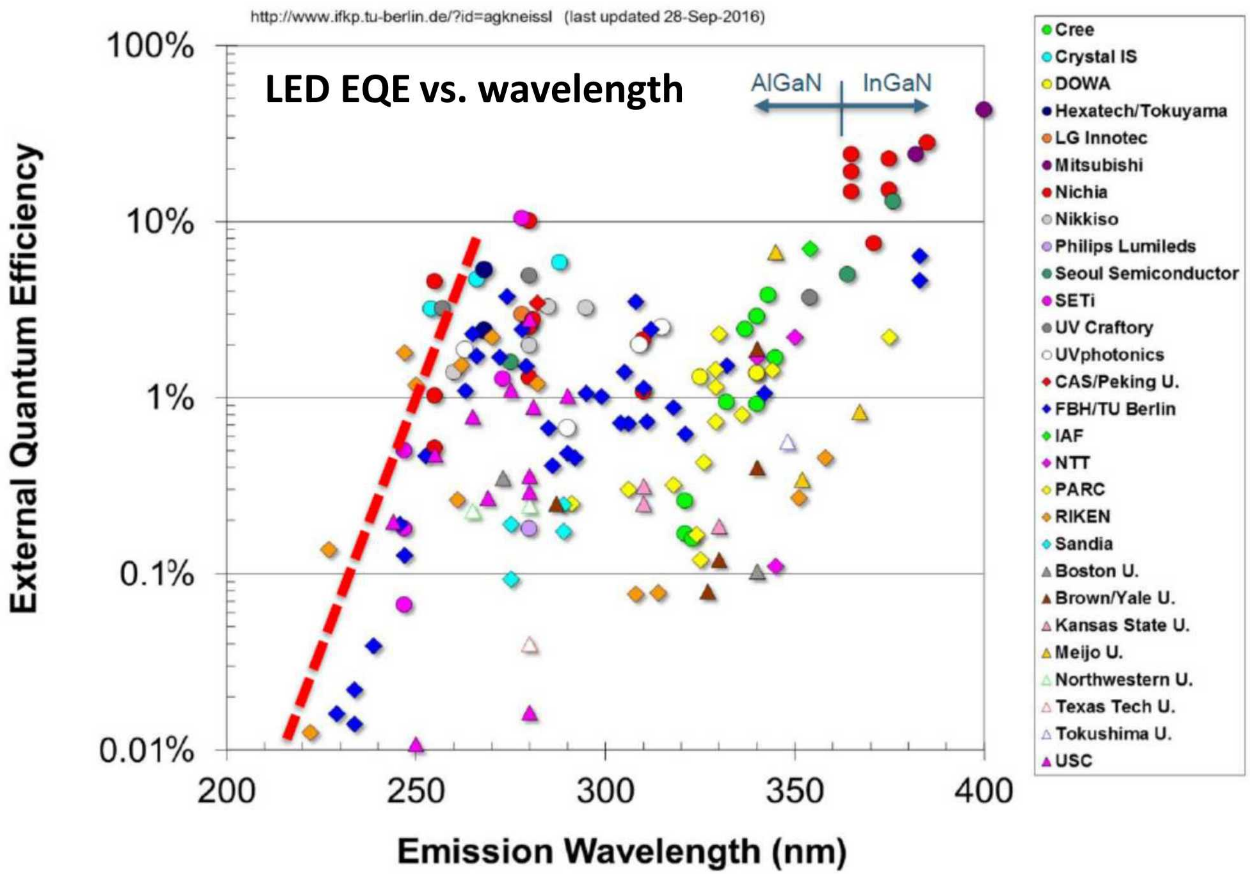


Radio-Frequency Applications

- 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



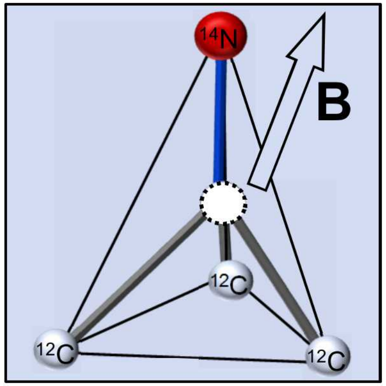
Rapid drop in efficiency for λ < 250nm
due to orientation-dependent TE/TM polarization switching

Applications:

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

N. Johnson, PARC

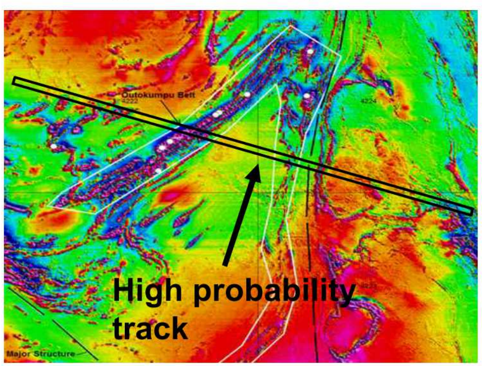
Other Possible Applications of UWBG Materials



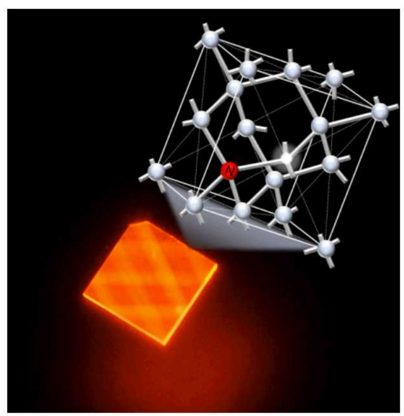
(N+ Vacancy) in Diamond

- 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

- Applications Motivating the Development of UWBG Semiconductors
- **Impact of UWBG Semiconductor Properties on Devices**
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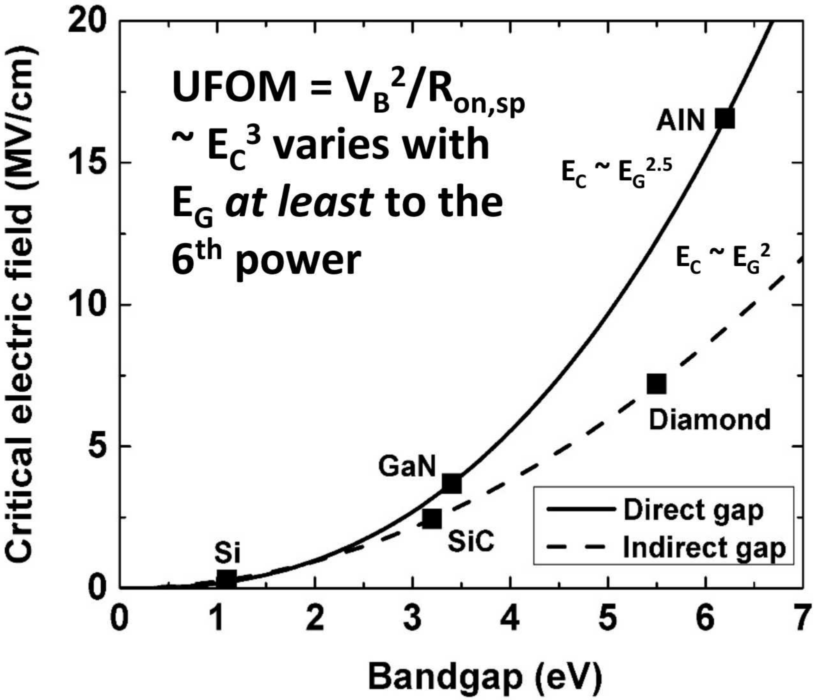
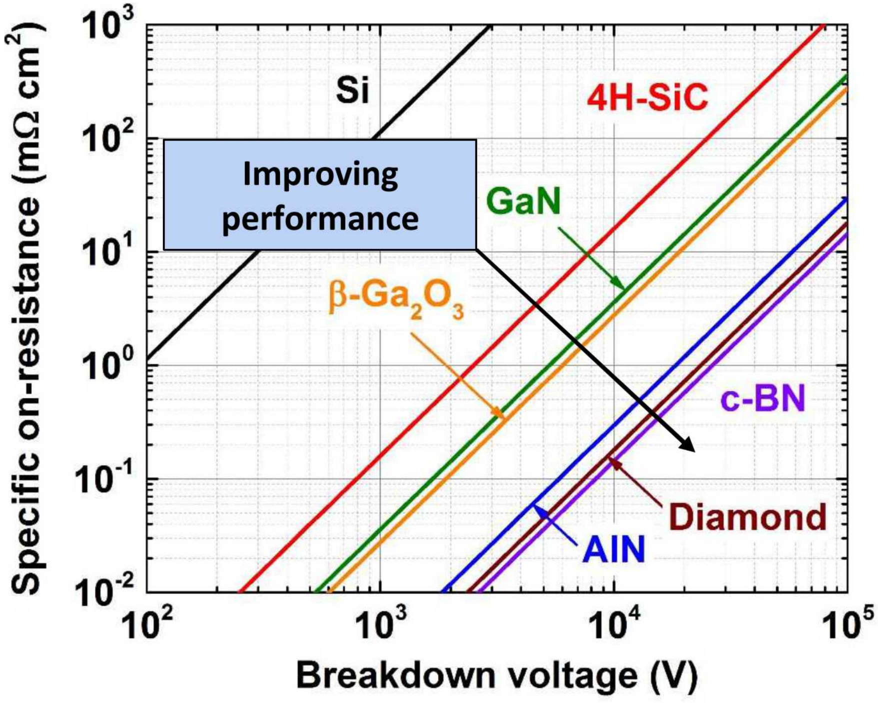
Generations of Semiconductors

- **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 Scales with Bandgap and Determines Unipolar FOM

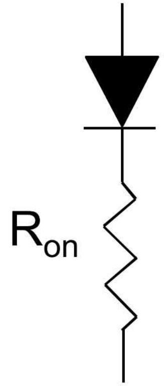


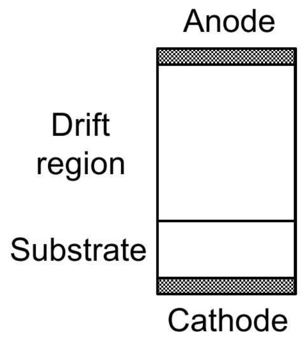


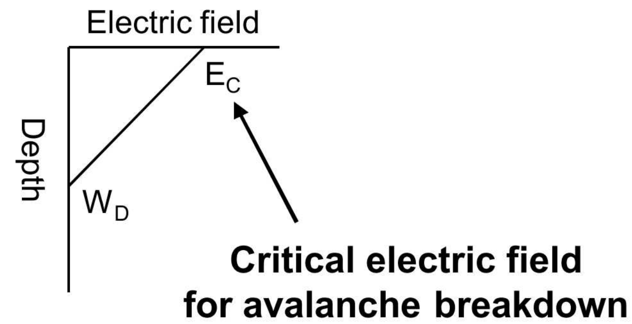
Unipolar FOM = $V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$

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

Derivation of Unipolar Figure-of-Merit







- Off-state: Integrate electric field to get breakdown voltage: $\mathbf{V_B = W_D E_C / 2}$ (1)
- Gauss' law: $\varepsilon \mathbf{E_C = q N_D W_D}$ (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: $\mathbf{V_B = \varepsilon E_C^2 / 2qN_D}$

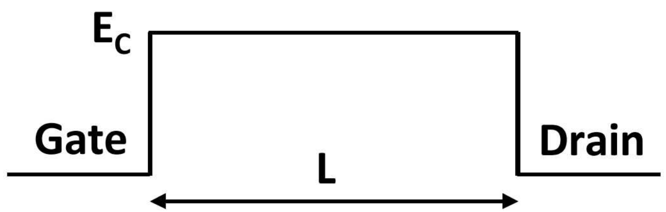
- Combining (1), (2), and (3) one obtains the **unipolar "figure-of-merit"**:
  $R_{on,sp} = 4V_B^2/\varepsilon\mu_n E_C^3 \rightarrow \mathbf{V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4}$

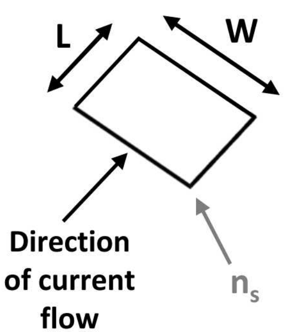
Depends on cube of E_C

Depends on square of E_C

Lateral Power Device Figure of Merit

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



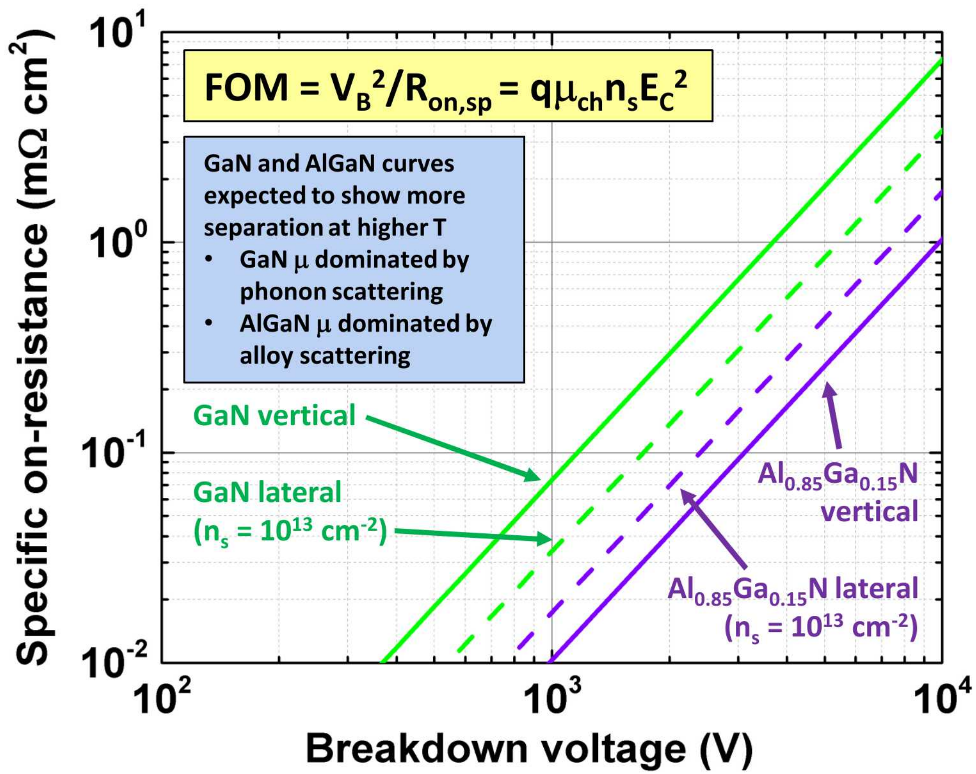


$$V_B = E_C L$$

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

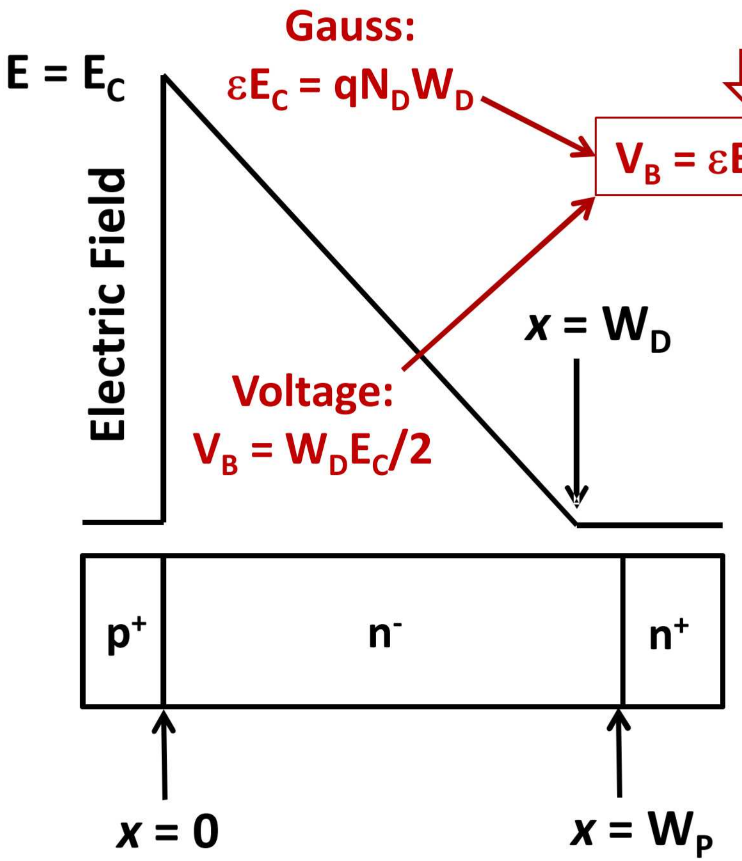
$$R_{on,sp} = R_{on} W L = \frac{L^2}{q \mu_{ch} n_s}$$

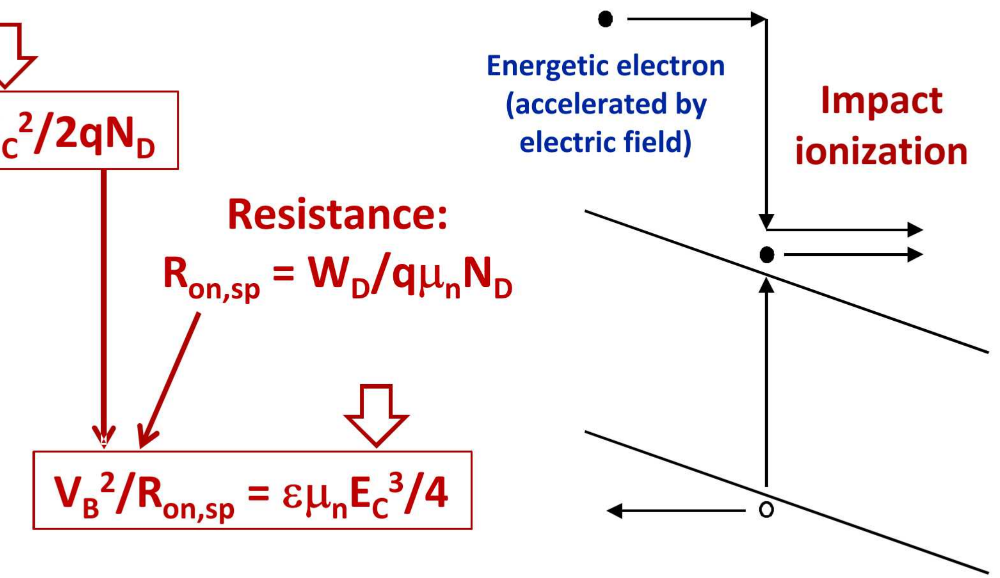
$$FOM = \frac{V_B^2}{R_{on,sp}} = q \mu_{ch} n_s E_C^2$$



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

Definition of Critical Electric Field



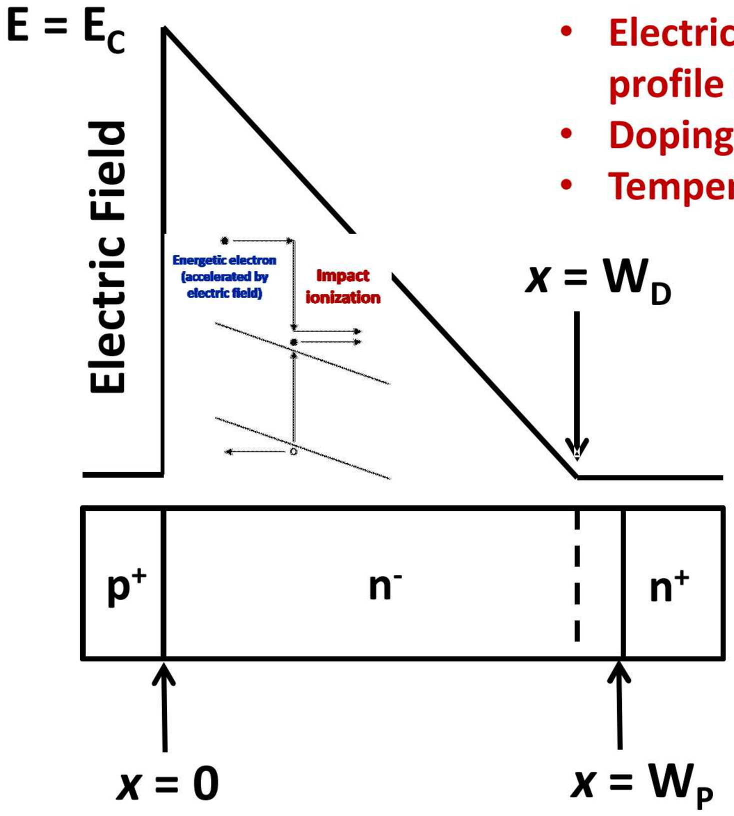


$$N(x) = \frac{exp\left[\int_0^x (\alpha_p - \alpha_n)dx'\right]}{1 - \int_0^{W(E_C)} \alpha_n exp\left[\int_0^x (\alpha_p - \alpha_n)dx'\right]dx}$$

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 a Constant



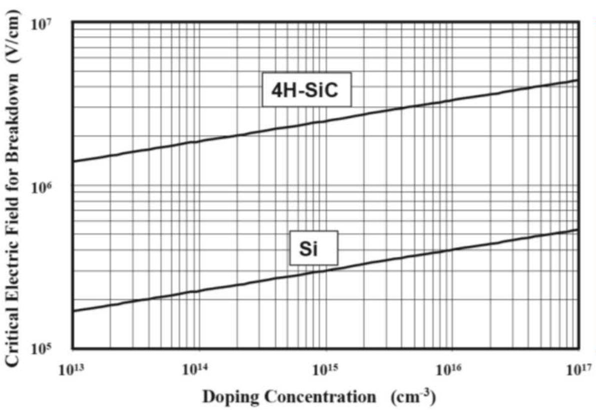
Critical electric field depends on:

- **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)**

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

Avalanche occurs when denominator approaches zero

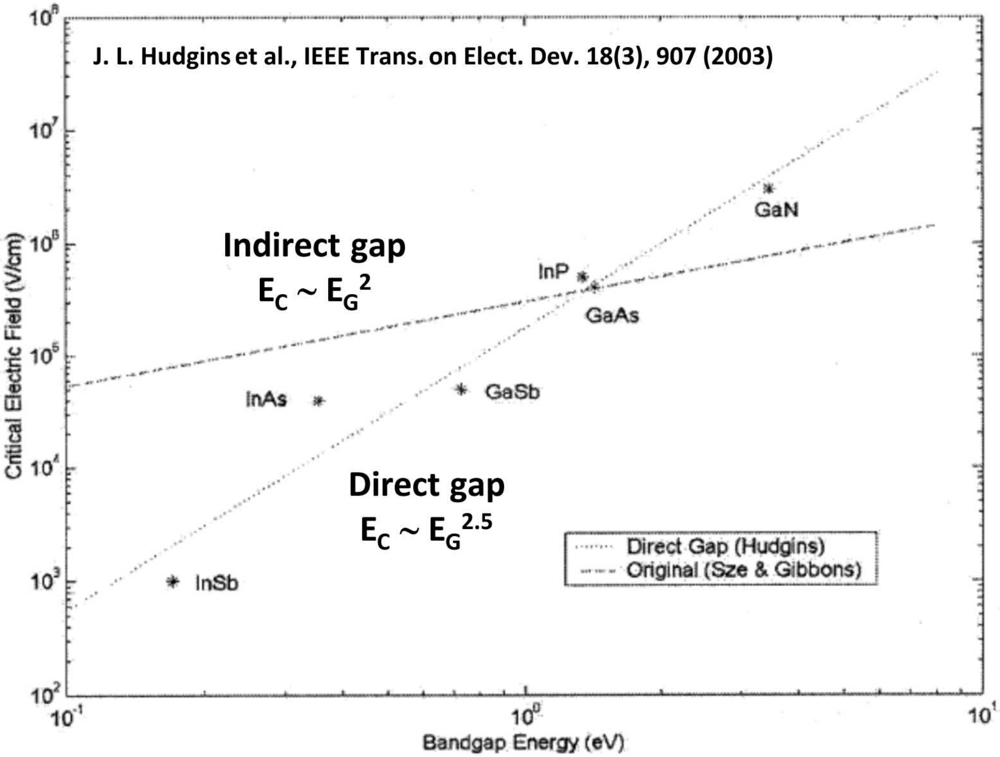
The critical electric field is defined as the peak electric field that leads to avalanche breakdown in a 1D model



Impact ionization and critical electric field are not well characterized for GaN and UWBG semiconductors!

B. J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer (2008)

Many Predictions of UWBG Device Performance are Based on Old Data



The critical electric field of GaN is not 3.3 MV/cm!

- **Empirical fits to data from the literature (no existing theory)**
- **Not normalized to doping, PT vs. NPT, temperature**

UWBG Working Group Parameter Refresh

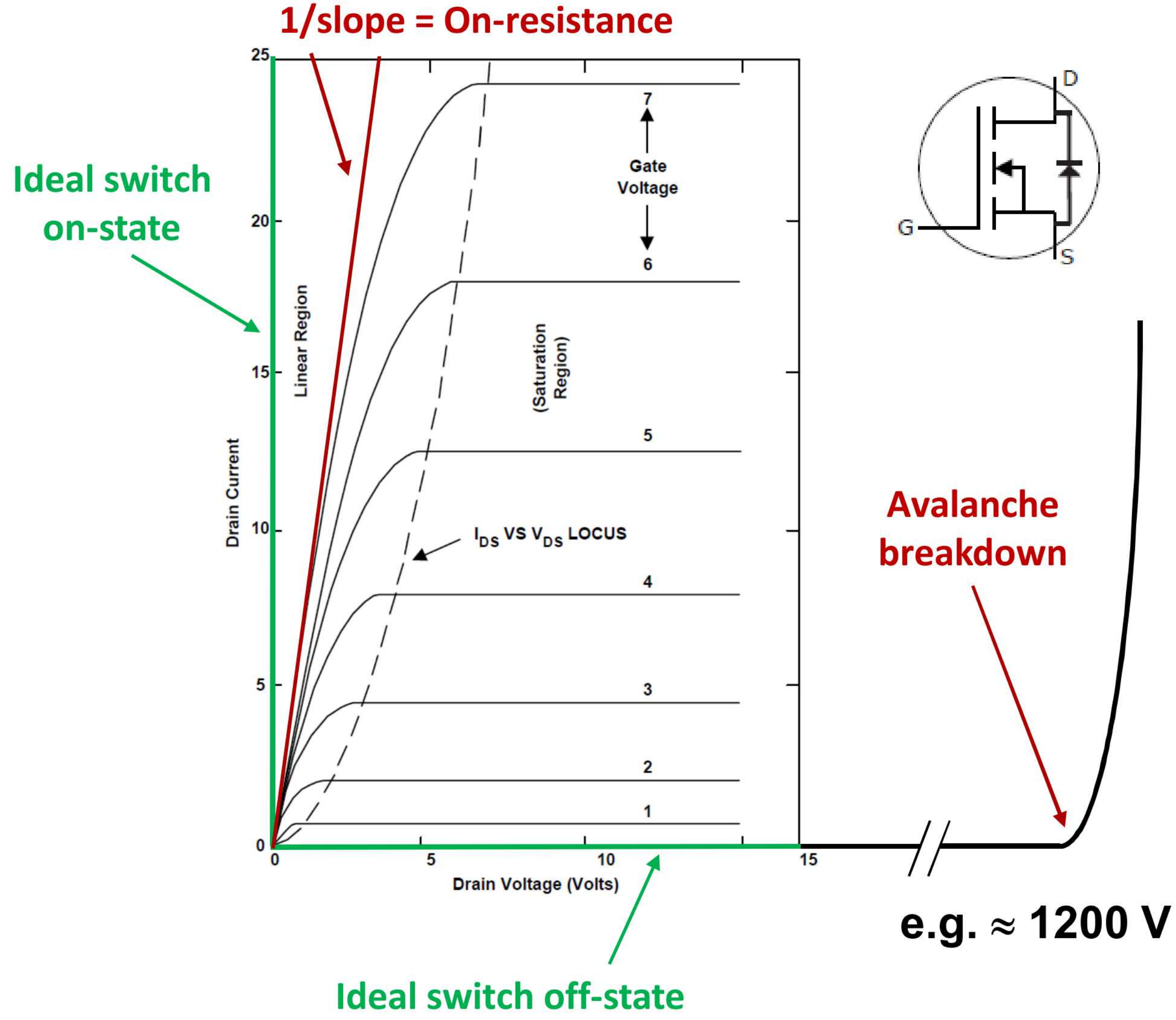
Material-Properties Table for Electronic Applications

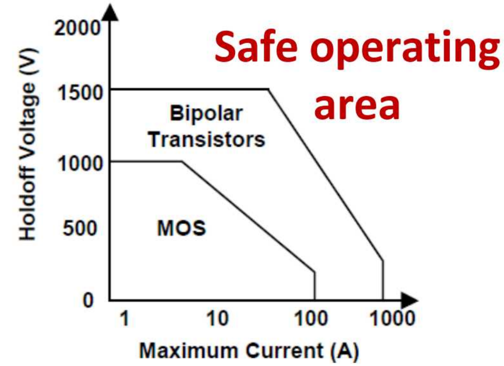
Parameter at 27°C	GaN (for reference)	$Al_xGa_{1-x}N$	AlN	Example AlN/GaN HEMT [1]	β-Ga_2O_3	Cubic BN	Diamond	Diamond MOS
Bandgap (eV)	3.4 [3]	Interpolation [37]	6.0 [4]	multiple	4.9 [5]	6.4 [6]	5.5 [7]	multiple
Proj. bulk E_C (MV/cm at doping = 10^{16} cm^{-3})	4.95 [8] (measured baseline)	Varies non-uniformly 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.]					

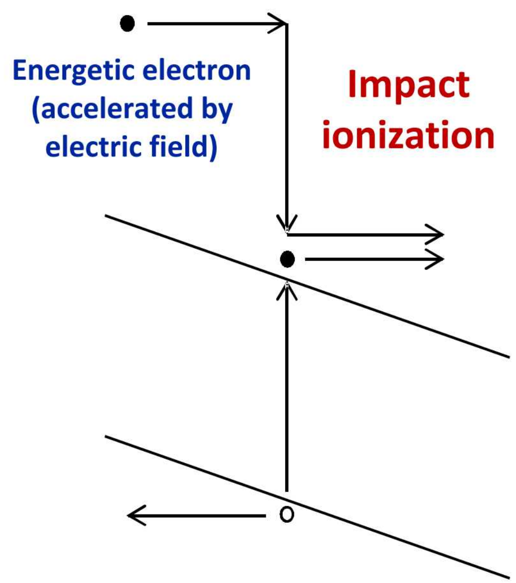
- **Working group study reviewed the literature and determined best-known parameters for WBG and UWBG materials**
- **Materials included are:**
  - **GaN (reference)**
  - **AlGaN**
  - **AlN**
  - **AlGaN/GaN HEMT**
  - **β-Ga_2O_3**
  - **c-BN**
  - **Diamond**
  - **Diamond MOS**

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

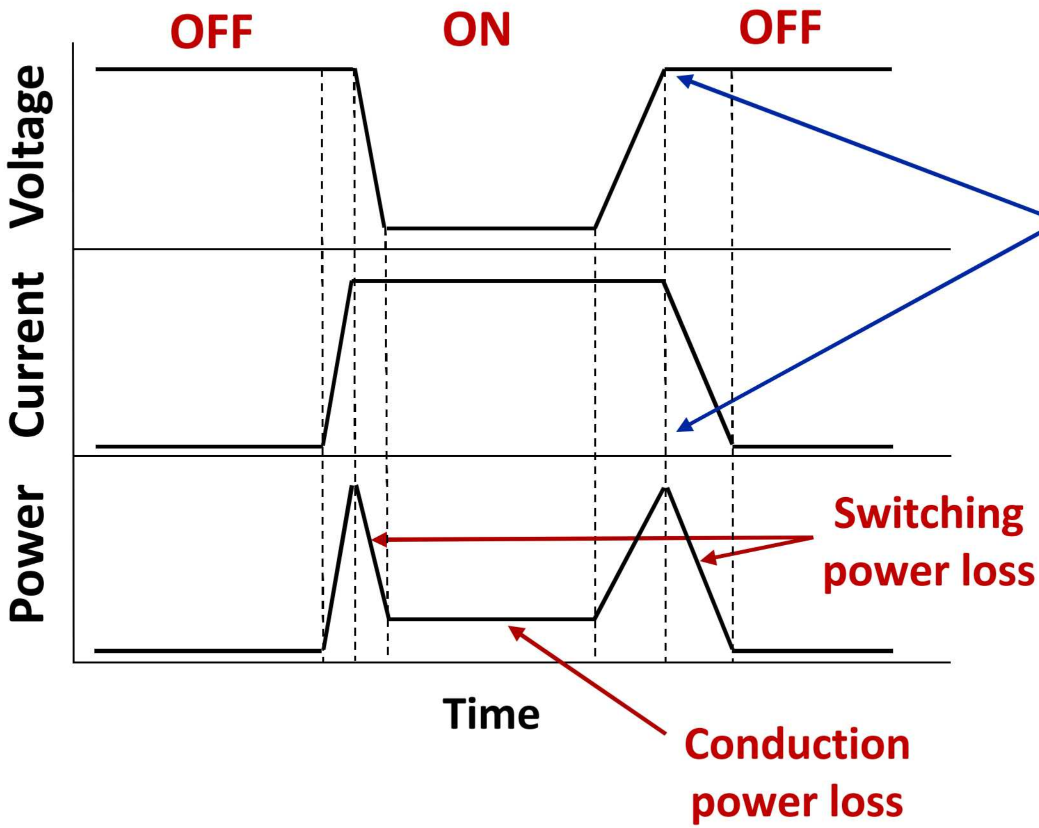
Semiconductor Devices Are Not Ideal Switches



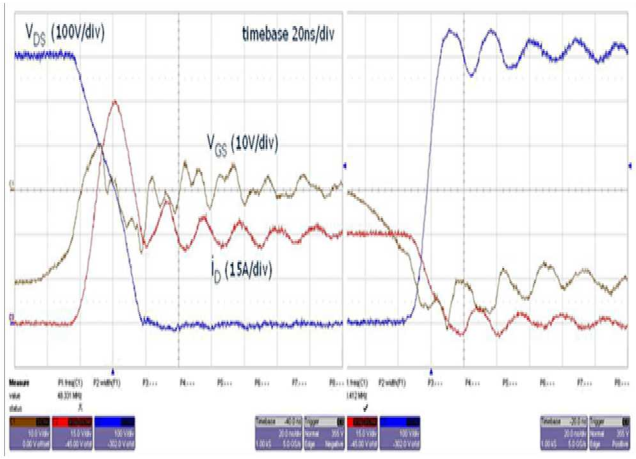




How Do Better FOMs for UWBG Semiconductors Translate to Better Power Converters?



A real circuit will have voltage and current overshoot and oscillations that must be minimized

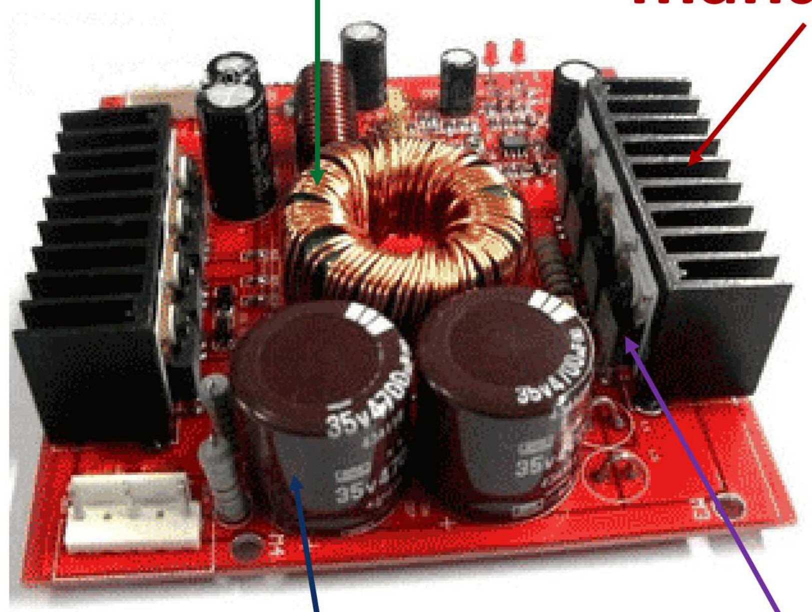


Minimum ON-state loss: ***Need low*** R_{on}

Minimum switching loss: ***Need fast switching transients***

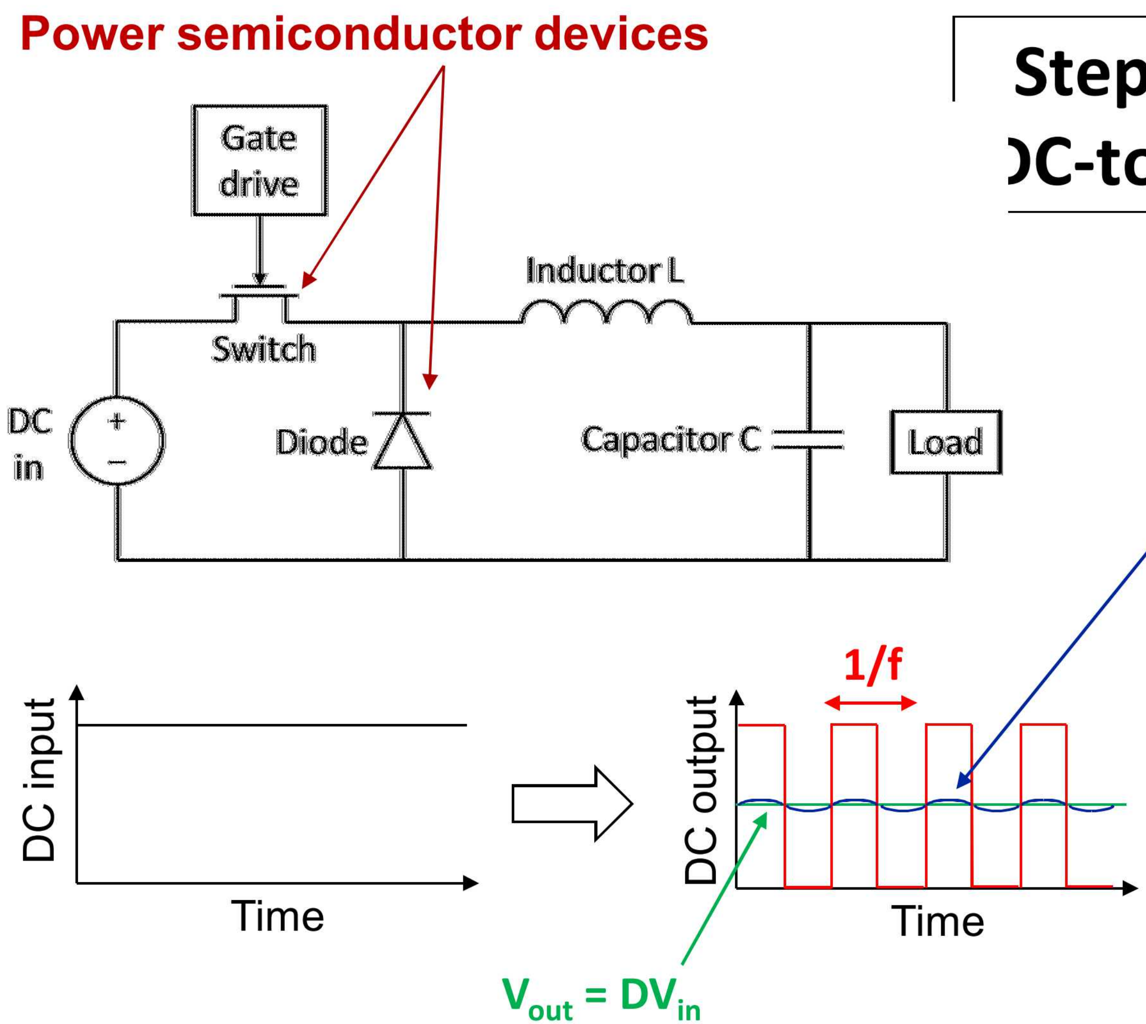
Power Electronics Volume and Weight Considerations

Passive elements and thermal management comprise the bulk of the volume and mass of a power converter



Higher Switching Frequency Enables Reduction in Passive Element Volume and Weight

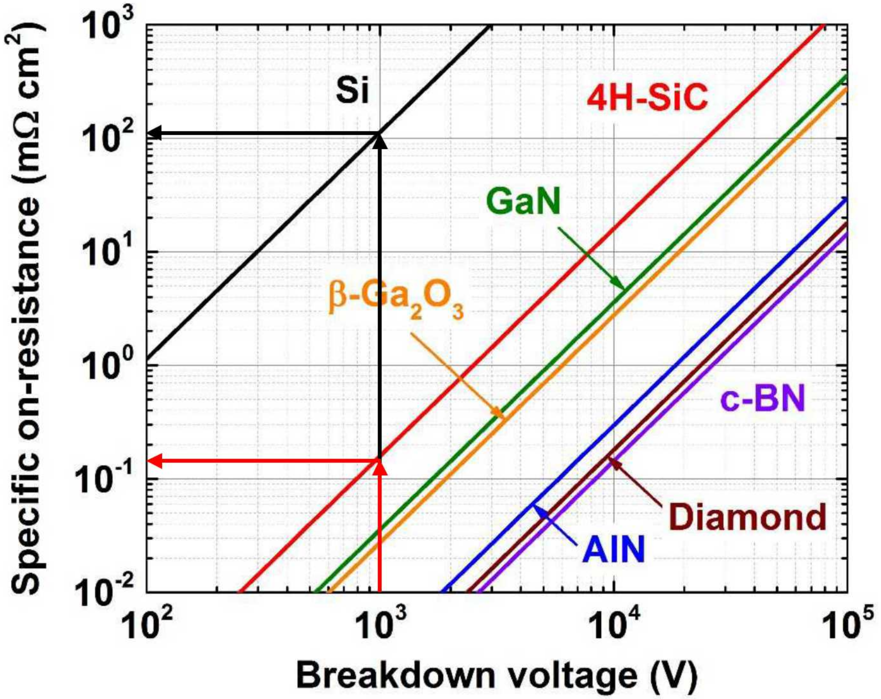
Step-Down (Buck) DC-to-DC Converter



$$\frac{V_{ripple}}{V_{out}} = \frac{1 - D}{8LCf^2}$$

Increasing f allows one to reduce L and C while keeping the ripple constant

How Do WBGs and UWBGs Lead to Higher Switching Frequency and Lower Loss?

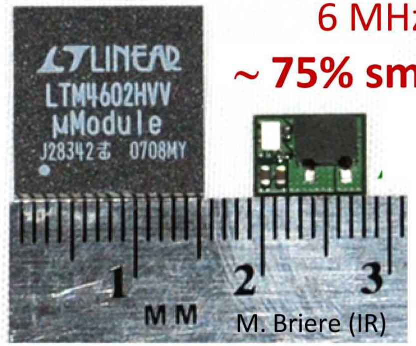


- For equivalent breakdown voltage, get lower $R_{on}A$ for (U)WBG device
  - For same R_{on}, (U)WBG device can have *smaller area*
  - Smaller area results in *less capacitance*
  - Gives a *faster switching transient* and *lower loss per switching cycle*

Si
15x15mm²
100 kHz

GaN
6x9mm²
6 MHz

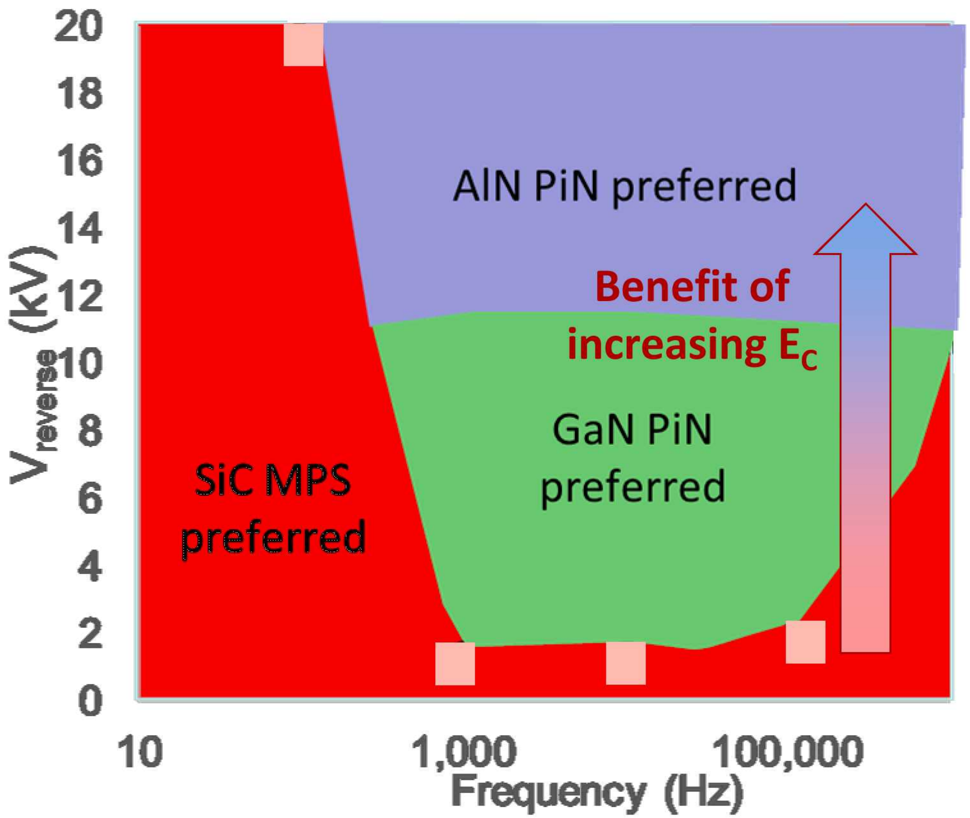
~ 75% smaller



1.2 kV, 12 A switch

The scaling that results from the properties of WBG and UWBG materials can be utilized to optimize for switching frequency, conduction loss, and switching loss

Analysis of WBG/UWBG Preferred Application Ranges



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

GaN and AlN preferred at high voltages over mid-frequency range

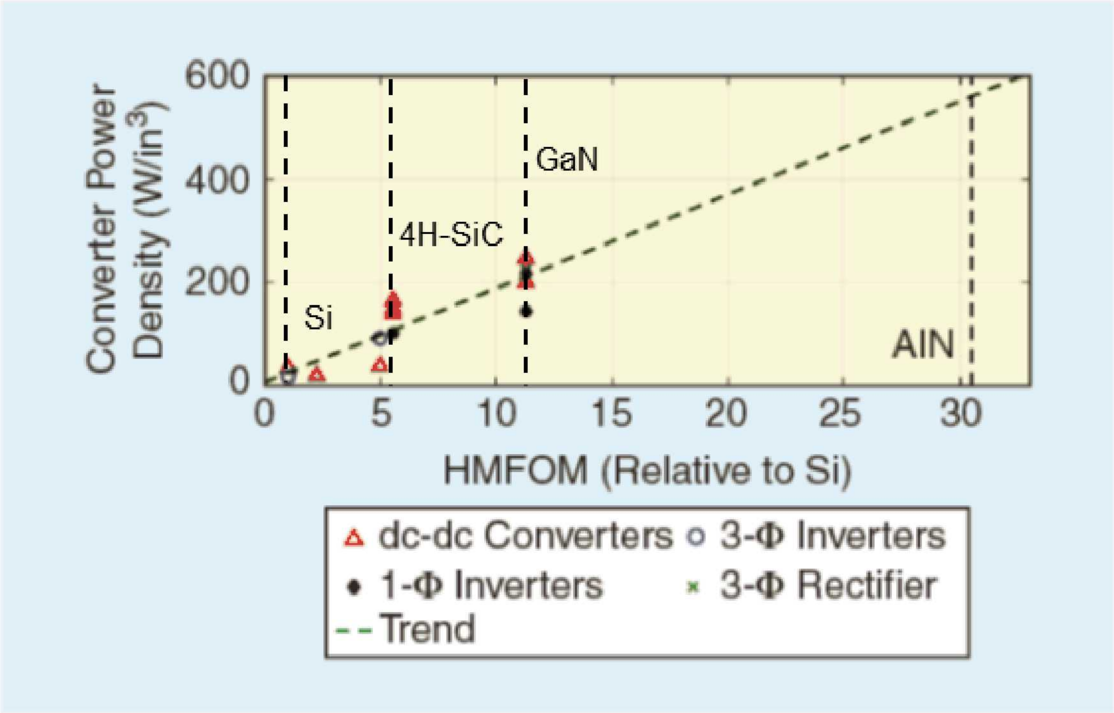
- Benefit of higher E_C
- Not as beneficial at low and high frequency (low conductivity modulation and increasing reverse recovery)

Examined PiN diodes since peak field is buried below surface

- Part of more advanced devices
- Also must consider Schottky

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

Power Density Scaling with Semiconductor Material Properties



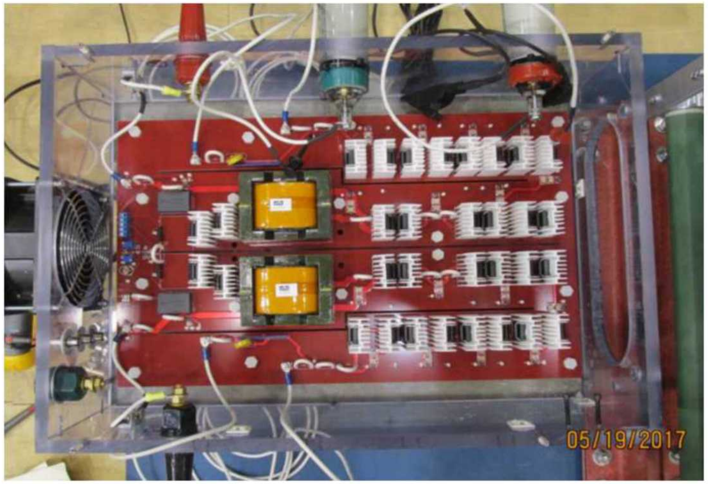
Relative Figures of Merit:

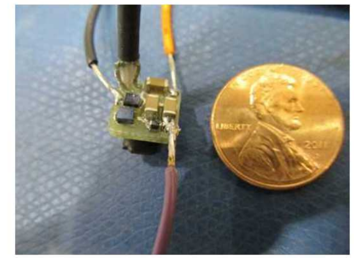
- **Vertical UFOM = $\varepsilon\mu_n E_C^3$**
- **Huang Material FOM = $E_C\mu_n^{1/2}$**

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

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

Efficient and Compact Power Conversion Enabled by WBG Semiconductors





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

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

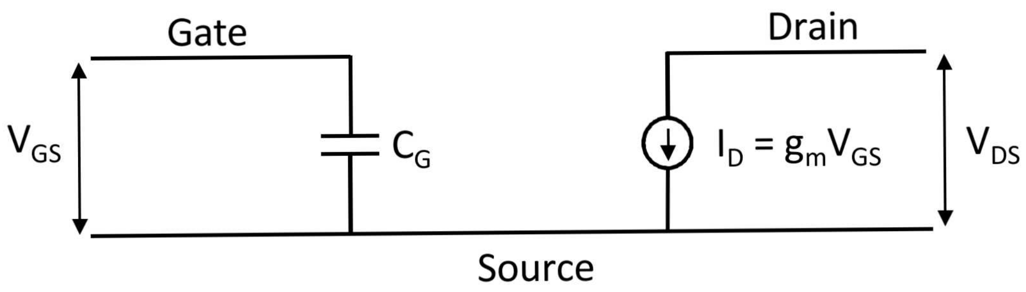
- **First prototype: 0.5 kV → 10.1 kV (gain = 16.8) at 2.6 kW, 95.3% efficient, 410 in^3**
- **Second prototype: +2% efficiency, 55% volume**

SNL GaN HEMT microinverter
400 W in 2.4 in^3 → 167 W/in^3

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

SOA commercial microinverter
250 W in 59 in^3 → 4.2 W/in^3

RF Devices: Derivation of Johnson Figure-of-Merit



Gate length = L_G
Electric field = E_C over L_G
Electron transit time = $\tau_G = L_G/v_{sat}$

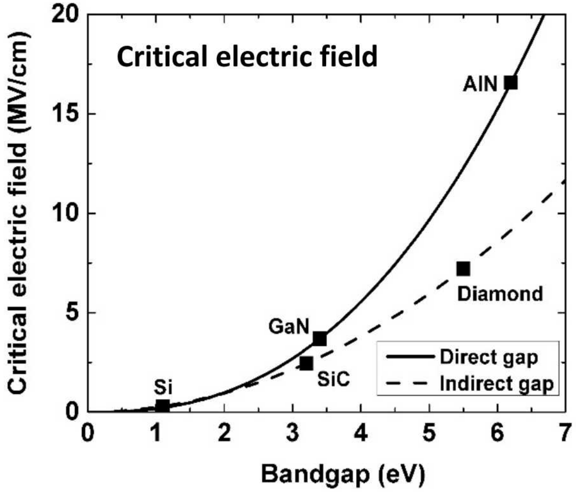
$$Gain = \left|\frac{I_D}{I_G}\right| = \left|\frac{g_m V_{GS}}{V_{GS}/Z_G}\right| = \left|\frac{g_m}{i2\pi f C_G}\right| = \frac{g_m}{2\pi f C_G}$$

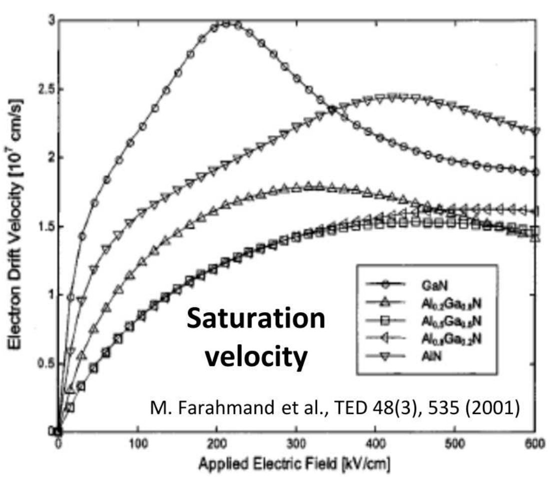
$$g_m = \frac{dI_D}{dV_{GS}} = \frac{dI_D}{dQ_G}\frac{dQ_G}{dV_{GS}} = \frac{C_G}{\tau_G} \rightarrow Gain = \frac{1}{2\pi f \tau_G}$$

$$Gain = 1 \;@\; f = f_T \rightarrow f_T = \frac{1}{2\pi\tau_G}$$

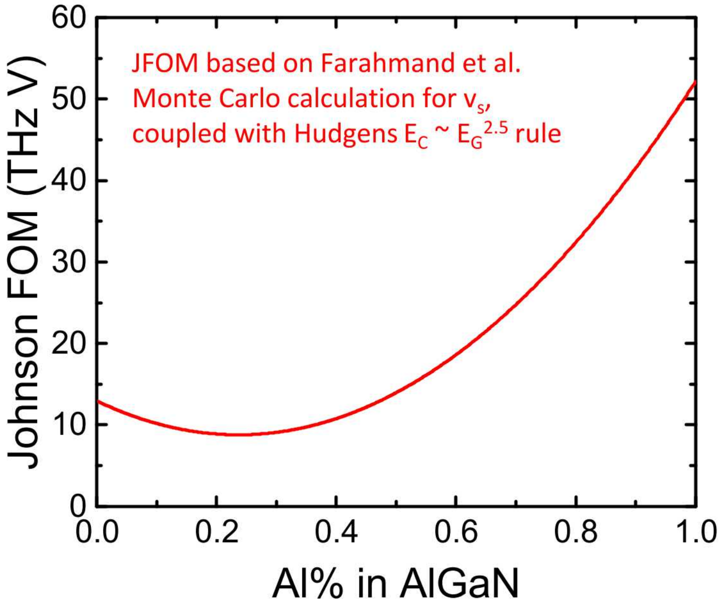
$$V_B f_T = \frac{E_C L_G}{2\pi\tau_G} = \frac{E_C L_G}{2\pi\, L_G/v_{sat}} = \frac{E_C v_{sat}}{2\pi}$$

Advantages of UWBGs for Radio-Frequency Devices





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

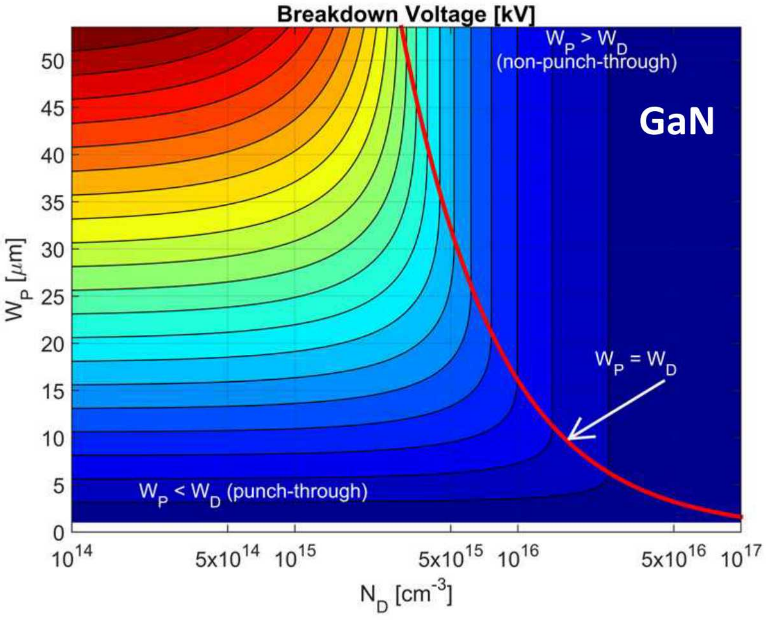


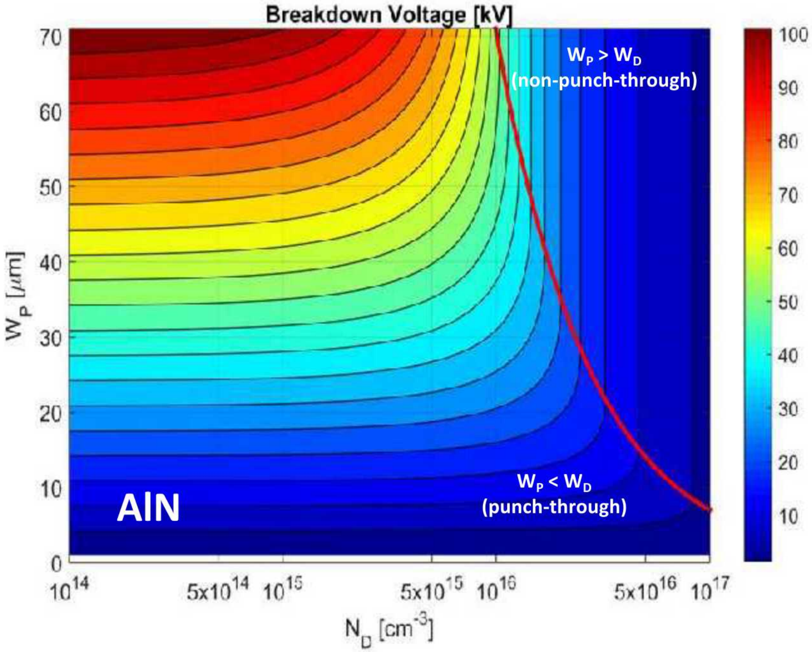
Al-rich AlGaN yields better JFOM than GaN due to higher E_C and comparable v_{sat}

Outline

- Applications Motivating the Development of UWBG Semiconductors
- Impact of UWBG Semiconductor Properties on Devices
- **UWBG Device Design and Fabrication Considerations**
- Examples of UWBG Devices

Impact of Critical Electric Field on Breakdown Voltage

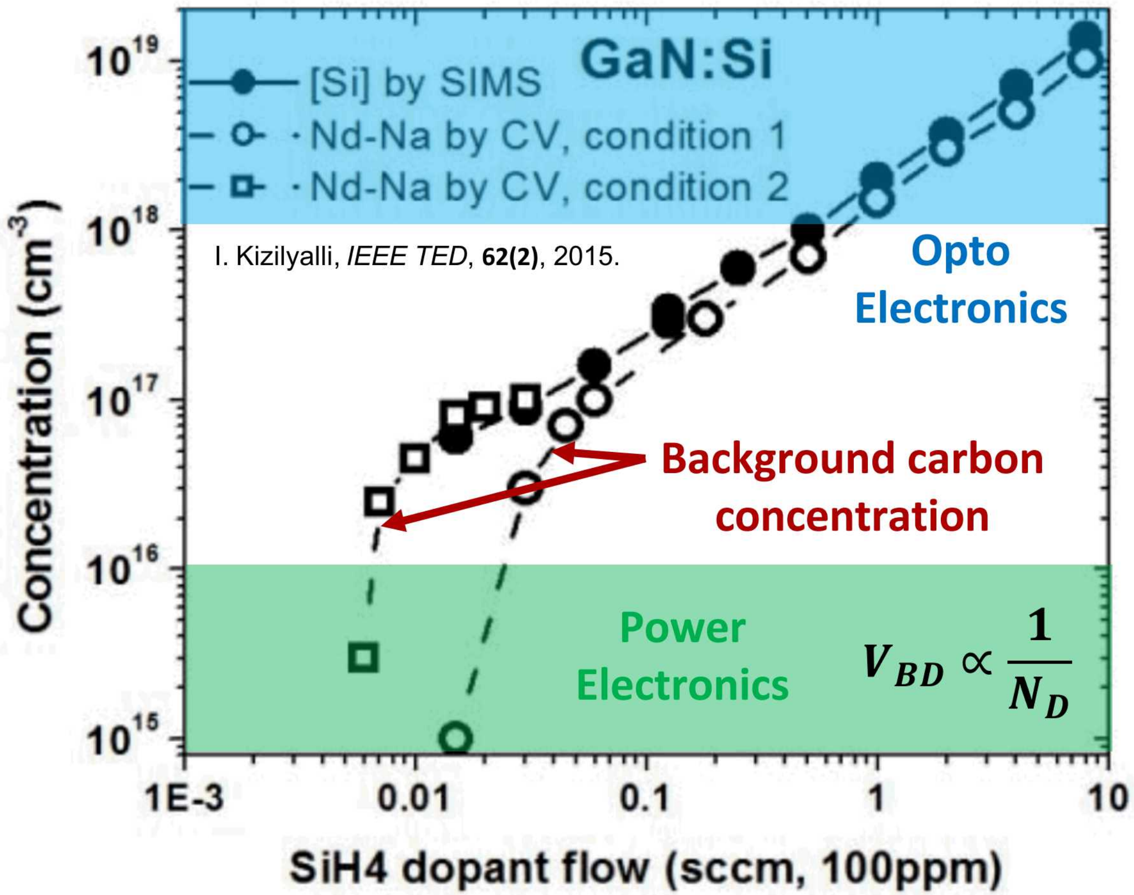


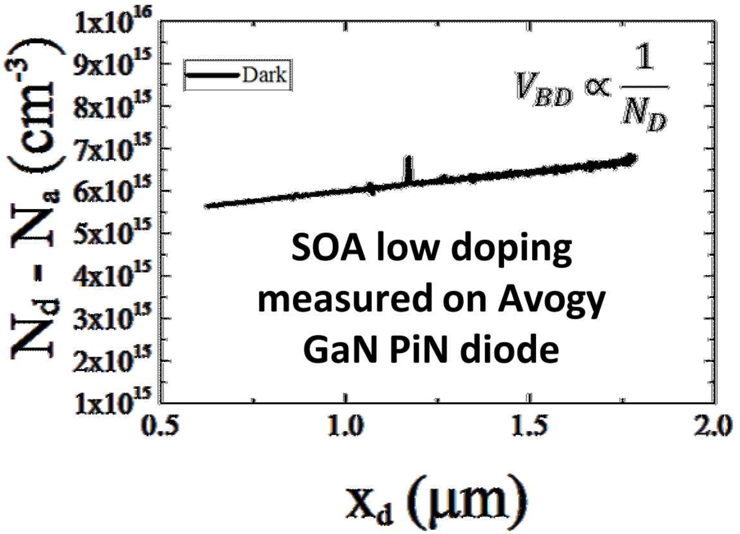


- **Increasing E_C may significantly increase V_B**
  - **100 kV device may be possible using materials like AlN**
  - **But low doping and thick drift layers are also required**

J. Dickerson, SNL

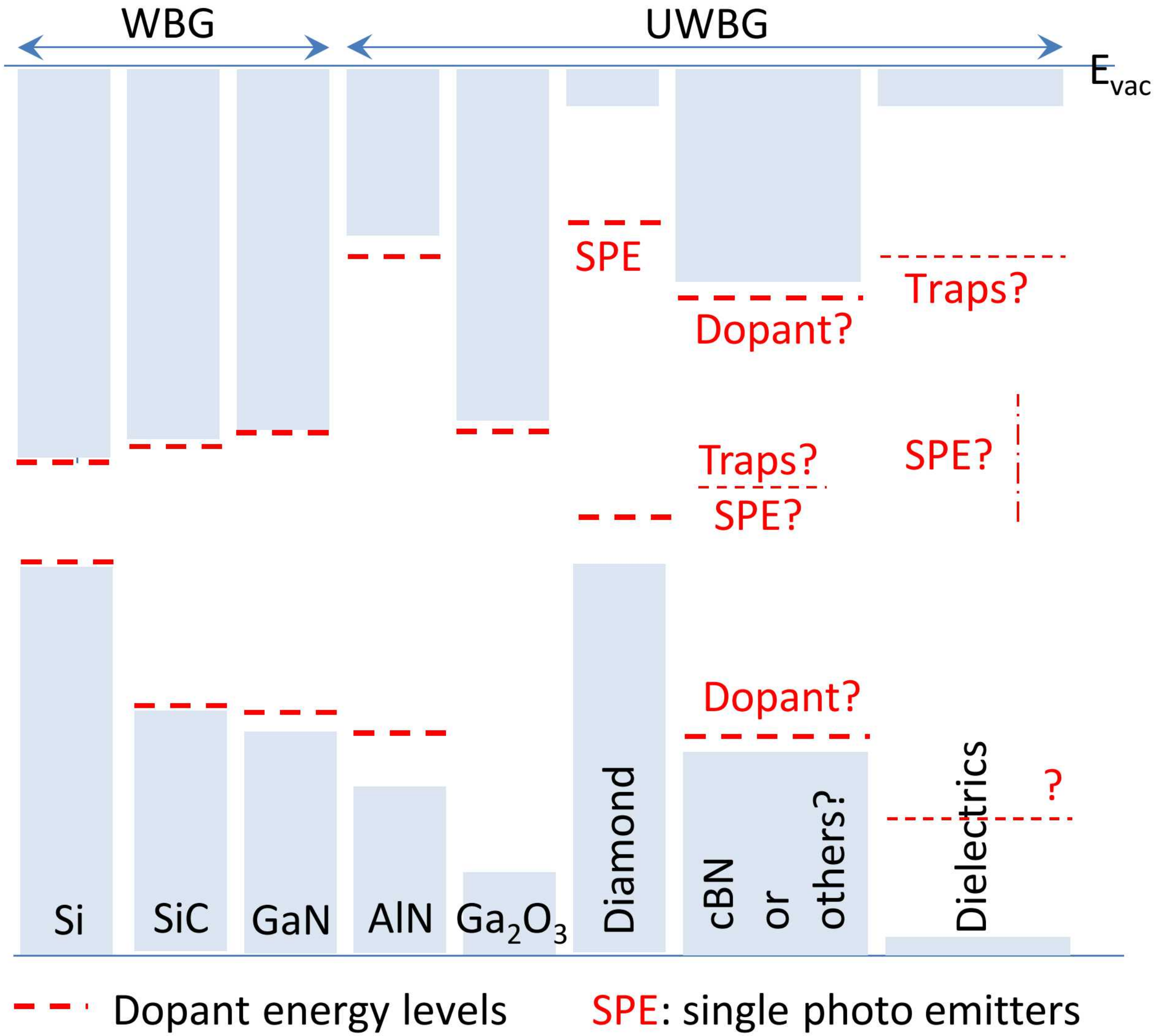
Low Doping in GaN Drift Regions

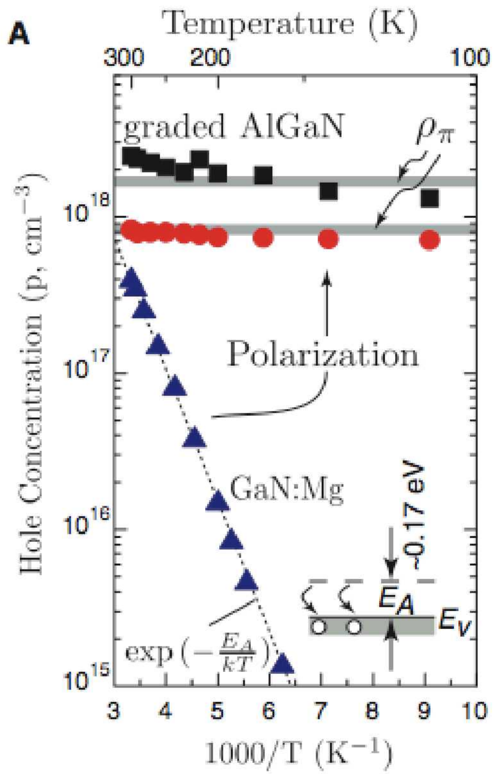




For GaN drift regions, the background acceptor concentration may be the same order of magnitude as the intentional dopant concentration!

enges in terials



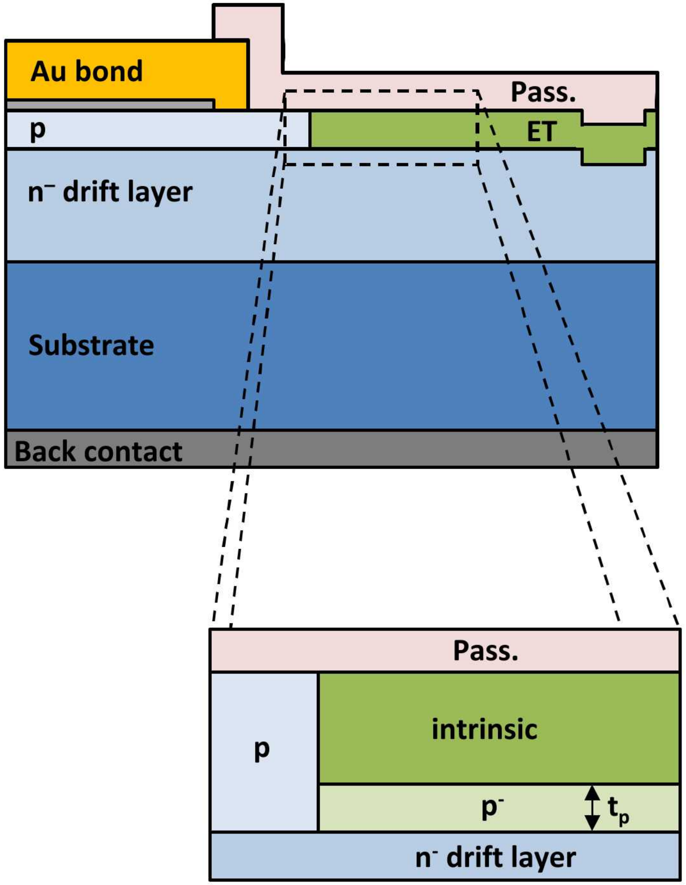


Simon et al., Science 327, 60 (2010)

Fundamentally new science of conductivity control
- **E.g. bulk polarization-doping in nitrides and oxides)**

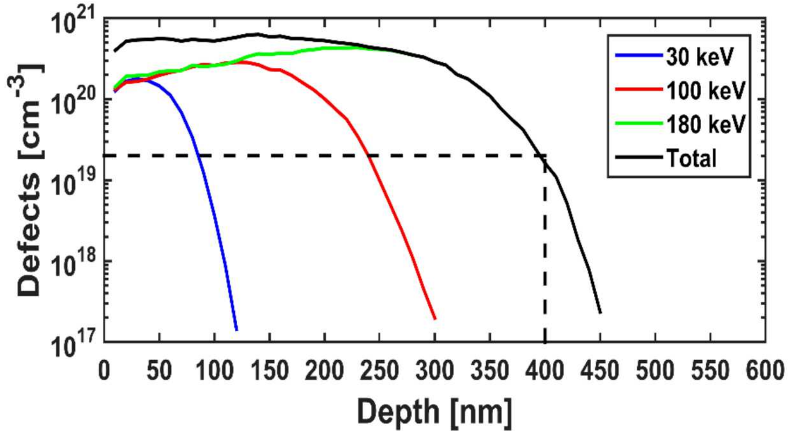
Grace Xing, Cornell U.

Edge Termination for High Breakdown Voltage

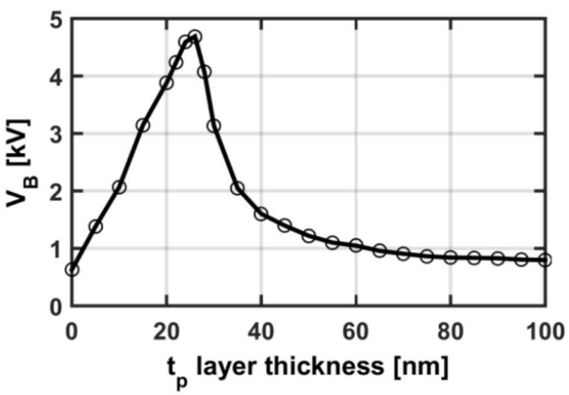


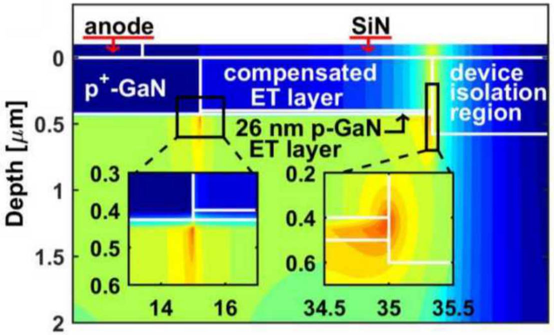
Junction Termination Extension (JTE)

Effective edge termination is required to avoid premature lateral breakdown



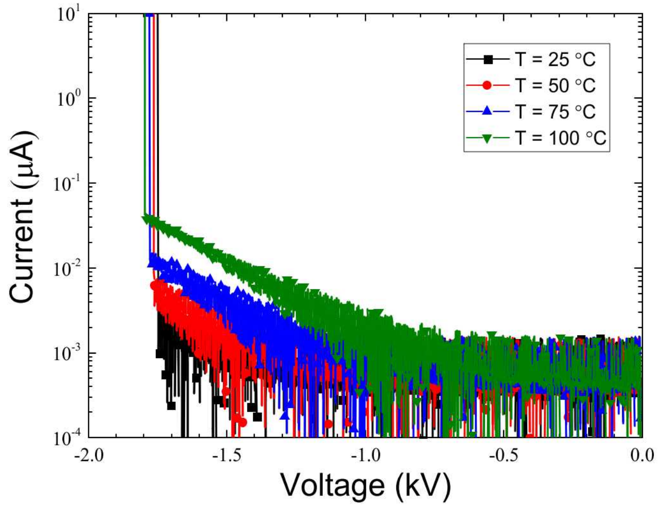
Ion implantation is used to create edge termination

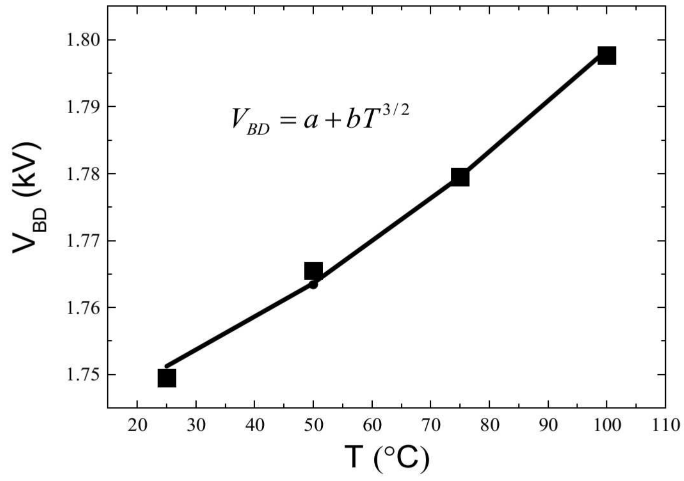


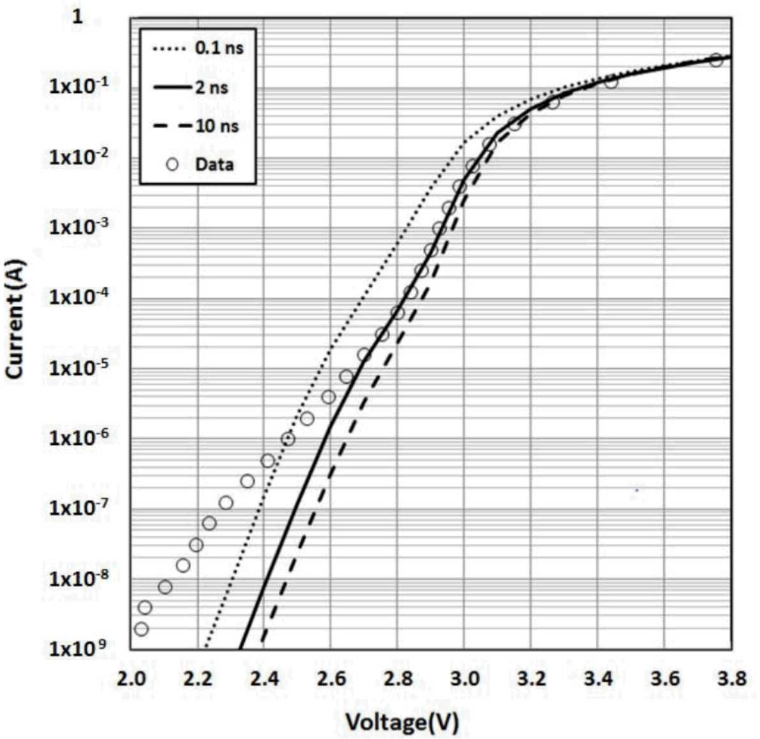


J. Dickerson et al., IEEE TED 63(1), 419 (2016)

Breakdown Mechanism and Carrier Lifetime





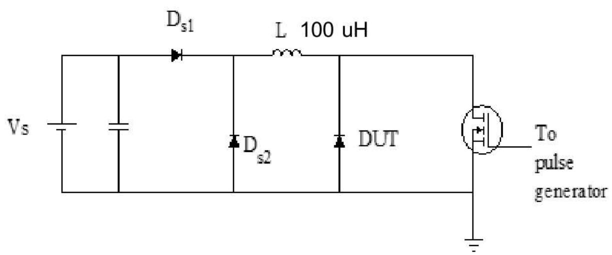


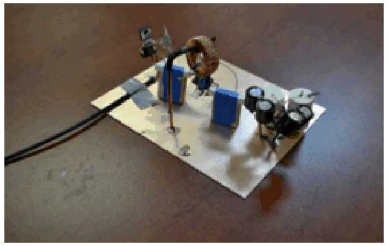
- **Breakdown in vertical GaN is consistent with avalanche**
  - **Temperature dependence consistent with phonon-scattering limitation**
  - **Not yet demonstrated for UWBGs**
- **Short carrier lifetime consistent with direct-gap material**

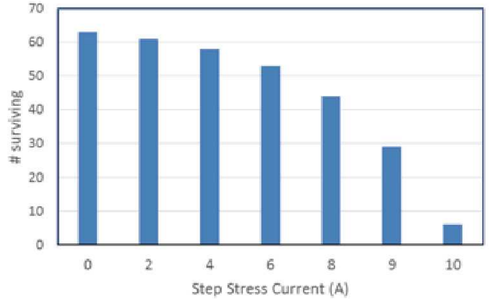
M. P. King et al., Trans. Nuc. Sci. 62 (6), 2912 (2015); I. C. Kizilyalli et al., Trans. Elec. Dev. 62 (2), 414 (2015)

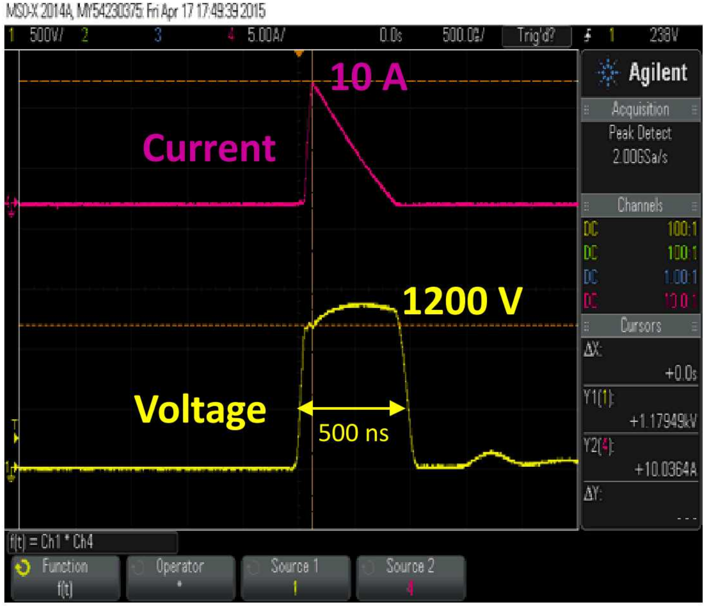
Avalanche Ruggedness

Avalanche test circuit









GaN vertical p-n diodes (A=0.36 mm^2) can withstand 10^5 / 5kHz pulses at 10A and 1200V for 10's of ns

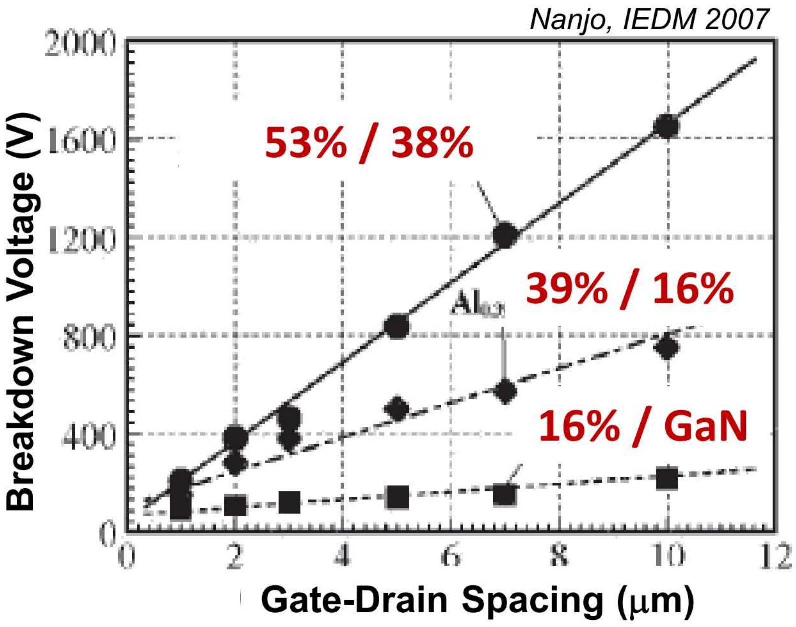
- **1200 V GaN PiN diode, 0.36 mm^2, packaged in TO220**
- **Avalanche peak power 12 kW → Energy per pulse 3 mJ**
- **Avalanche current increased after each 10^5 pulse cycle**
- **Number of surviving parts recorded; no parametric degradation for survivors**
- ***Demonstrated for vertical GaN, but not UWBG materials***

O. Aktas and I. C. Kizilyalli, IEEE EDL 36(9), 890 (2015); I. Kizilyalli et al., Mic. Rel. 55, 1654 (2015)

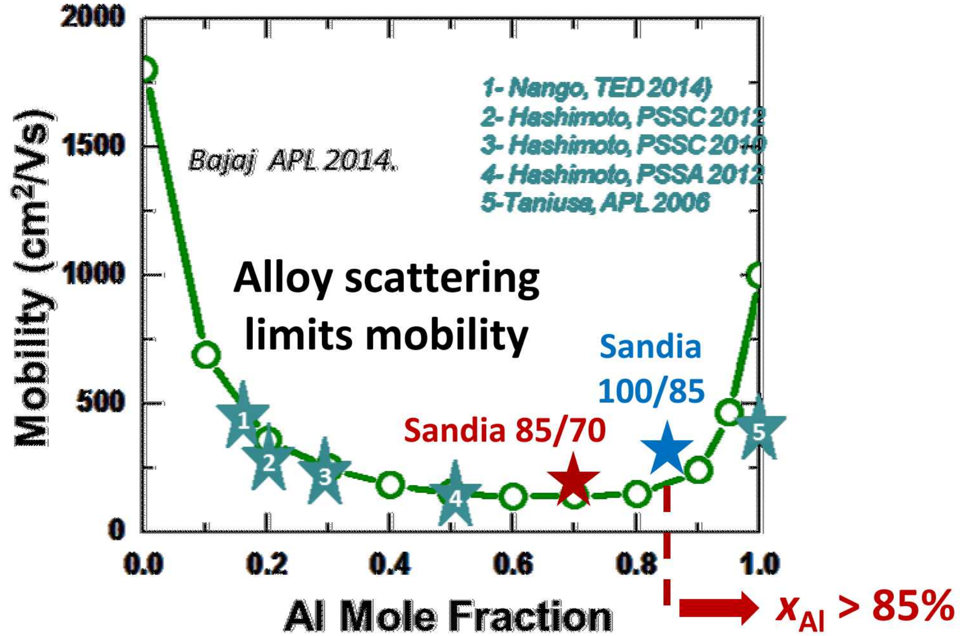
U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Tradeoffs Between Higher Critical Field and Reduced Mobility

Breakdown voltage of AlGaN HEMTs vs. G-D spacing



Electron mobility vs. AlGaN channel composition



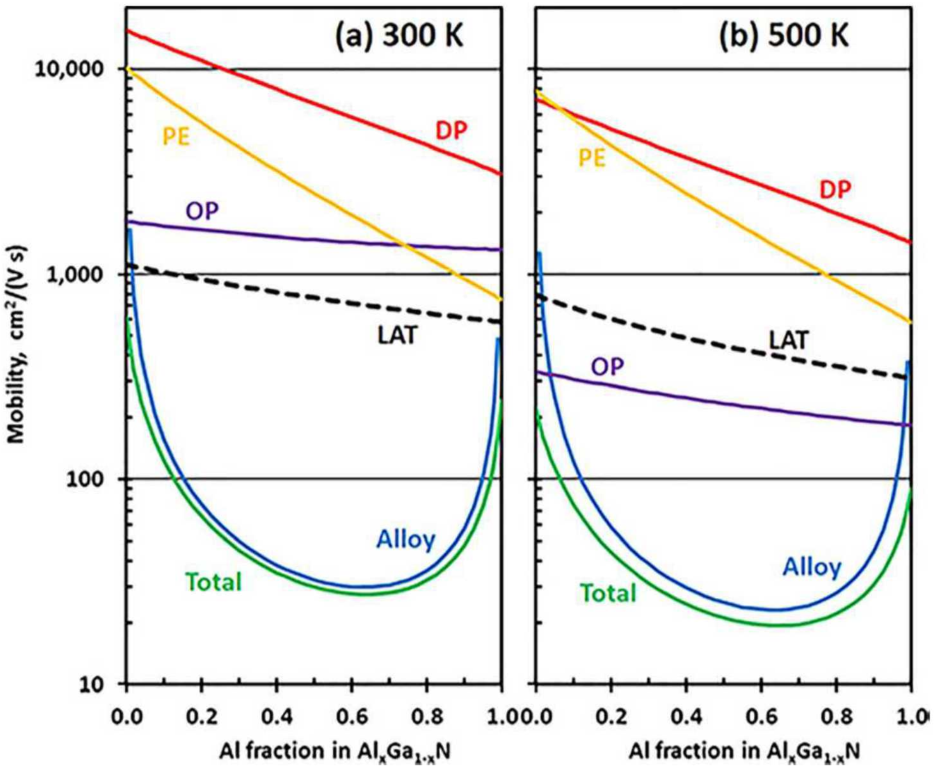
Higher Al compositions:
➡ ***Higher breakdown voltages***

Highest Al compositions:
➡ ***Higher mobility is predicted***

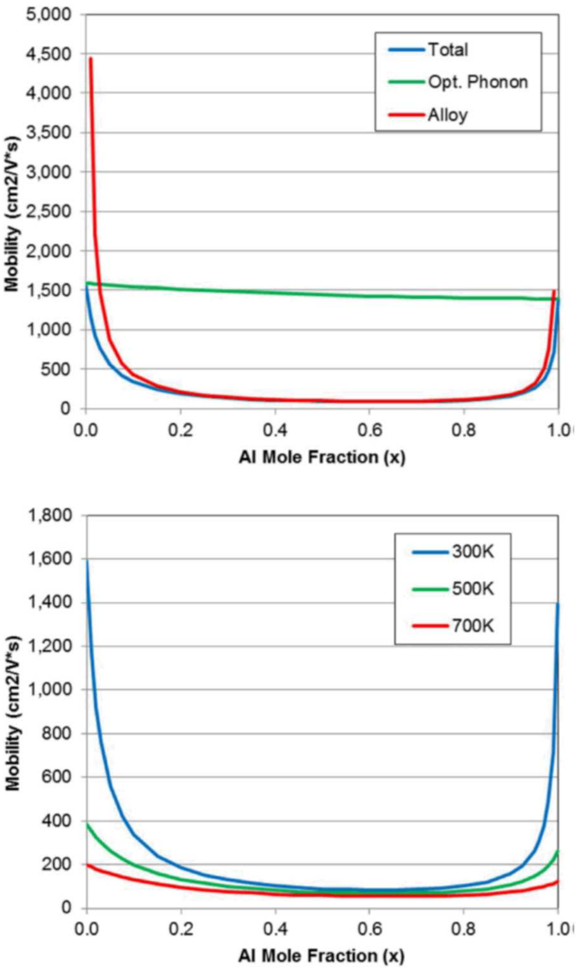
Thermal conductivity has similar issue

Bulk and 2DEG Transport in AlGaN

Bulk



2DEG

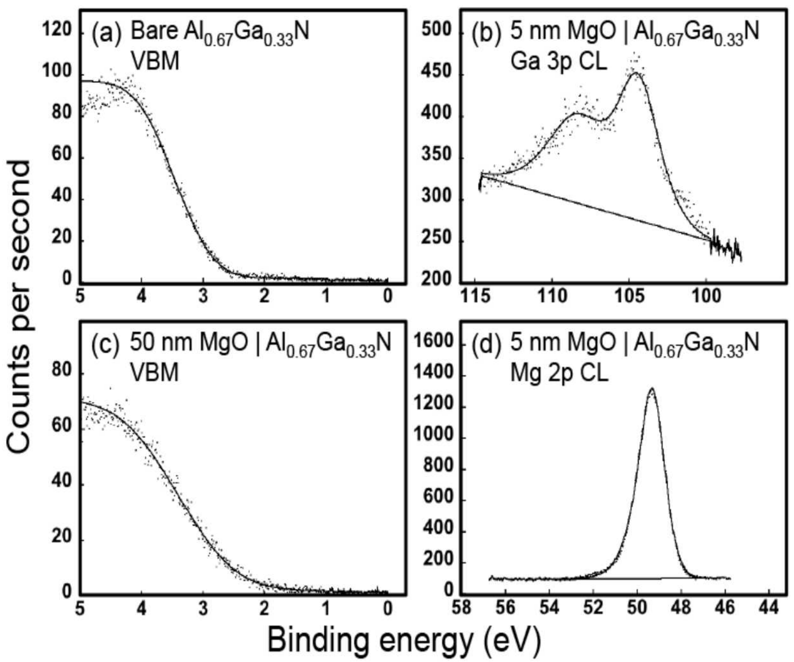


- **Alloy scattering dominates low-field transport in AlGaN**
- **Results in weak temperature dependence**

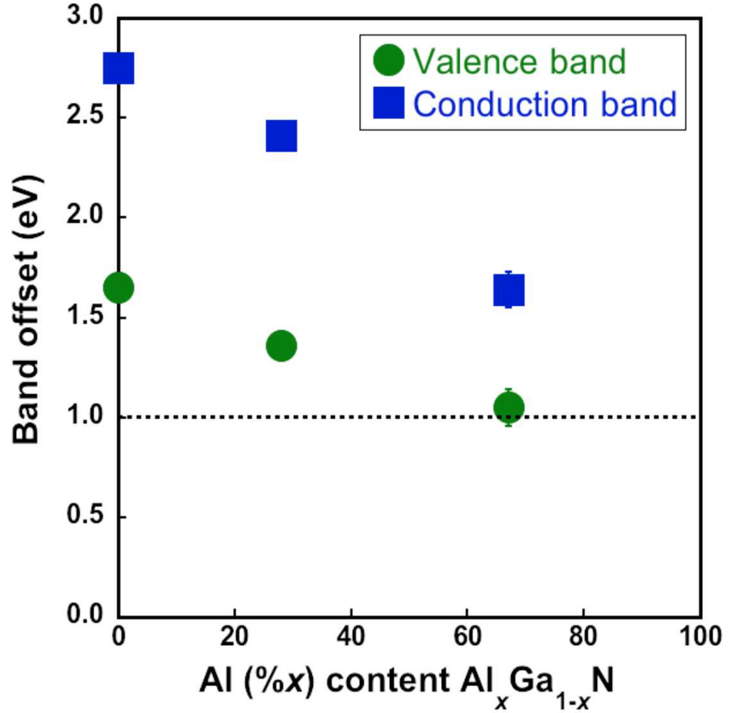
M. E. Coltrin and R. J. Kaplar, J. Appl. Phys. 121, 055706 (2017); M. E. Coltrin, A. G. Baca, and R. J. Kaplar, ECS J. Solid-State Sci. Tech. 6 (11), S3114 (2017)

Gate Dielectrics for UWBG Materials

XPS Spectra



Band Offsets

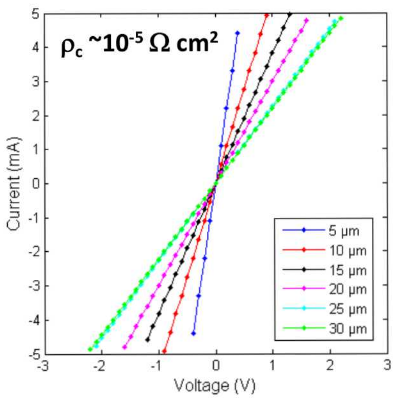


Difficult to find gate dielectrics on UWBG materials that have:

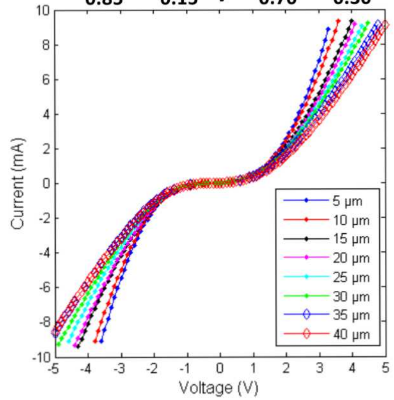
- **Sufficient band offsets**
- **Low interfacial defect density**

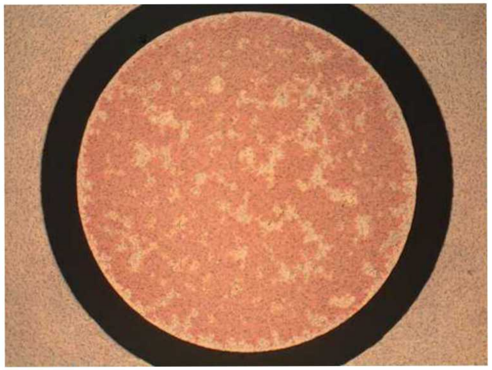
E. A. Paisley et al., Appl. Phys. Lett. 107, 102101 (2015)

Ohmic Contact Development



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





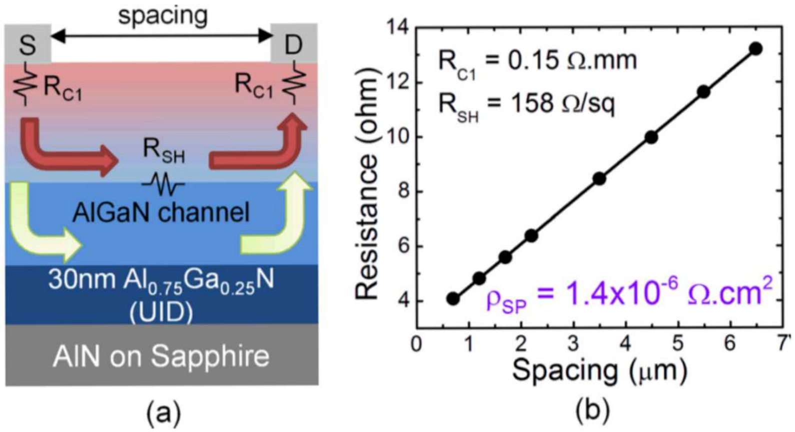
Au 50 nm
Ni 15 nm
Al 100 nm
Ti 25 nm
AlGaN/Substrate

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

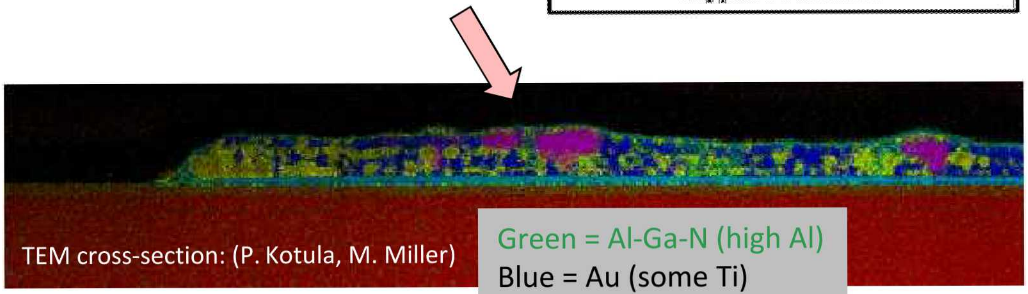
25 nm $Al_{0.85}Ga_{0.15}N$
400 nm $Al_{0.7}Ga_{0.3}N$
Graded Layer 50 nm
2.9 mm AlN
Sapphire Substrate

Graded heterostructure approach



(a) (b)

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

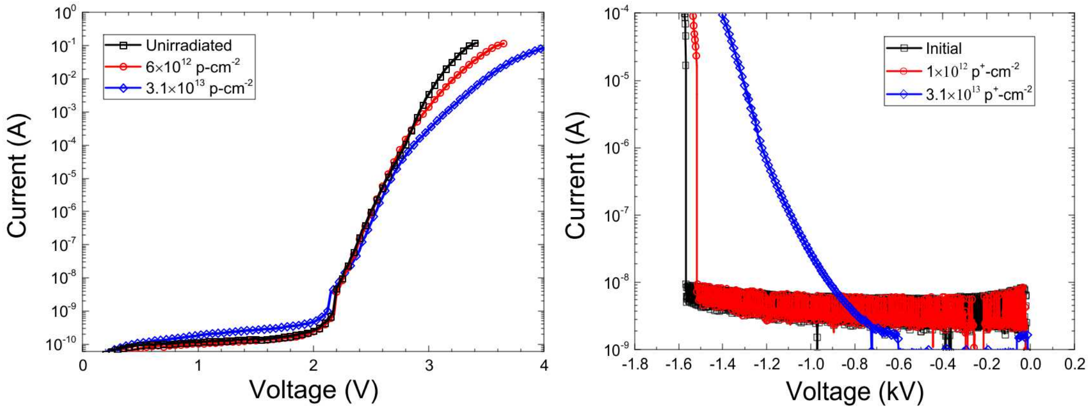


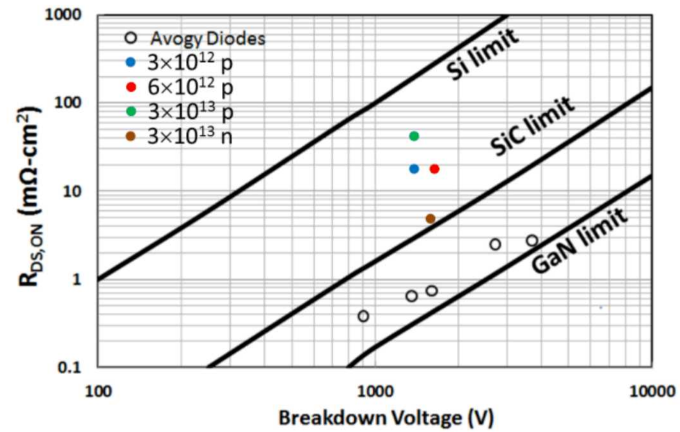
Green = Al-Ga-N (high Al)
Blue = Au (some Ti)
Cyan = Ti-Au-Al
Magenta = Ni-Al
Yellow = Al-O
Red = Al-Ga-N (low Al)

B. Klein, SNL

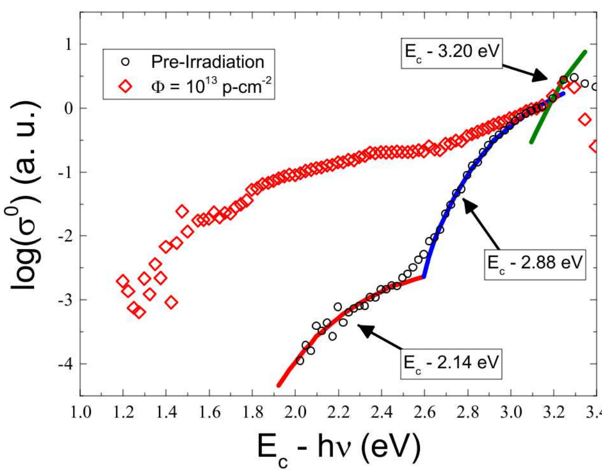
Radiation Effects

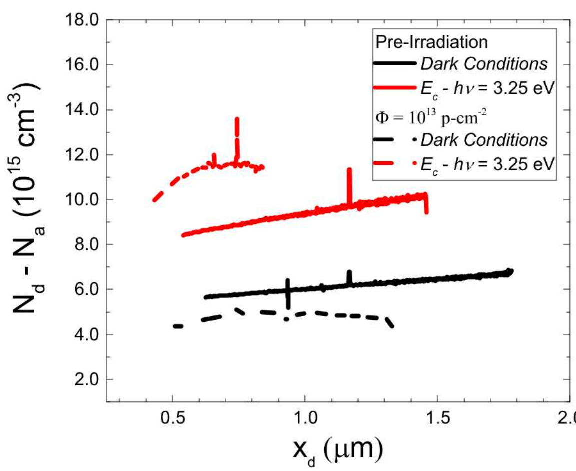
Radiation-induced changes in electrical behavior of vertical GaN PiN diodes





Performance is still better than un-irradiated Si!





Radiation-induced defects affect compensating deep-levels and carrier density; may be responsible for changes in breakdown

M. P. King et al., IEEE TNS 62(6), 2912 (2015)

Outline

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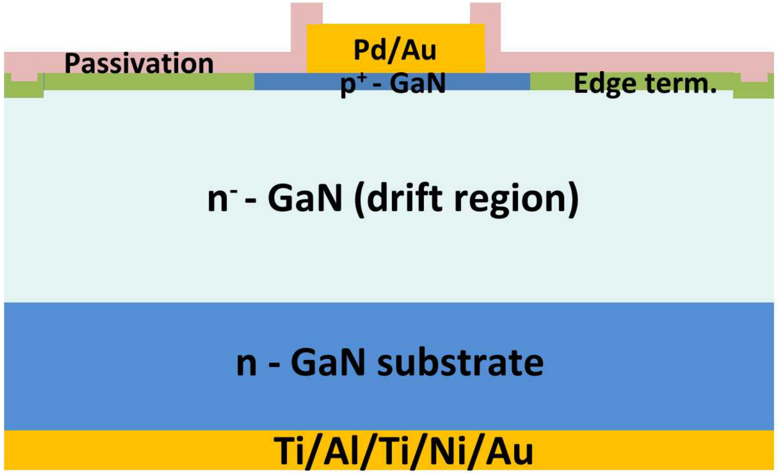
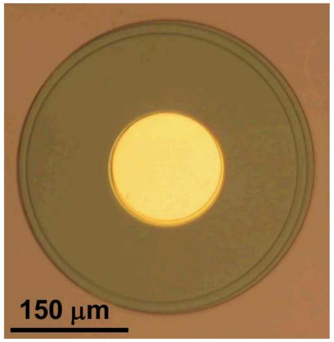
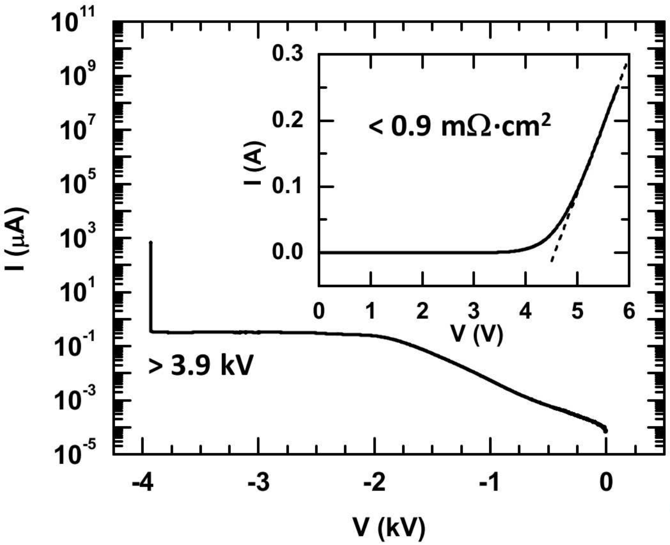
- UWBG Device Design and Fabrication Considerations
- **Examples of UWBG Devices**

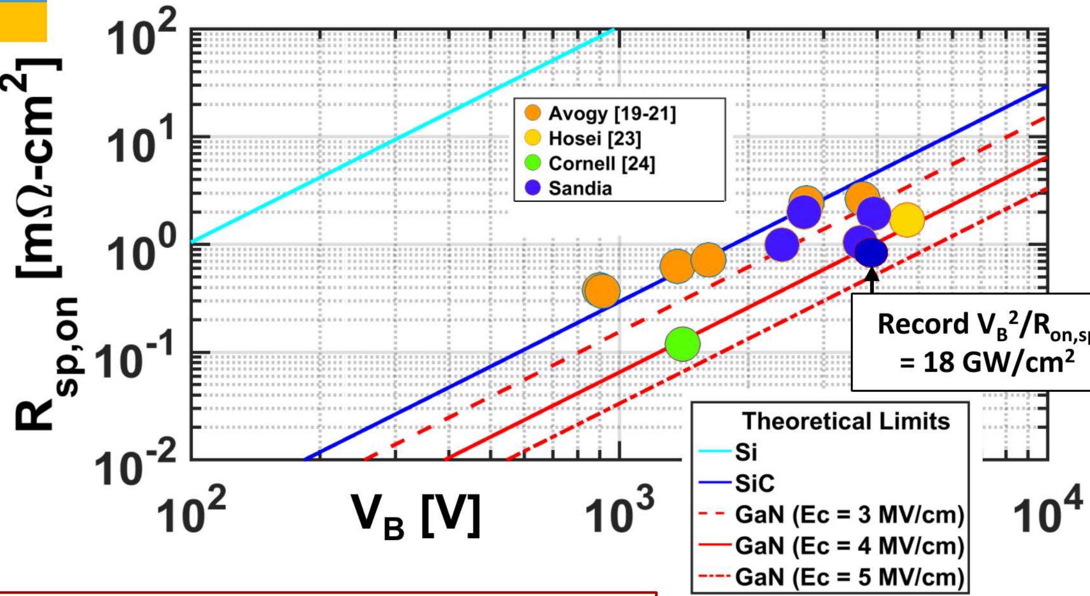
Vertical GaN PiN Diodes





- Grown by MOCVD on bulk GaN substrates
- Drift region doping mid-10^{15} cm^{-3}
- 30 μm thick drift layer





A. Armstrong et al., Elec. Lett. 52(13), 1170 (2016)

Unipolar FOM $V_B^2/R_{on,sp}$ = 18 GW/cm²

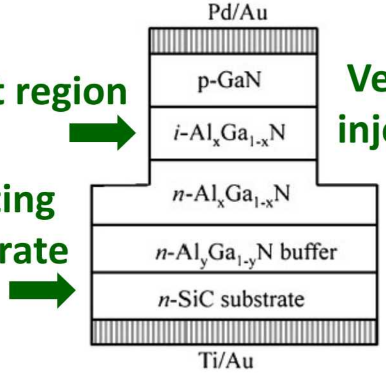
AlGaN PiN Diodes

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

- **Drift Layer: ~ 0.2 μm, N_o ~ $2x10^{16}$ cm^{-3}**
- **N-SiC substrates, $R_{on,sp}$ = 1.45 mΩ-cm² (x_{Al} = 0.22)**

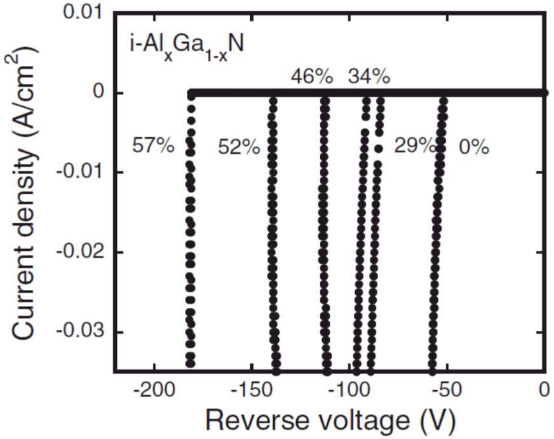
Drift region

Conducting SiC substrate

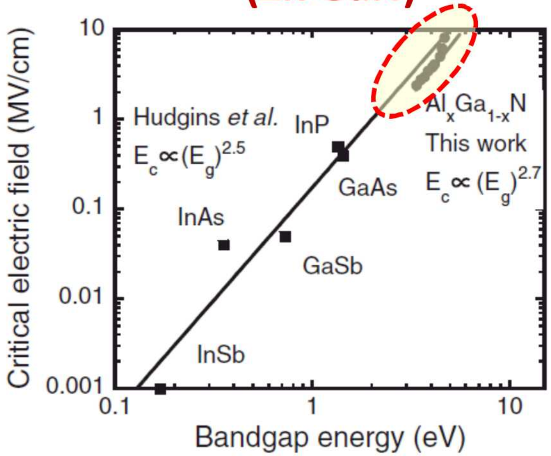


Vertical injection

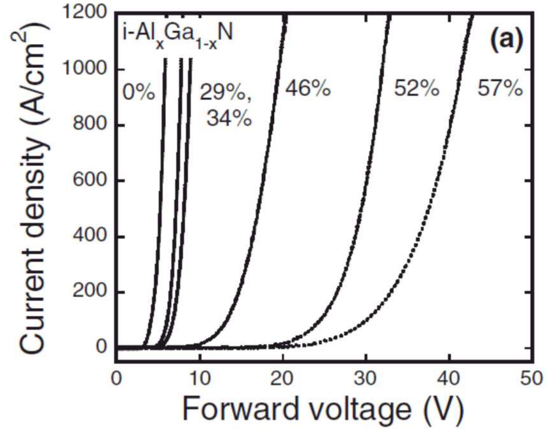
Reverse breakdown < 200 V



E_C ~ 8 MV/cm (2x GaN)



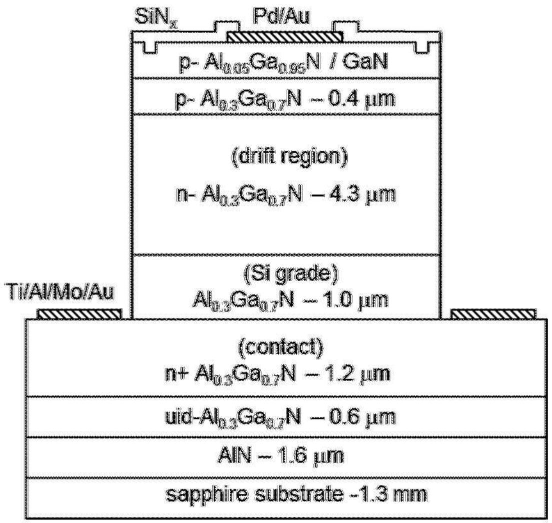
Higher forward turn-on for increasing Al %



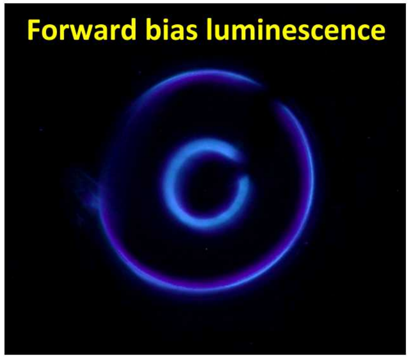
- **Breakdown voltage increases with larger bandgap**
- **Critical electric field scales as $E_G^{2.7}$**

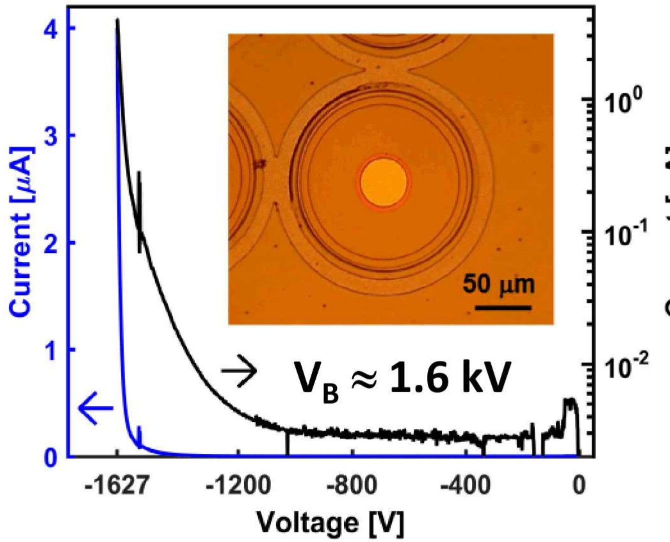
Nishikawa et al. JJAP 46 (4B), 2316 (2007)

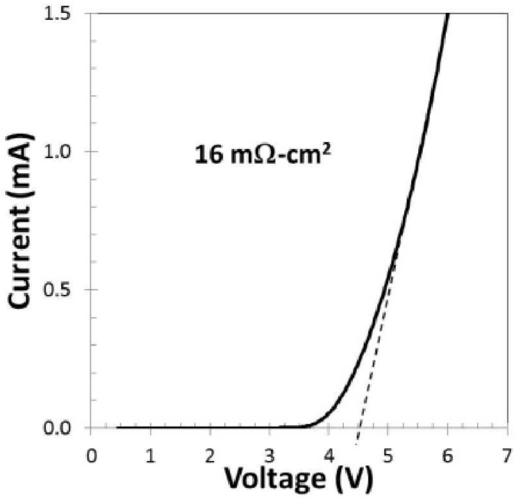
si-Vertical
iN Diode



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



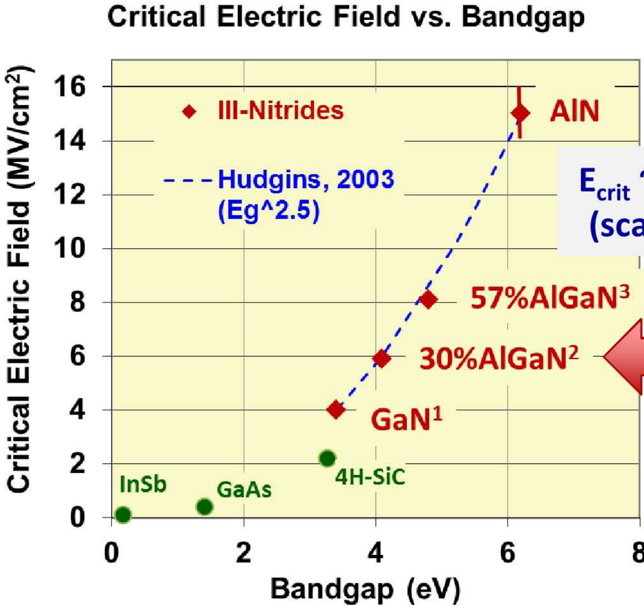




On-resistance likely limited by quasi-vertical design

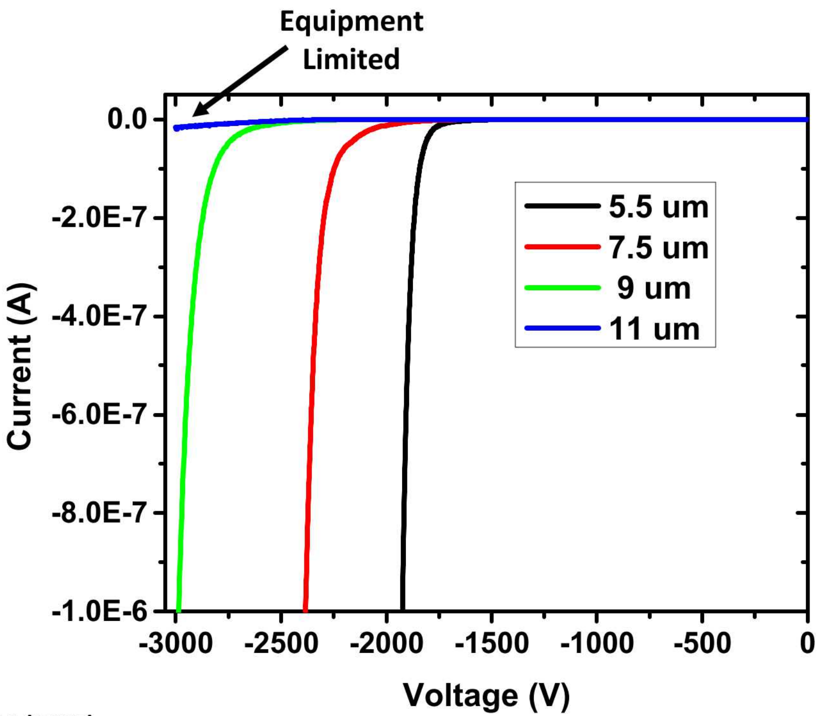
A. Allerman et al., Elec. Lett. 52(15), 1319 (2016)

Critical Electric Field Scaling and Thicker Drift Regions for Higher V_B



E_{crit} ~ 5.9 MV/cm (scaling as $E_g^{2.5}$)

- **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~$E_G^{2.5}$ scaling**

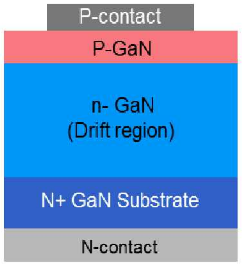


Devices grown using thicker drift regions show higher breakdown voltage

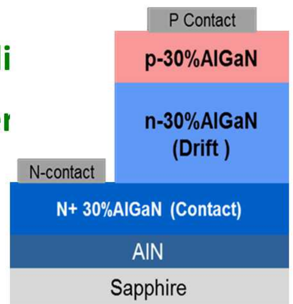
1 – Armstrong EL 2016; 2 – Allerman EL 2016; 3 – Nishikawa et al. JJAP 46 (4B), 2316 (2007)

Comparison of Breakdown Voltages Reported for III-N PiN Diodes

GaN diode (Vertical)



AlGaN di (Quasi-ver



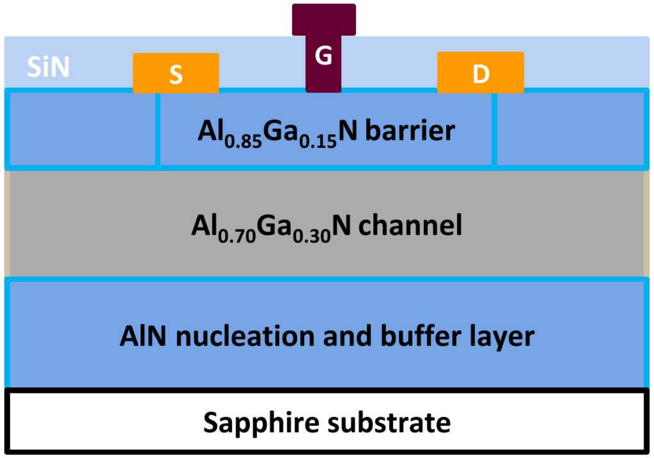
Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7 / 5.0	2-16e15	33	GaN	Hosei Univ.	EDL 36 p1180 (2015) / Jpn J Appl. P. 57 (2018)
4.0	2-5e15	40	GaN	Avogy	EDL 36 p1073 (2015)
3.9	3e15	30	GaN	Sandia	EL 52 p1170 (2016)
3.7	5e15	>30	GaN	Avogy	EDL 35 p247 (2014)
3.5	1-12e15	32	GaN	Hosei Univ.	IEDM15-237 (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

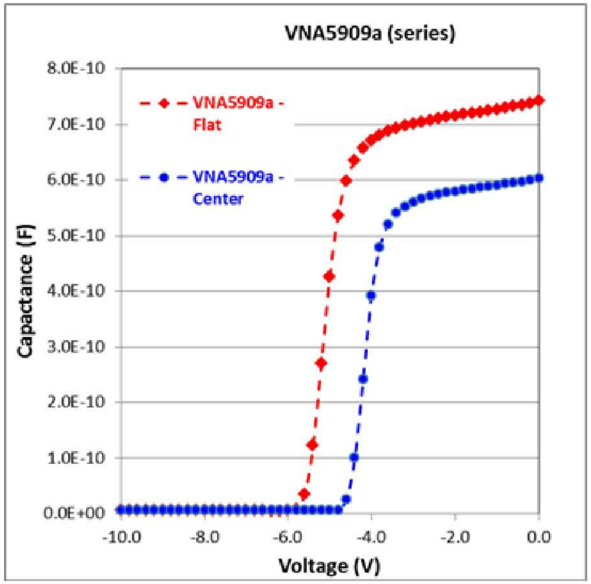
	GaN	$Al_{0.3}Ga_{0.7}N$	
N_o (cm^{-3})	low 10^{15}	low 10^{16}	← Larger E_C & E_G
Drift (μm)	20-30	~10	
TDD (cm^{-2})	≤ 10^6	low 10^9	← Impact?

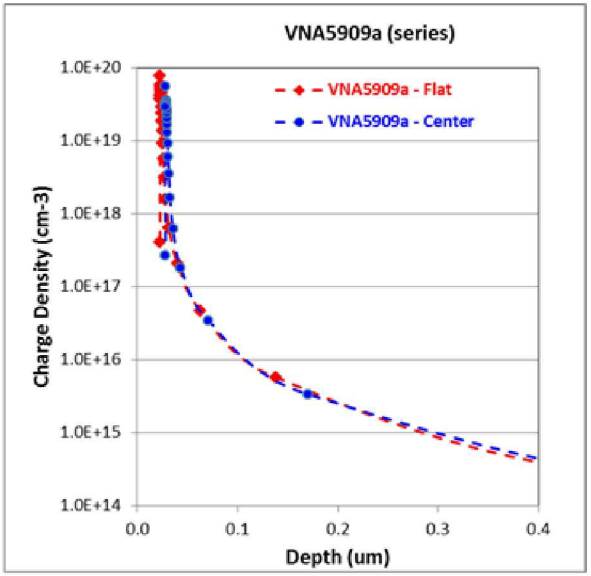
A. Allerman, SNL

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



CV Characterization





Process Steps:

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

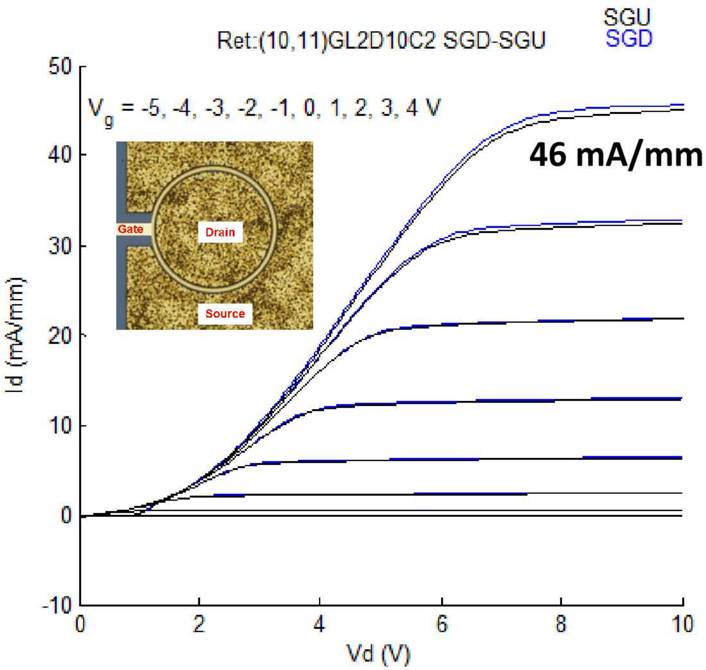
Planar source and drain contacts

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

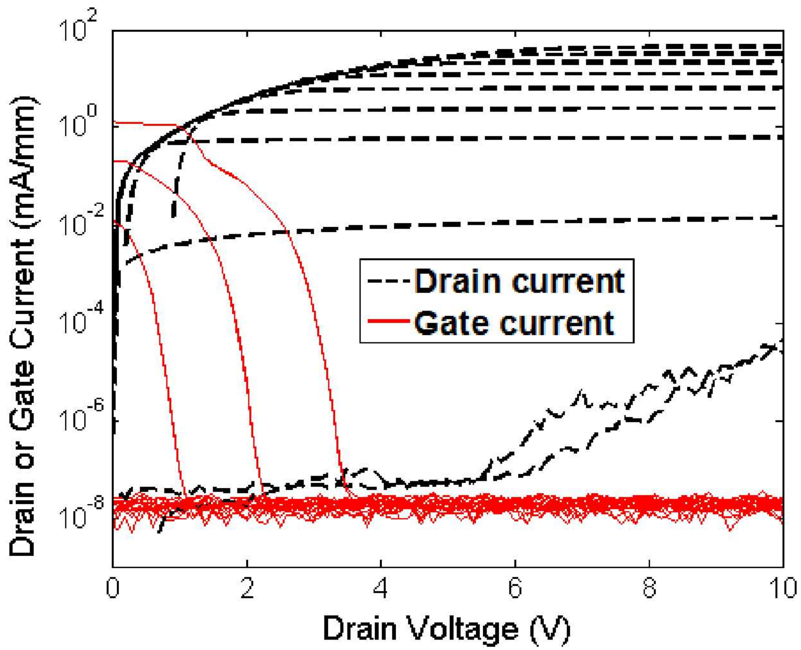
A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017); R. J. Kaplar et al., ECS Fall Meeting (2017)

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

Linear Scale



Log Scale

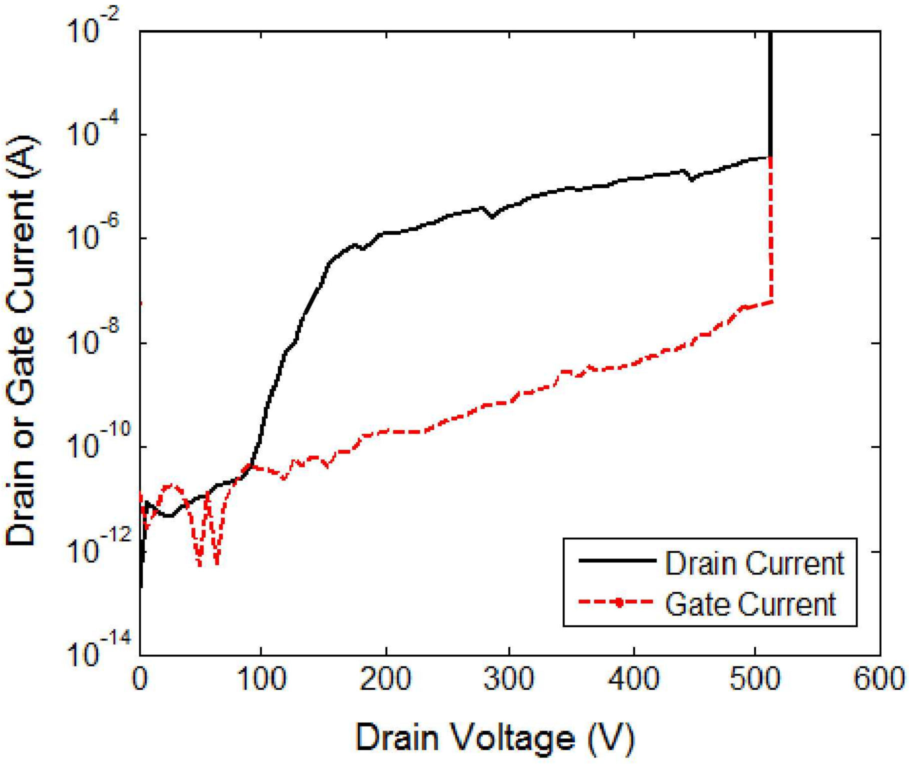


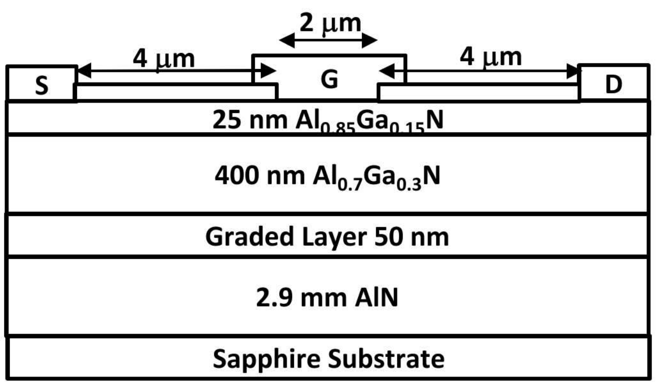
- **Better Ohmic contacts**
  - **Current density of 46 mA/mm > 20x better than first generation, but still < 2x expected**
  - **Due to remaining rectifying behavior in source and drain contacts**
  - **Again have low gate and drain leakage current**
- **Sub-threshold slope comparable to first generation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

Latest results > 120 mA/mm

A. G. Baca et al., ECS J. Solid-State Sci. Tech. 6 (12), Q161 (2017); R. J. Kaplar et al., ECS Fall Meeting (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 (single device with misalignment)**
- **Breakdown field = 95-320 V/μm (≈ 0.8-3.2 MV/cm)**
  - **Exceeds previous generation device (81 V/μm)**
  - **GaN HEMT typical breakdown field ≈ 100 V/μm**

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

Summary

- UWBG semiconductors represent the next generation of semiconductors
- Driven by applications in power switching, RF electronics, UV optoelectronics, quantum information, others
- 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 is full of examples of UWBG devices – and this is growing rapidly!